15EC81

Wireless Cellular and LTE 4G Broadband

Robin Singla
Assistant Prof.
Dept. of ECE
BMSIT

Syllabus:-
Module – 1

Key Enablers for LTE features: OFDM, Single carrier FDMA, Single carrier FDE, Channel Dependent Multiuser Resource Scheduling, Multiantenna Techniques, IP based Flat network Architecture, LTE Network Architecture. (Sec 1.4- 1.5 of Text).

Wireless Fundamentals: Cellular concept, Broadband wireless channel (BWC), Fading in BWC, Modeling BWC – Empirical and Statistical models, Mitigation of Narrow band and Broadband Fading. (Sec 2.2 – 2.7of Text).

Text Book :- Arunabha Ghosh, Jan Zhang, Jefferey Andrews, Riaz Mohammed, ‘Fundamentals of LTE’, Prentice Hall, Communications Engg. and Emerging Technologies.

Brief History

1. **First generation Cellular system:** Advanced mobile phone service (AMPS)
2. **2G digital cellular systems:** GSM , IS-95 CDMA, IS-136 TDMA
3. **3G broadband wireless system:** W-CDMA, CDMA-2000, EV-DO, HSPA
4. **Beyond 3G:** HSPA+, WiMAX and LTE

Brief History

1. **First generation Cellular system:** Advanced mobile phone service (AMPS)

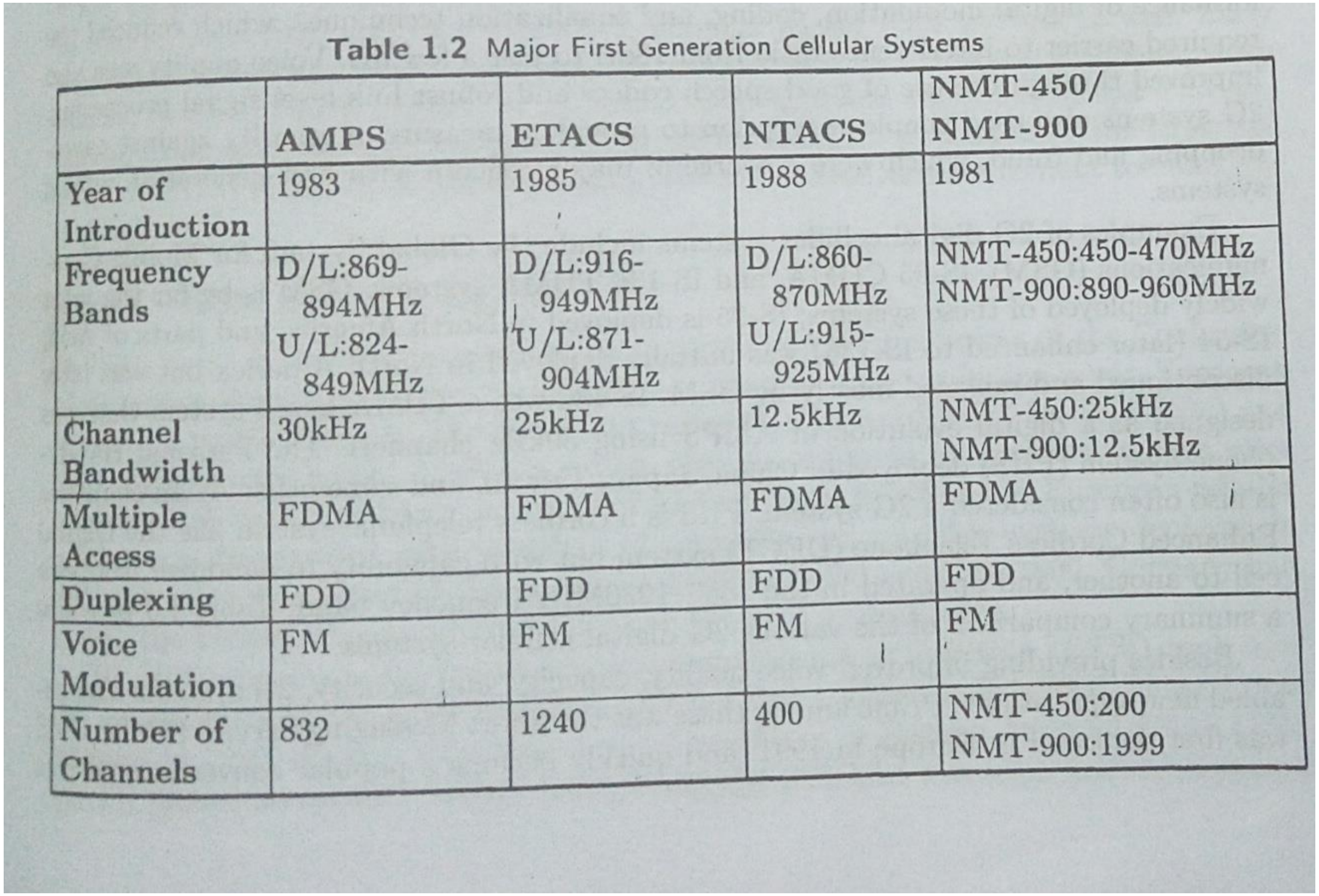


Table 1.2 Major First Generation Cellular Systems

	AMPS	ETACS	NTACS	NMT-450/ NMT-900
Year of Introduction	1983	1985	1988	1981
Frequency Bands	D/L:869-894MHz U/L:824-849MHz	D/L:916-949MHz U/L:871-904MHz	D/L:860-870MHz U/L:915-925MHz	NMT-450:450-470MHz NMT-900:890-960MHz
Channel Bandwidth	30kHz	25kHz	12.5kHz	NMT-450:25kHz NMT-900:12.5kHz
Multiple Access	FDMA	FDMA	FDMA	FDMA
Duplexing	FDD	FDD	FDD	FDD
Voice Modulation	FM	FM	FM	FM
Number of Channels	832	1240	400	NMT-450:200 NMT-900:1999

Brief History

2. 2G digital cellular systems: GSM , IS-95 CDMA, IS-136 TDMA

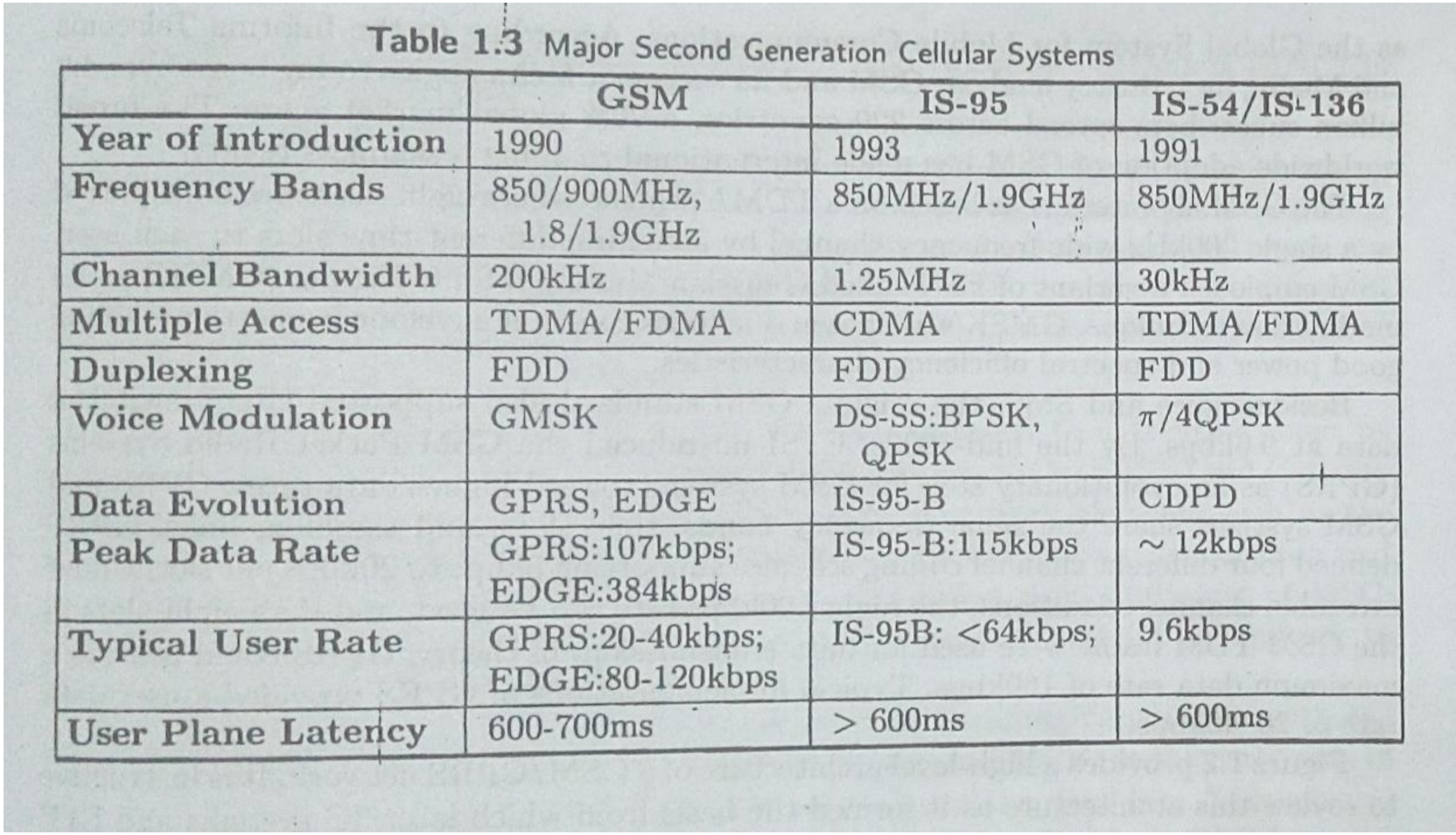


Table 1.3 Major Second Generation Cellular Systems

	GSM	IS-95	IS-54/IS-136
Year of Introduction	1990	1993	1991
Frequency Bands	850/900MHz, 1.8/1.9GHz	850MHz/1.9GHz	850MHz/1.9GHz
Channel Bandwidth	200kHz	1.25MHz	30kHz
Multiple Access	TDMA/FDMA	CDMA	TDMA/FDMA
Duplexing	FDD	FDD	FDD
Voice Modulation	GMSK	DS-SS:BPSK, QPSK	$\pi/4$QPSK
Data Evolution	GPRS, EDGE	IS-95-B	CDPD
Peak Data Rate	GPRS:107kbps; EDGE:384kbps	IS-95-B:115kbps	~ 12kbps
Typical User Rate	GPRS:20-40kbps; EDGE:80-120kbps	IS-95B: <64kbps;	9.6kbps
User Plane Latency	600-700ms	> 600ms	> 600ms

Brief History

2. **2G digital cellular systems:** GSM , IS-95 CDMA, IS-136 TDMA

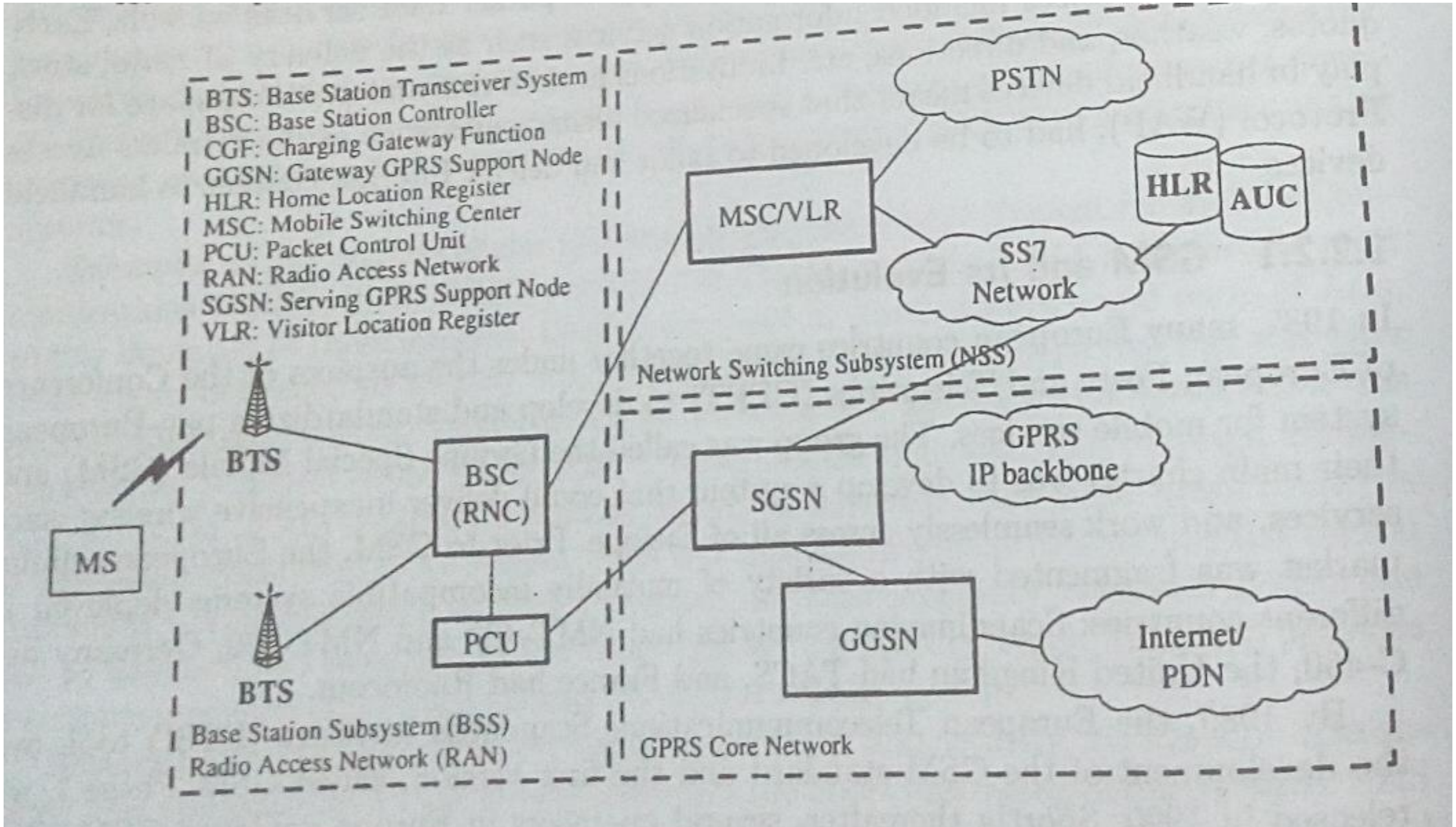


Figure 1.2 GSM network architecture.

Brief History

3. **3G broadband wireless system:** W-CDMA, CDMA-2000, EV-DO, HSPA

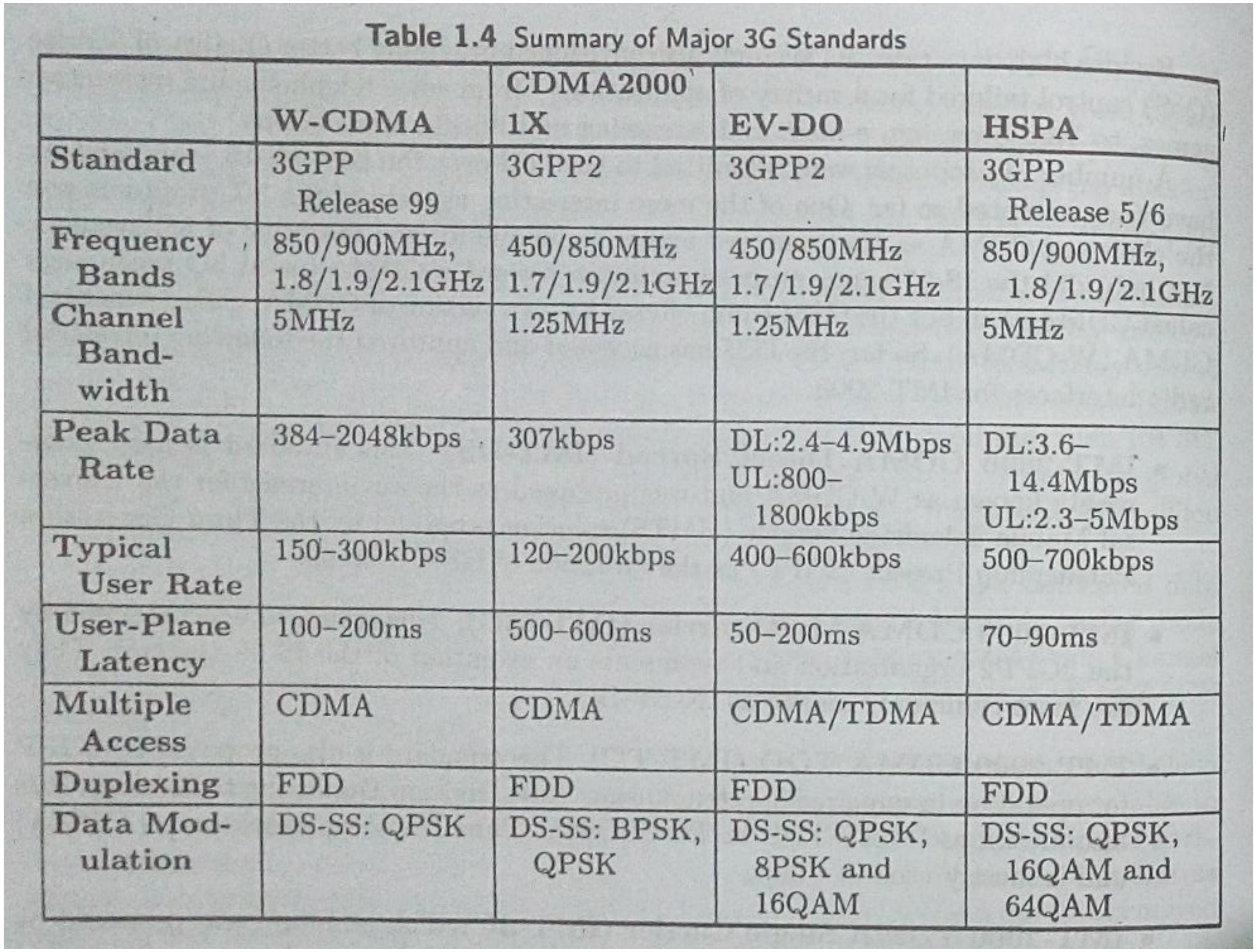


Table 1.4 Summary of Major 3G Standards

	W-CDMA	CDMA2000 1X	EV-DO	HSPA
Standard	3GPP Release 99	3GPP2	3GPP2	3GPP Release 5/6
Frequency Bands	850/900MHz, 1.8/1.9/2.1GHz	450/850MHz 1.7/1.9/2.1GHz	450/850MHz 1.7/1.9/2.1GHz	850/900MHz, 1.8/1.9/2.1GHz
Channel Bandwidth	5MHz	1.25MHz	1.25MHz	5MHz
Peak Data Rate	384–2048kbps	307kbps	DL:2.4–4.9Mbps UL:800–1800kbps	DL:3.6–14.4Mbps UL:2.3–5Mbps
Typical User Rate	150–300kbps	120–200kbps	400–600kbps	500–700kbps
User-Plane Latency	100–200ms	500–600ms	50–200ms	70–90ms
Multiple Access	CDMA	CDMA	CDMA/TDMA	CDMA/TDMA
Duplexing	FDD	FDD	FDD	FDD
Data Modulation	DS-SS: QPSK	DS-SS: BPSK, QPSK	DS-SS: QPSK, 8PSK and 16QAM	DS-SS: QPSK, 16QAM and 64QAM

Brief History

4. **Beyond 3G:** HSPA+, WiMAX and LTE

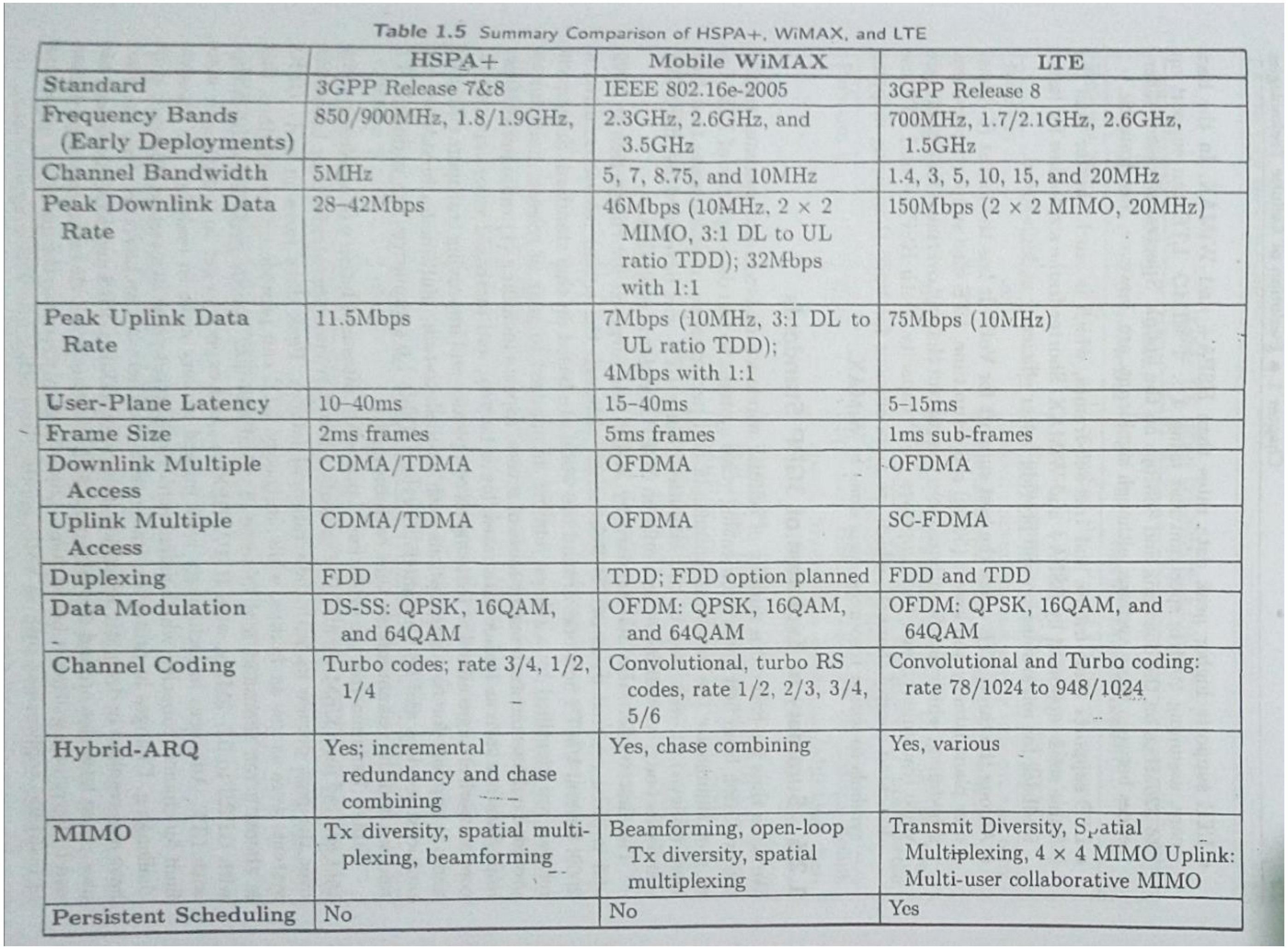


Table 1.5 Summary Comparison of HSPA+, WiMAX, and LTE

	HSPA+	Mobile WiMAX	LTE
Standard	3GPP Release 7&8	IEEE 802.16e-2005	3GPP Release 8
Frequency Bands (Early Deployments)	850/900MHz, 1.8/1.9GHz,	2.3GHz, 2.6GHz, and 3.5GHz	700MHz, 1.7/2.1GHz, 2.6GHz, 1.5GHz
Channel Bandwidth	5MHz	5, 7, 8.75, and 10MHz	1.4, 3, 5, 10, 15, and 20MHz
Peak Downlink Data Rate	28–42Mbps	46Mbps (10MHz, 2 × 2 MIMO, 3:1 DL to UL ratio TDD); 32Mbps with 1:1	150Mbps (2 × 2 MIMO, 20MHz)
Peak Uplink Data Rate	11.5Mbps	7Mbps (10MHz, 3:1 DL to UL ratio TDD); 4Mbps with 1:1	75Mbps (10MHz)
User-Plane Latency	10–40ms	15–40ms	5–15ms
Frame Size	2ms frames	5ms frames	1ms sub-frames
Downlink Multiple Access	CDMA/TDMA	OFDMA	OFDMA
Uplink Multiple Access	CDMA/TDMA	OFDMA	SC-FDMA
Duplexing	FDD	TDD; FDD option planned	FDD and TDD
Data Modulation	DS-SS: QPSK, 16QAM, and 64QAM	OFDM: QPSK, 16QAM, and 64QAM	OFDM: QPSK, 16QAM, and 64QAM
Channel Coding	Turbo codes; rate 3/4, 1/2, 1/4	Convolutional, turbo RS codes, rate 1/2, 2/3, 3/4, 5/6	Convolutional and Turbo coding: rate 78/1024 to 948/1024
Hybrid-ARQ	Yes; incremental redundancy and chase combining	Yes, chase combining	Yes, various
MIMO	Tx diversity, spatial multiplexing, beamforming	Beamforming, open-loop Tx diversity, spatial multiplexing	Transmit Diversity, Spatial Multiplexing, 4 × 4 MIMO Uplink: Multi-user collaborative MIMO
Persistent Scheduling	No	No	Yes

Demand drivers for LTE

1. **Growth in high bandwidth applications**

2. **Proliferation of smart mobile devices**

3. **Intense competition leading to flat revenues**

Key requirements for LTE design

1. **Performance on par with wired broadband**

2. **Flexible spectrum usage**

3. **Co-existence and interworking with 3G systems**

4. **Reducing cost per megabyte**

1.4 Key Enabling Technologies and Features of LTE

- LTE was required to deliver a peak data rate of 100 Mbps in the downlink and 50 Mbps in the uplink.

- LTE was required to support a spectral efficiency three to four times greater than that of Release 6 WCDMA in the downlink and two to three times greater in the uplink.

- Latency is another important issue, particularly for time-critical applications such as voice and interactive games.

1.4.1 Orthogonal Frequency Division Multiplexing (OFDM)

1.4.2 SC-FDE and SC-FDMA

1.4.3 Channel Dependent Multi-user Resource Scheduling

1.4.4 Multi-antenna Techniques

1.4 Key Enabling Technologies and Features of LTE

1.4.1 Orthogonal Frequency Division Multiplexing (OFDM)

1.1 Elegant solutions to multipath interference

1.2 Reduced computational complexity

1.3 Graceful degradation of performance under excess delay

1.4 Exploitation of frequency diversity

1.5 Enables efficient multi-access scheme

1.6 Robust against narrowband interference

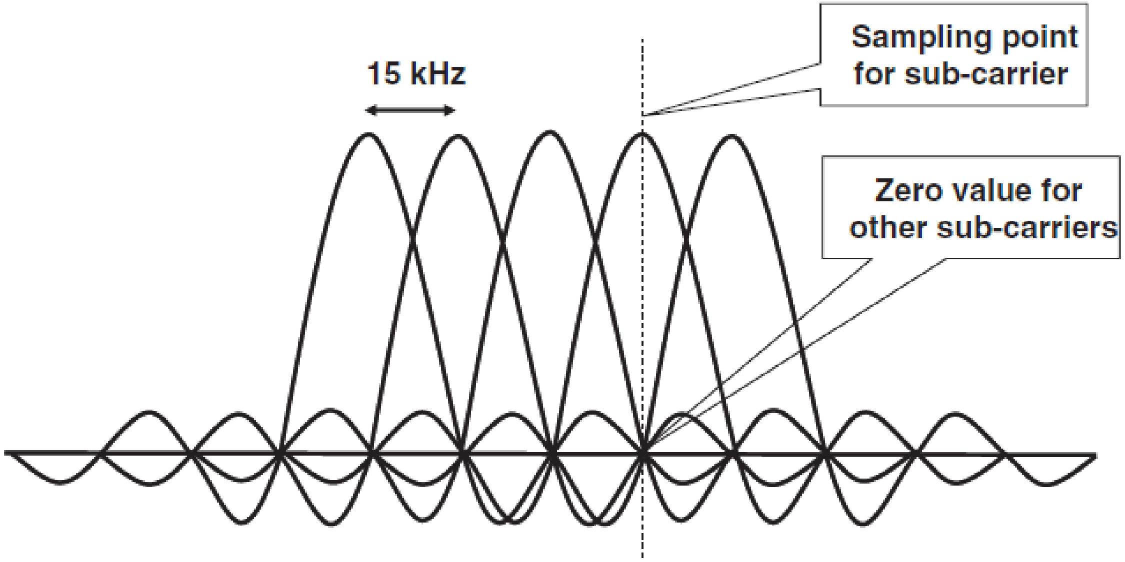
1.7 Suitable for coherent demodulation

1.8 Facilitates use of MIMO

1.9 Efficient support for broadcast services

1.4 Key Enabling Technologies and Features of LTE

1.4.1 Orthogonal Frequency Division Multiplexing (OFDM)



1.4 Key Enabling Technologies and Features of LTE

1.4.2 SC-FDE and SC-FDMA

Single Carrier Frequency Domain Equalization

The uplink of LTE implements a multiuser version of SC-FDE, called SC-FDMA

1.4 Key Enabling Technologies and Features of LTE

1.4.3 Channel Dependent Multi-user Resource Scheduling

The OFDMA scheme used in LTE provides enormous flexibility in how channel resources are allocated. OFDMA allows for allocation in both, time and frequency, and it is possible to design algorithms to allocate resources in a flexible and dynamic manner to meet arbitrary throughput, delay and other requirements.

1.4 Key Enabling Technologies and Features of LTE

1.4.4 Multi-antenna Techniques

4.1 Transmit diversity

4.2 Beamforming

4.3 Spatial multiplexing

4.4 Multi-user MIMO

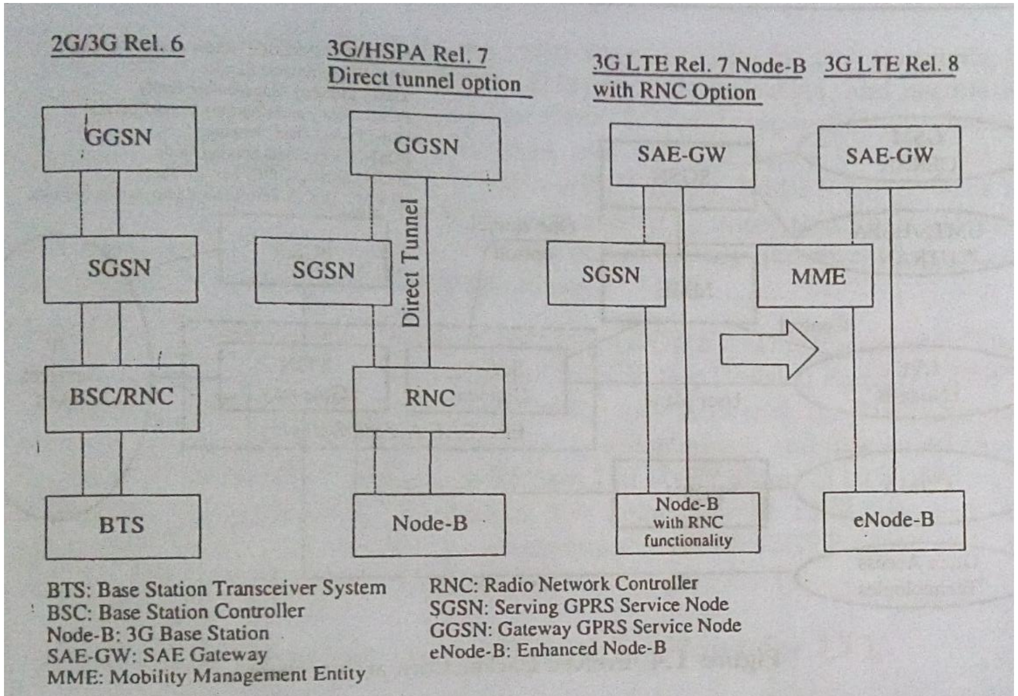
1.4.5 IP-Based Flat Network Architecture

- “Flat” here implies fewer nodes and less hierarchical structure for the network.

- The lower cost and lower latency requirements drove the design toward a flat architecture since fewer nodes obviously implies a lower infrastructure cost.

- It also means fewer interfaces and protocol related processing, and reduced interoperability testing, which lowers the development and deployment cost.

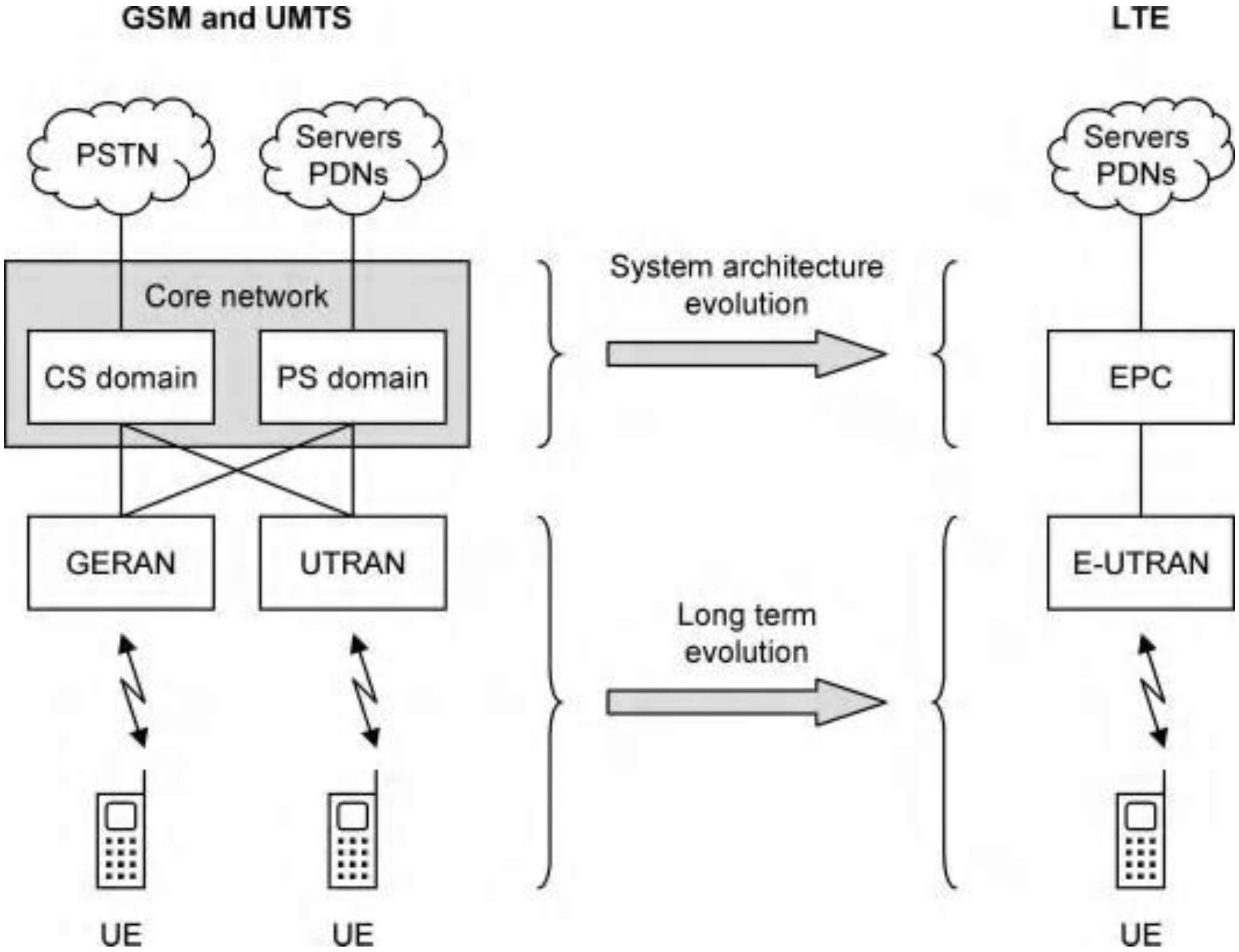
- The key aspect of LTE flat architecture is that all services, including voice, supported on IP packet network using IP protocol.



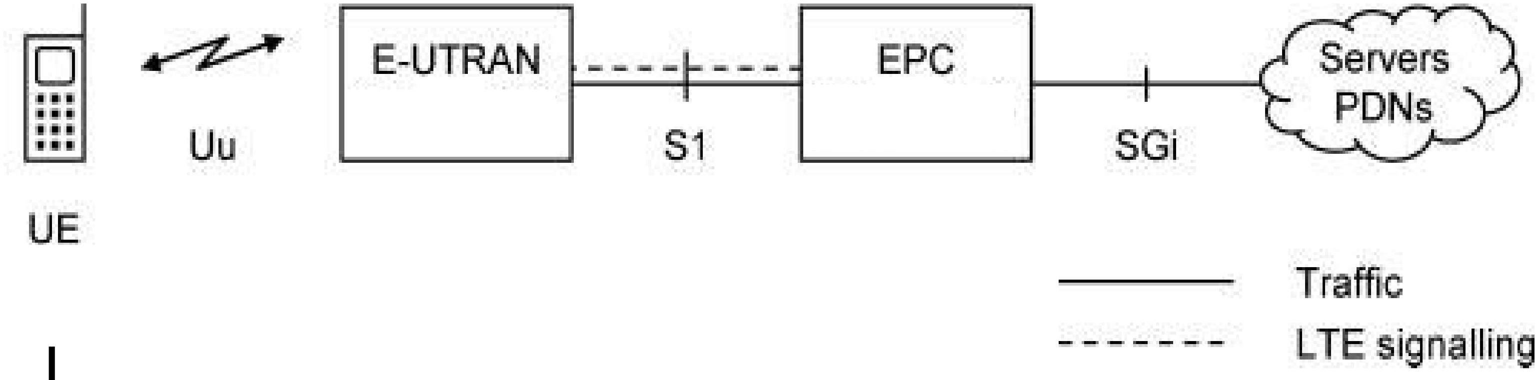
BTS: Base Station Transceiver System
BSC: Base Station Controller
Node-B: 3G Base Station
SAE-GW: SAE Gateway
MME: Mobility Management Entity
RNC: Radio Network Controller
SGSN: Serving GPRS Service Node
GGSN: Gateway GPRS Service Node
eNode-B: Enhanced Node-B

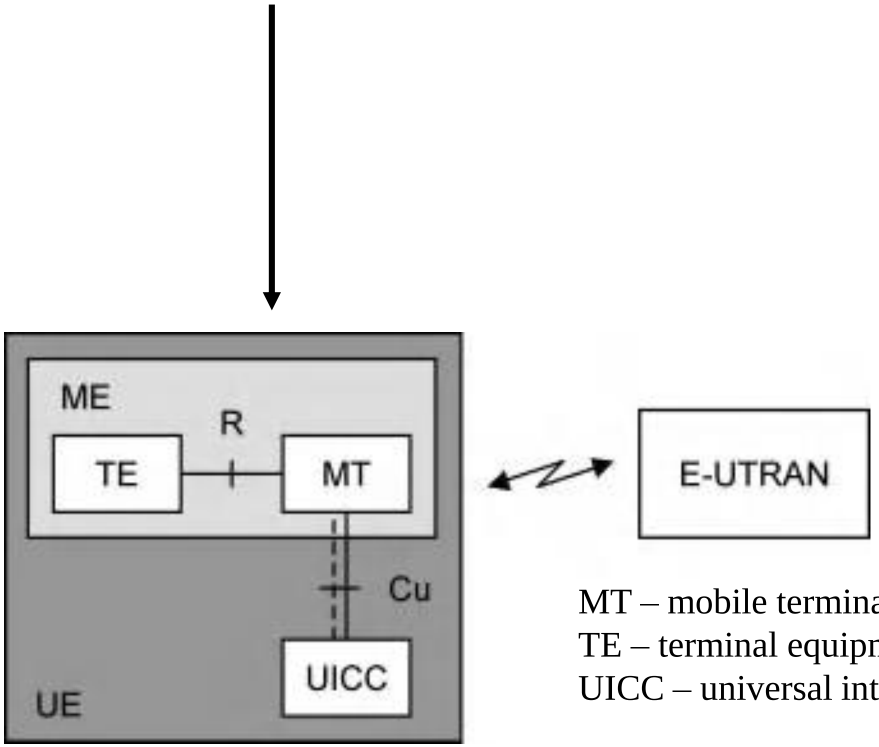
Figure 1.3 3GPP evolution toward a flat LTE SAE architecture.

1.4.5 IP-Based Flat Network Architecture



1.5 LTE Network Architecture



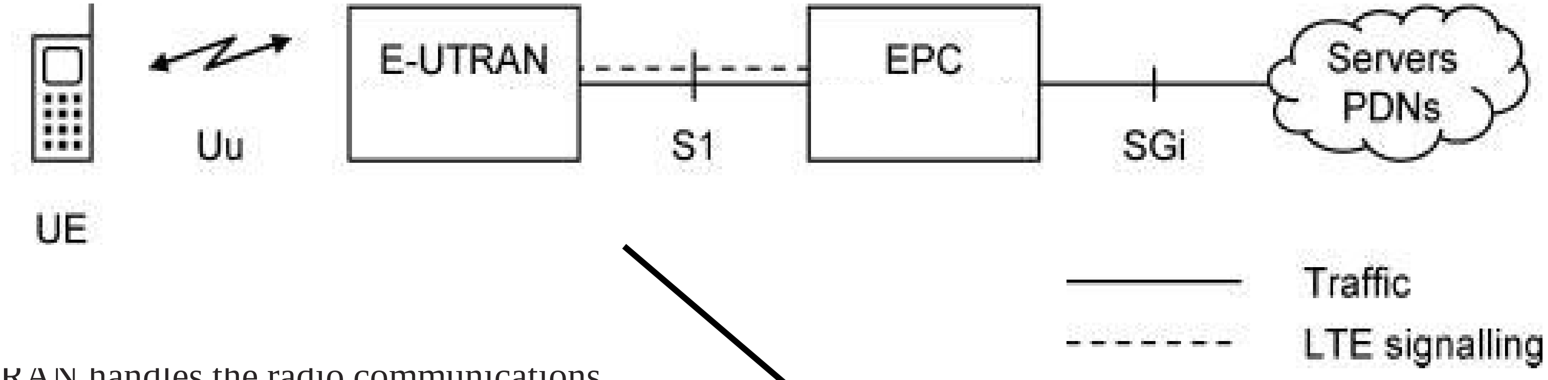


- *LTE supports mobiles that are using IP version 4 (IPv4), IP version 6 (IPv6), or dual stack IP version 4/version 6.*

MT – mobile termination
TE – terminal equipment
UICC – universal integrated circuit card

Architecture of User Equipment

1.5 LTE Network Architecture

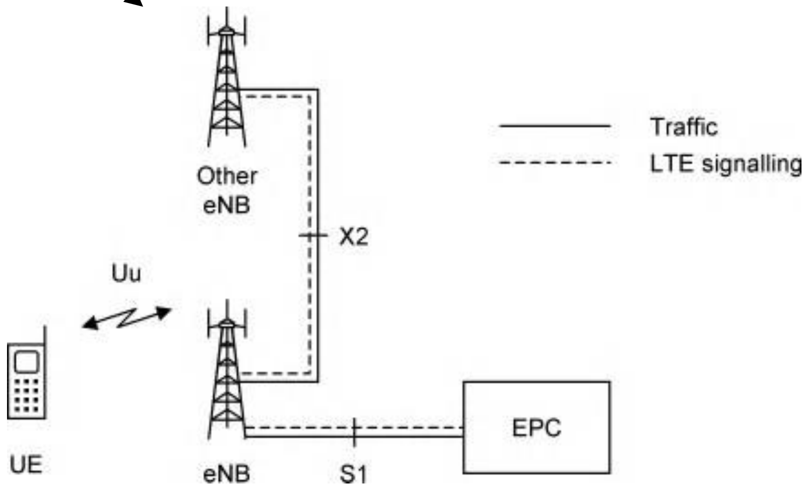


- The E-UTRAN handles the radio communications between the mobile and the evolved packet core and just has one component, the *evolved Node B* (eNB).

- Each eNB is a base station that controls the mobiles in one or more cells. A mobile communicates with just one base station and one cell at a time.

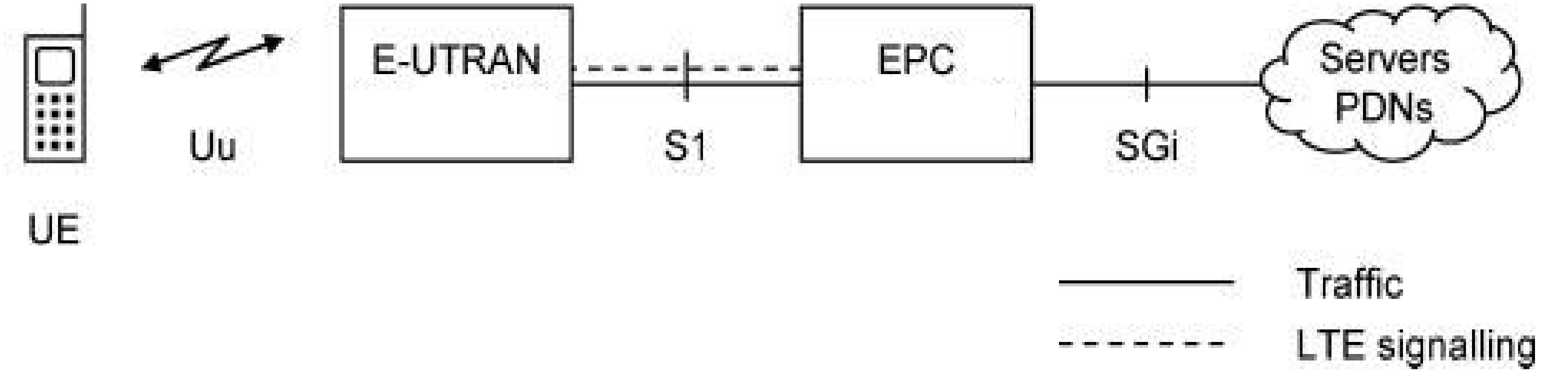
- The base station that is communicating with a mobile is known as its *serving eNB.*

- eNB sends radio transmissions to all its mobiles on the downlink and receives transmissions from them on the uplink, using the analogue and digital signal processing functions of the LTE air interface.



Architecture of the Evolved UMTS terrestrial radio access network (E-UTRAN)

1.5 LTE Network Architecture

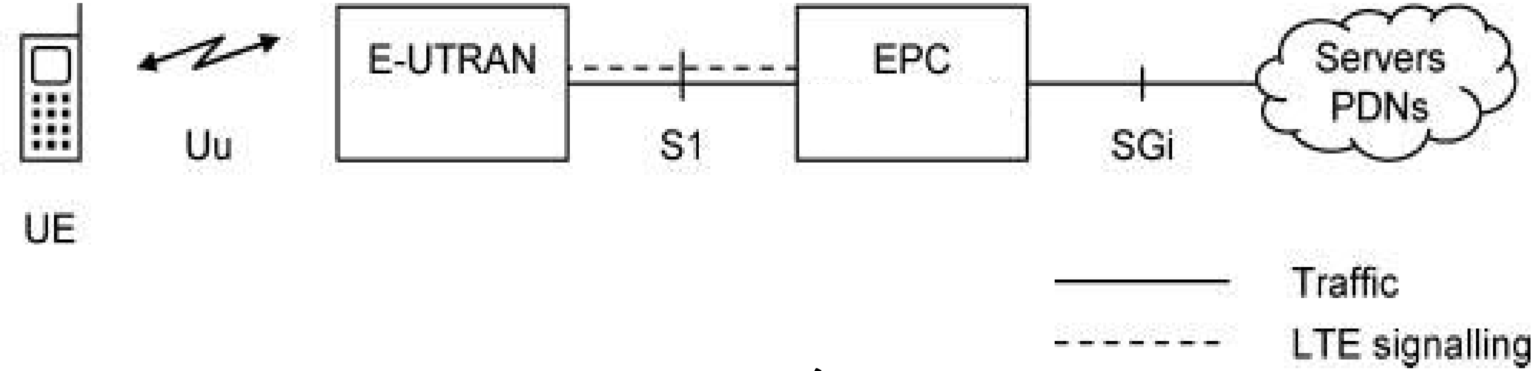


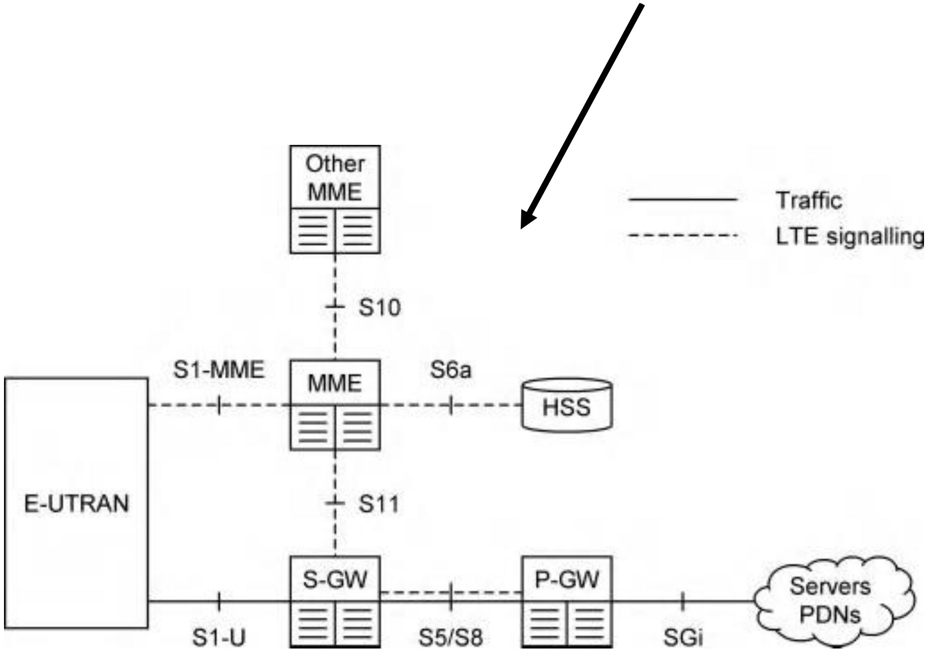
(E-UTRAN)

- eNB controls the low-level operation of all its mobiles, by sending them signalling messages such as handover commands that relate to those radio transmissions. In carrying out these functions, the eNB combines the earlier functions of the Node B and the radio network controller, to reduce the latency that arises when the mobile exchanges information with the network.

- Each base station is connected to the EPC by means of the S1 interface. It can also be connected to nearby base stations by the X2 interface, which is mainly used for signalling and packet forwarding during handover.

1.5 LTE Network Architecture





Evolved Packet Core Architecture (EPC)

1.5 LTE Network Architecture

Evolved Packet Core (EPC)

- The **EPC** is designed as a data pipe that simply transports information to and from the user and it is not concerned with the information content or with the application.

- This is similar to the behaviour of the internet, which transports packets that originate from any application software, but is different from that of a traditional telecommunication system, in which the voice application is an integral part of the system.

- Because of this, voice applications do not form part of LTE: instead, the **EPC** simply transports the voice packets in the same way as any other data stream.

- **EPC** is also required to support inter-system handovers between LTE and earlier 2G and 3G technologies. These cover not only UMTS and GSM, but also non 3GPP systems such as cdma2000 and WiMAX.

- **Home subscriber server (HSS),** which is a central database that contains information about all the network operator's subscribers. This is one of the few components of LTE that has been carried forward from UMTS and GSM.

1.5 LTE Network Architecture

Evolved Packet Core (EPC)

- **The *packet data network* (PDN)** *gateway* (P-GW) is the EPC's point of contact with the outside world.

- Through the SGi interface, each **PDN** gateway exchanges data with one or more external devices or packet data networks, such as the network operator's servers, the internet or the IP multimedia subsystem. Each packet data network is identified by an *access point name* (**APN**).

- Each mobile is assigned to a default **PDN** gateway when it first switches on, to give it always-on connectivity to a default packet data network such as the internet. Later on, a mobile may be assigned to one or more additional PDN gateways, if it wishes to connect to additional packet data networks such as private corporate networks. Each PDN gateway stays the same throughout the lifetime of the data connection.

- The ***serving gateway* (S-GW)** acts as a router, and forwards data between the base station and the PDN gateway. A typical network might contain a handful of serving gateways, each of which looks after the mobiles in a certain geographical region. Each mobile is assigned to a single serving gateway, but the serving gateway can be changed if the mobile moves sufficiently far.

- The ***mobility management entity* (MME)** controls the high-level operation of the mobile, by sending it signalling messages about issues such as security and the management of data streams that are unrelated to radio communications.

1.5 LTE Network Architecture

Evolved Packet Core (EPC)

- The ***mobility management entity*** **(MME)** controls the high-level operation of the mobile, by sending it signalling messages about issues such as security and the management of data streams that are unrelated to radio communications.

- Each mobile is assigned to a single **MME**, which is known as its ***serving MME***, but that can be changed if the mobile moves sufficiently far. The **MME** also controls the other elements of the network, by means of signalling messages that are internal to the EPC.

1.5 LTE Network Architecture

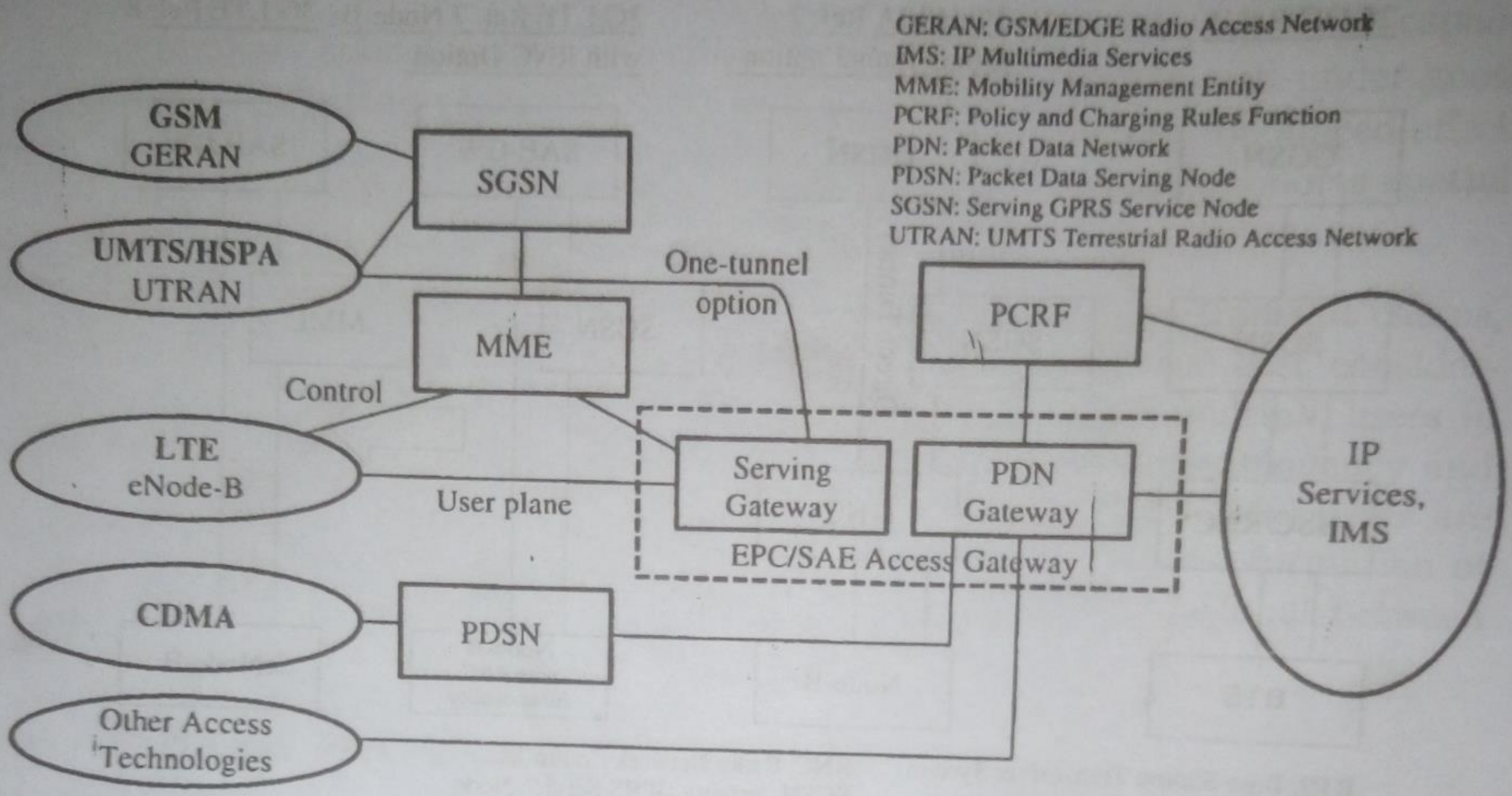


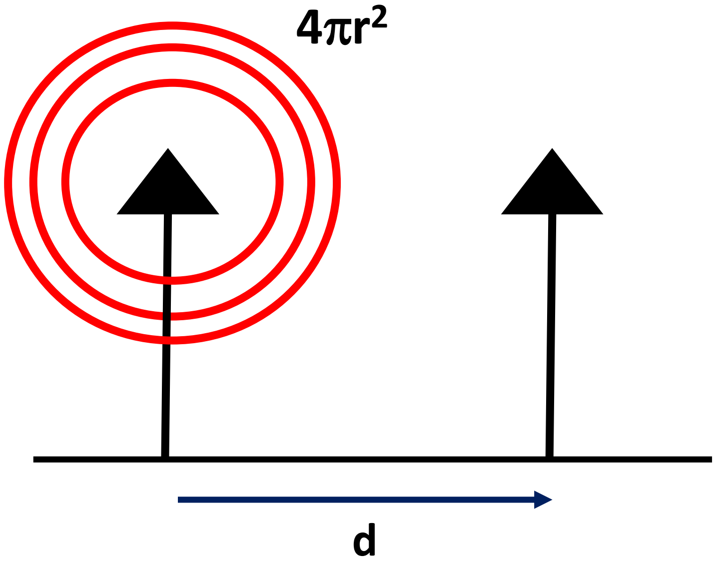
Figure 1.4 Evolved Packet Core architecture.

LTE Network Architecture from Text Book

Path Loss

- **What is Path Loss?**

  Reduction in power density of a transmitted electromagnetic wave as it propagates through space.



Pr = received power
Pt = transmitted power
λ = wavelength

$\lambda = c/f$

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

$$P_r = P_t P_0 (\frac{d_0}{d})^2$$

Shadowing

Shadowing is the effect that the received signal power fluctuates due to objects obstructing the propagation path between transmitter and receiver.

- **Is the free space in actual free?**

$$P_r = P_t P_0 \chi \left(\frac{d_0}{d}\right)^2$$

χ = sample of shadowing random process

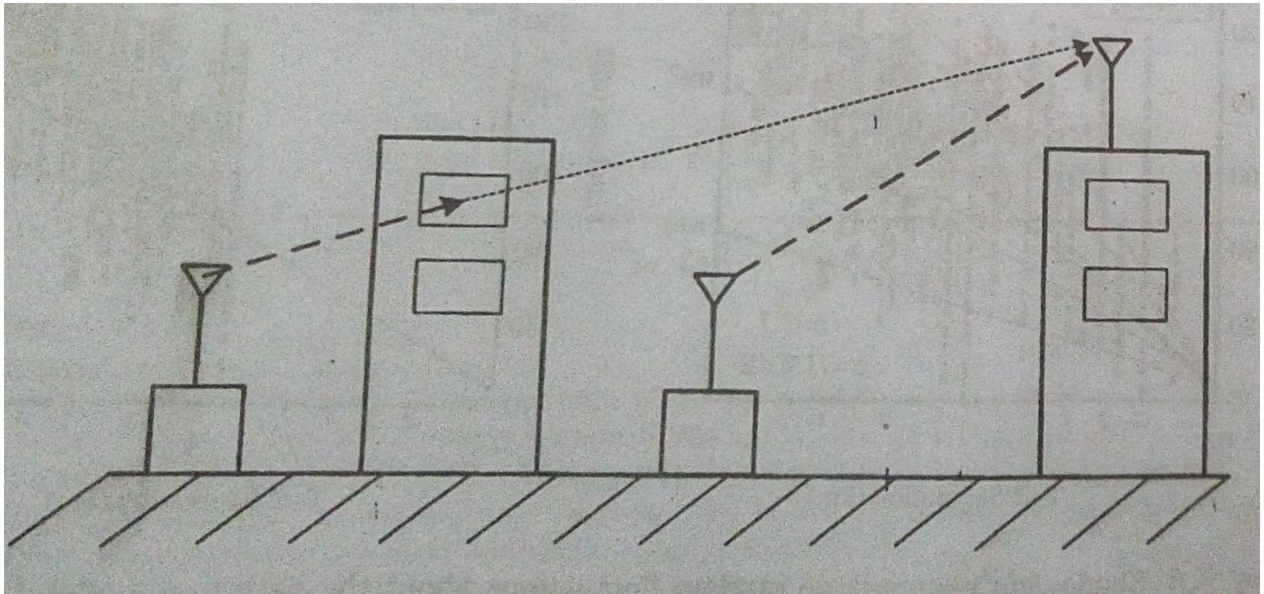


Figure 2.3 Shadowing can cause large deviations from path loss predictions.

Cellular Concept

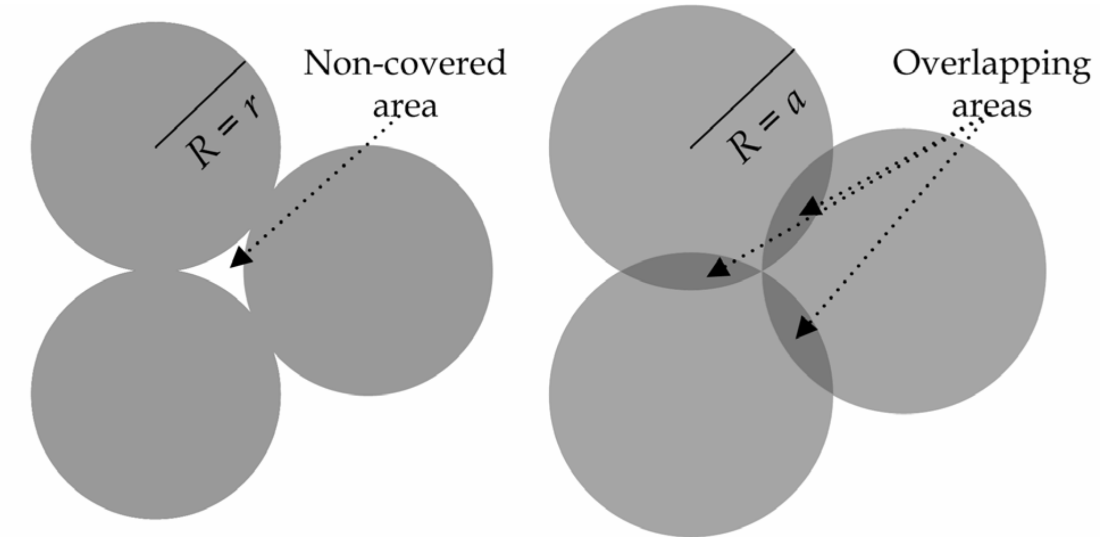
- In cellular system, the total service area is subdivided into smaller geographic areas called as cells.

- Each cell is served by their own base station.

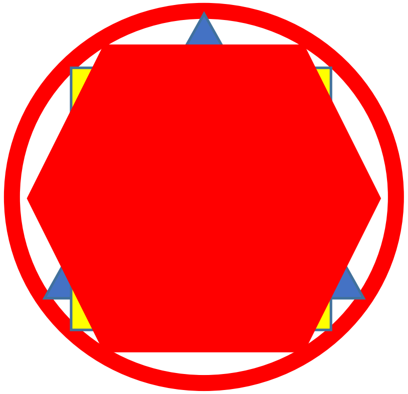
1. **Shape of area (one cell) to be covered by a base station?**
2. **How much area to be covered?**
3. **Which types of antennas to be used?**
4. **How many antennas to be used for each cell?**

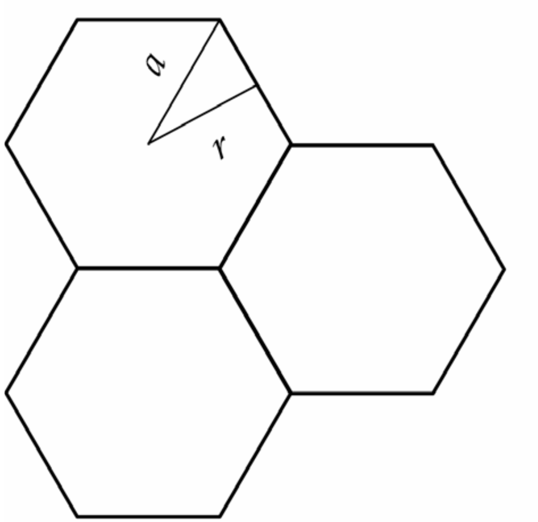
Cellular Concept

- ***Cell shape***
  - Circle
  - Triangle
  - Square
  - Hexagon



Hexagon is a regular polygon having largest area inside a circle as compared with a square or a triangle

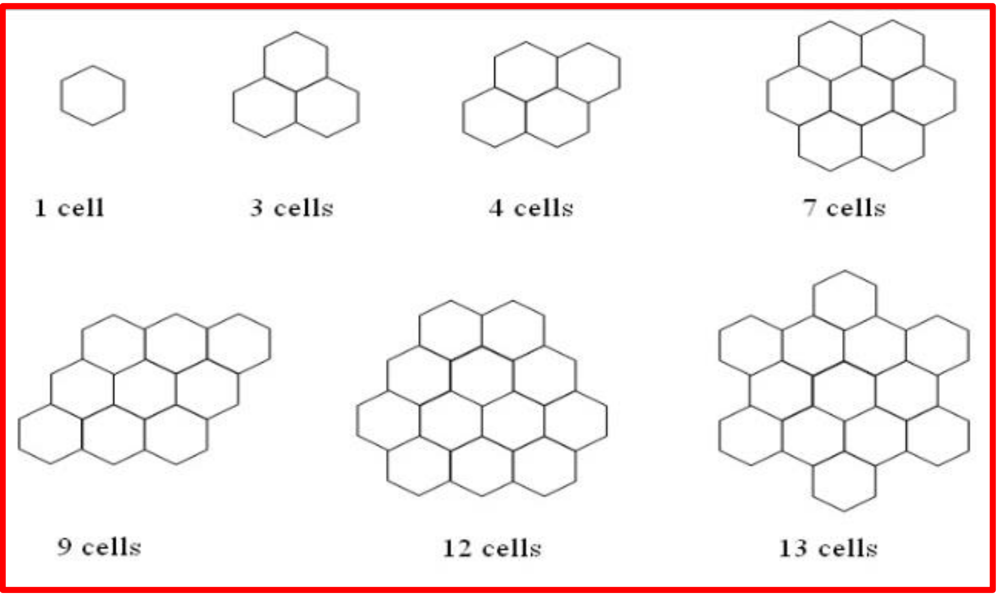


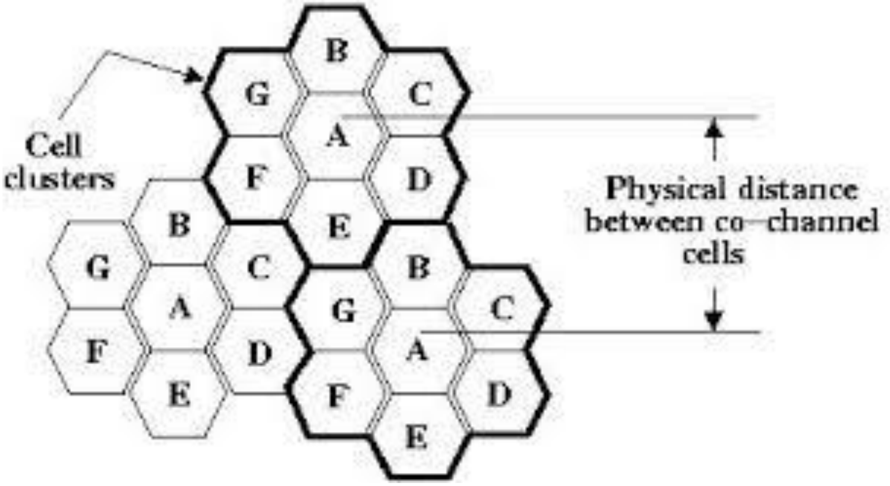


Cellular Concept

Frequency re-use

Cluster





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

f → frequency re-use factor

Cellular Concept

Frequency re-use

Co-channel interference (CCI)

$$Z = \frac{D}{R} = \sqrt{3/f}$$

Z = co-channel re-use ratio
D = distance b/w two co-channel cells
R = radius of a cell

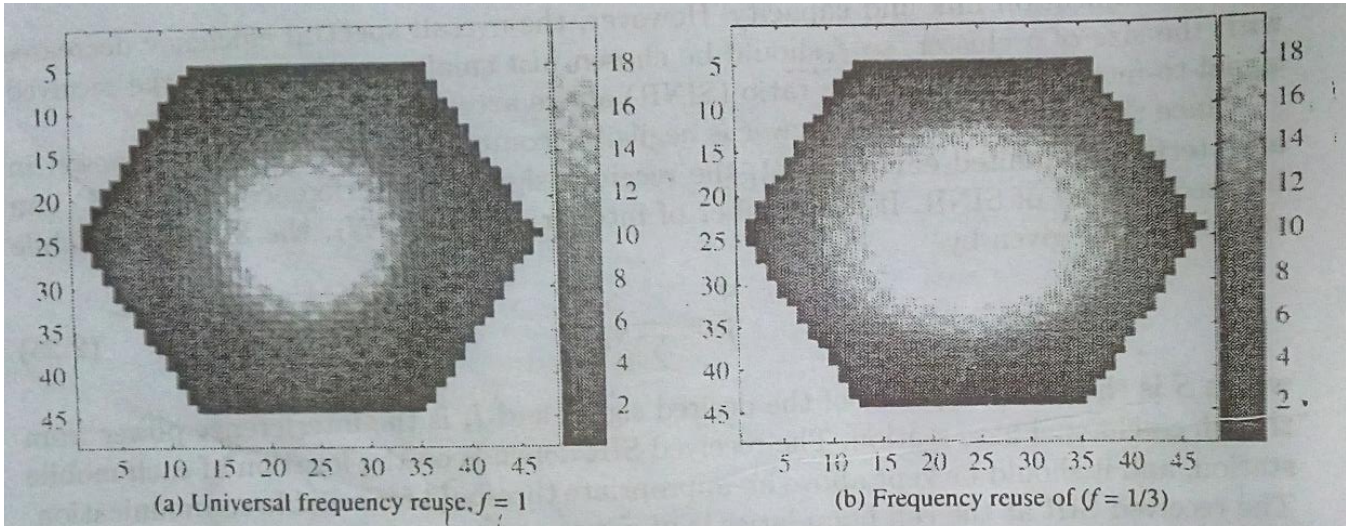
Signal to interference ratio (SIR)

$$\frac{S}{I} = \frac{S}{\sum_{i=1}^{Ni} I_i}$$

S = received power of desired signal
I_i = interference power from the ith co-channel cells
R = radius of a cell

Cellular Concept

Frequency re-use



(a) Universal frequency reuse, $f = 1$

(b) Frequency reuse of ($f = 1/3$)

Figure 2.7 The received SIR in a cell with path-loss exponent $\alpha = 3.5$. The scale on the right indicates the SIR bins, i.e., darker indicates lower SIR.

Improvement in SIR after frequency re-use

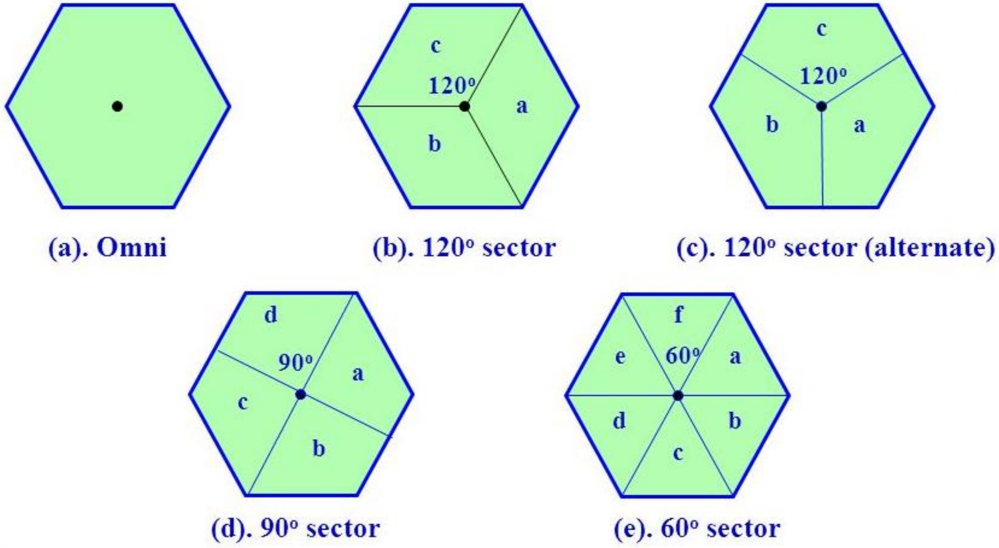
Cellular Concept

Sectoring

- Technique to improve SIR without affecting the bandwidth- sectorize the cell.

- Frequencies are re-used in each cells.

- For 3-sector cell, bandwidth increase the 3 times so the capacity of the cell.



(a). Omni

(b). 120° sector

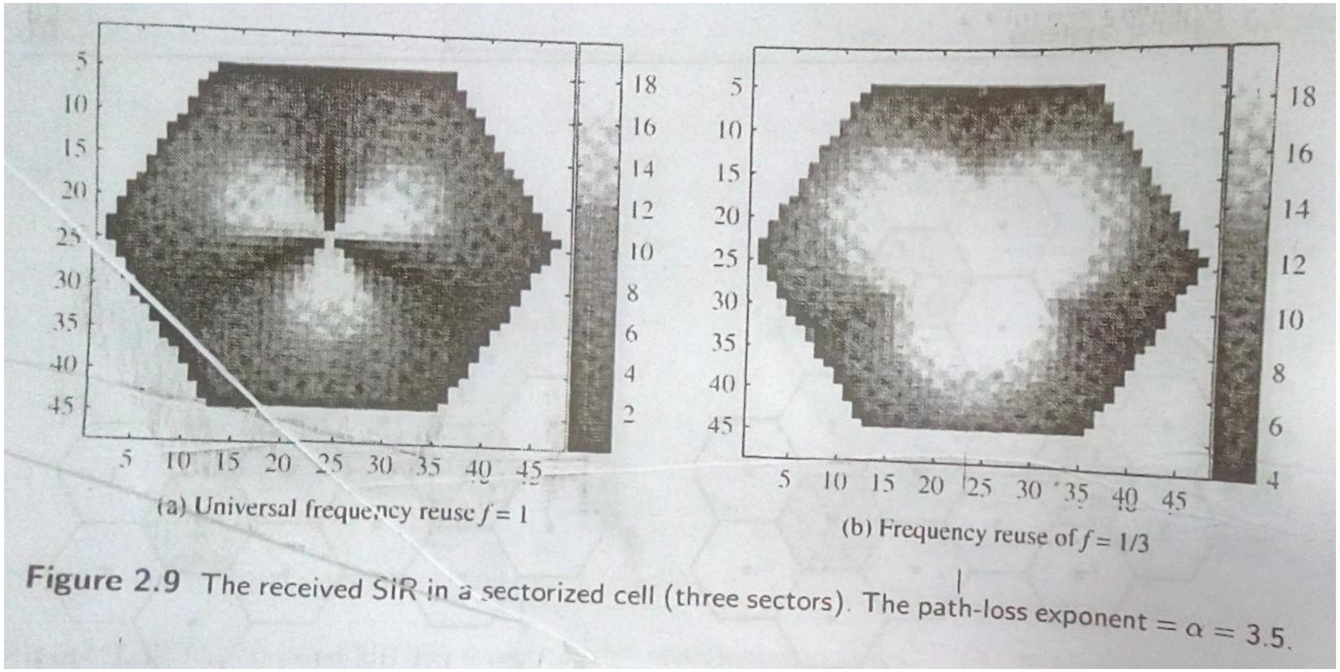
(c). 120° sector (alternate)

(d). 90° sector

(e). 60° sector

Cellular Concept

Frequency re-use



(a) Universal frequency reuse $f = 1$

(b) Frequency reuse of $f = 1/3$

Figure 2.9 The received SIR in a sectorized cell (three sectors). The path-loss exponent $= \alpha = 3.5$.

Improvement in SIR after sectoring

Multipath Fading

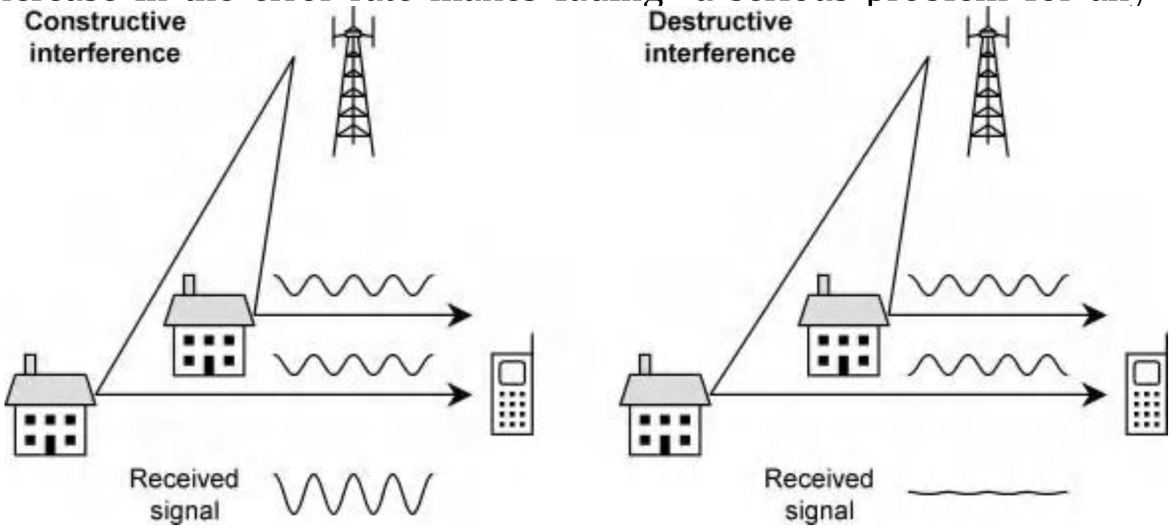
- Multipath fading occurs when signals reach a receiver via many paths and their relative strengths and phases changes.

- As a result of reflections, rays can take several different paths from the transmitter to the receiver.

- If the peaks of the incoming rays coincide then they reinforce each other, a situation known as ***constructive interference***.

- If, however, the peaks of one ray coincide with the troughs of another, then the result is ***destructive interference***, in which the rays cancel.

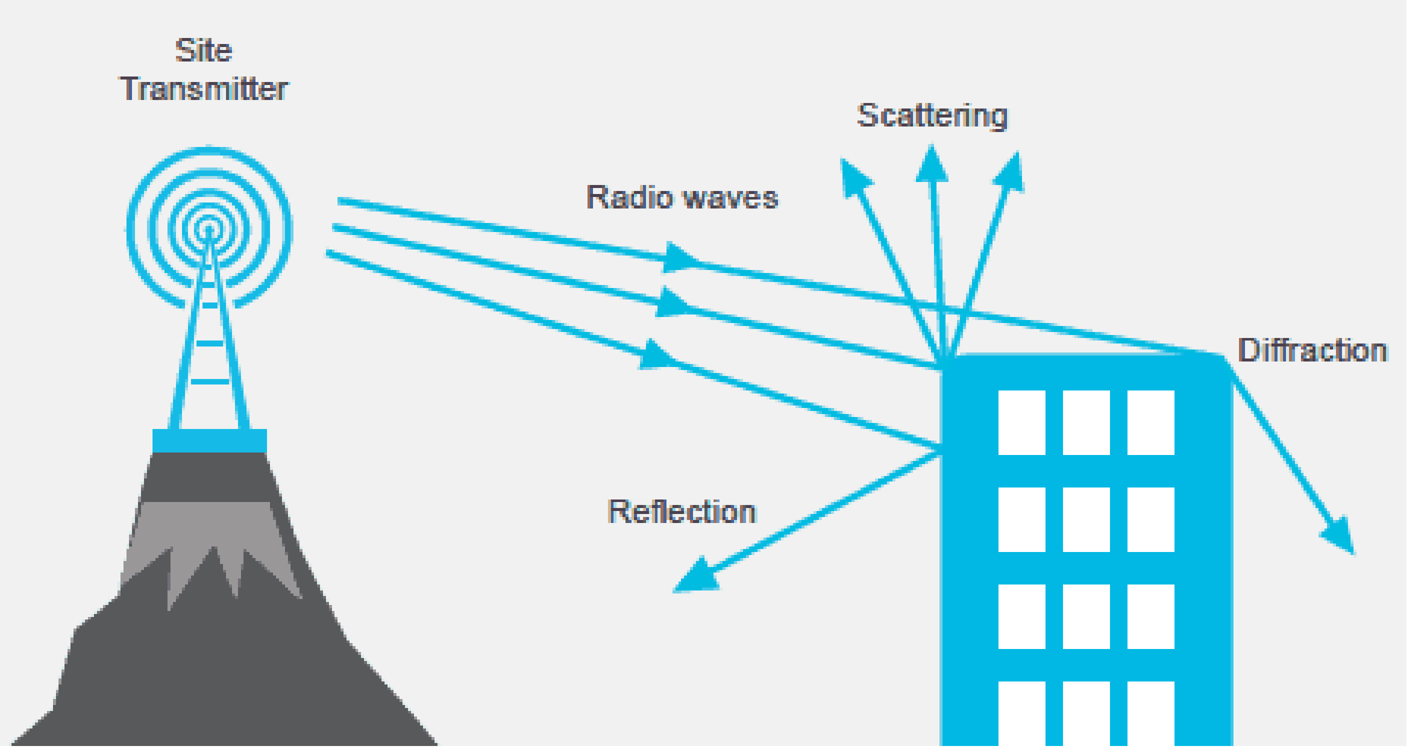
- Destructive interference can make the received signal power drop to a very low level, a situation known as ***fading***. The resulting increase in the error rate makes fading a serious problem for any mobile communication system.



Multipath Fading

Received signal will contain multiple copies of transmitted signal.

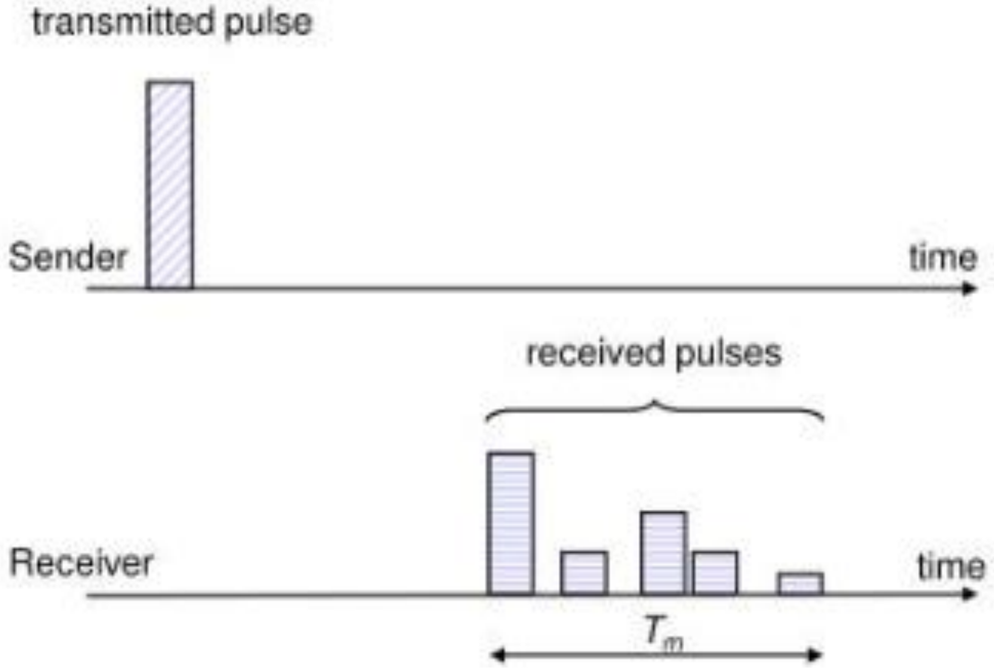
- Reflection
- Diffraction
- Scattering
- Refraction



Multipath Fading

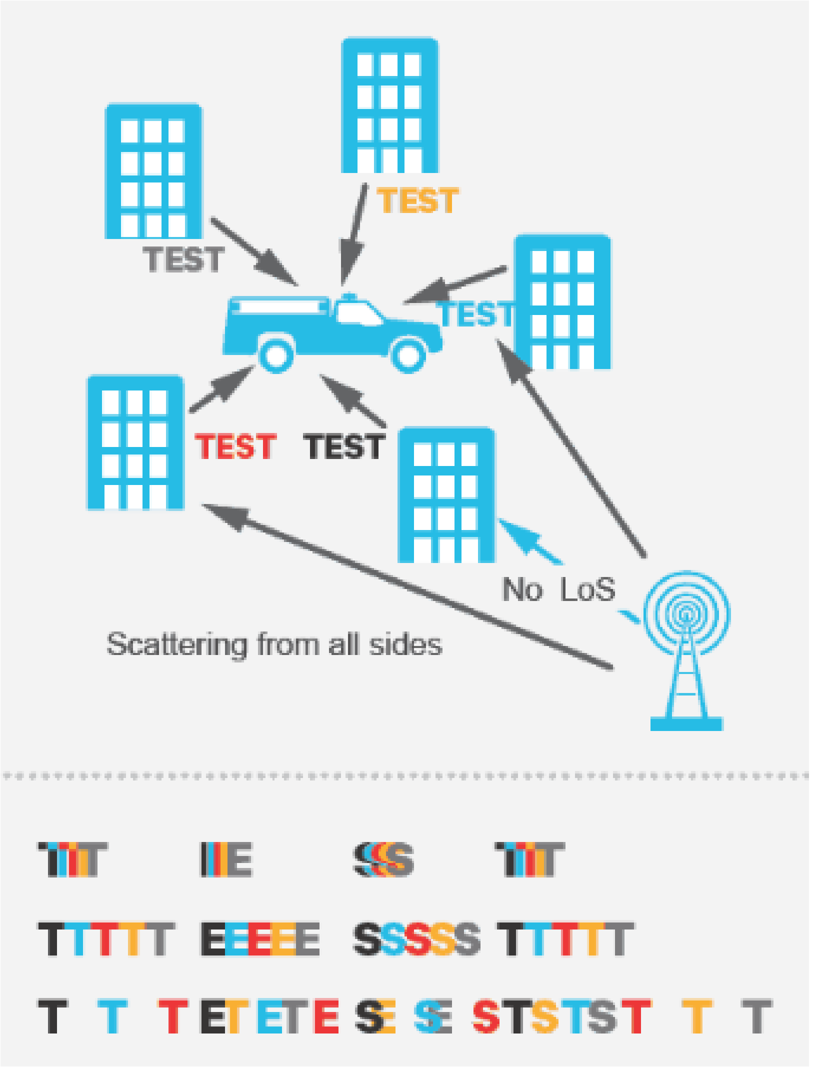
Delay Spread

- Due to different path taken by multipath signal, they may arrive t different time at the receiver.
- Delay spread, T_m , is defined as The time difference between the arrival of the first multipath component of the signal and the last (which will have arrived via a different path)



Multipath Fading

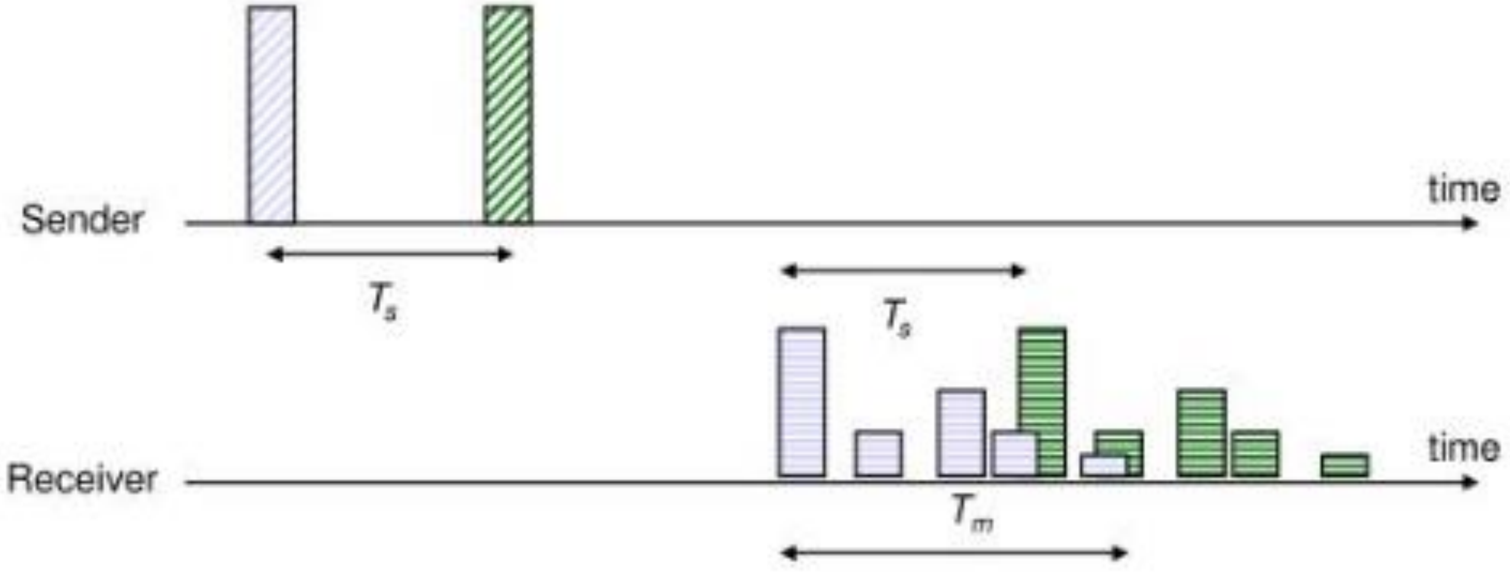
Delay Spread



Multipath Fading

Delay Spread cause Inter Symbol Interference (ISI)

- If the symbol period (T_s) is smaller than the delay spread (T_m), $T_s < T_m$, inter symbol interference will occur.



Multipath Fading

Coherence Bandwidth

- Coherence bandwidth, B_c , is the frequency domain dual of the channel delay spread.
- It gives a rough measure for the maximum separation between a frequency f_1 and a frequency f_2 where the channel frequency response is correlated.

$$B_c \approx \frac{1}{5\,T_{m_{(rms)}}} \approx \frac{1}{T_m}$$

- If the transmitted signal has a bandwidth much smaller than coherence bandwidth. i.e. BS << BC, then all frequency components will be attenuated similarly, **Flat fading**.
- Otherwise it will go as Frequency selective fading, with different components attenuates differently, this cause distortion in the signal.

$$|\mathrm{f1} - \mathrm{f2}| \leq Bc \ \rightarrow H(f1) \approx H(f2)$$

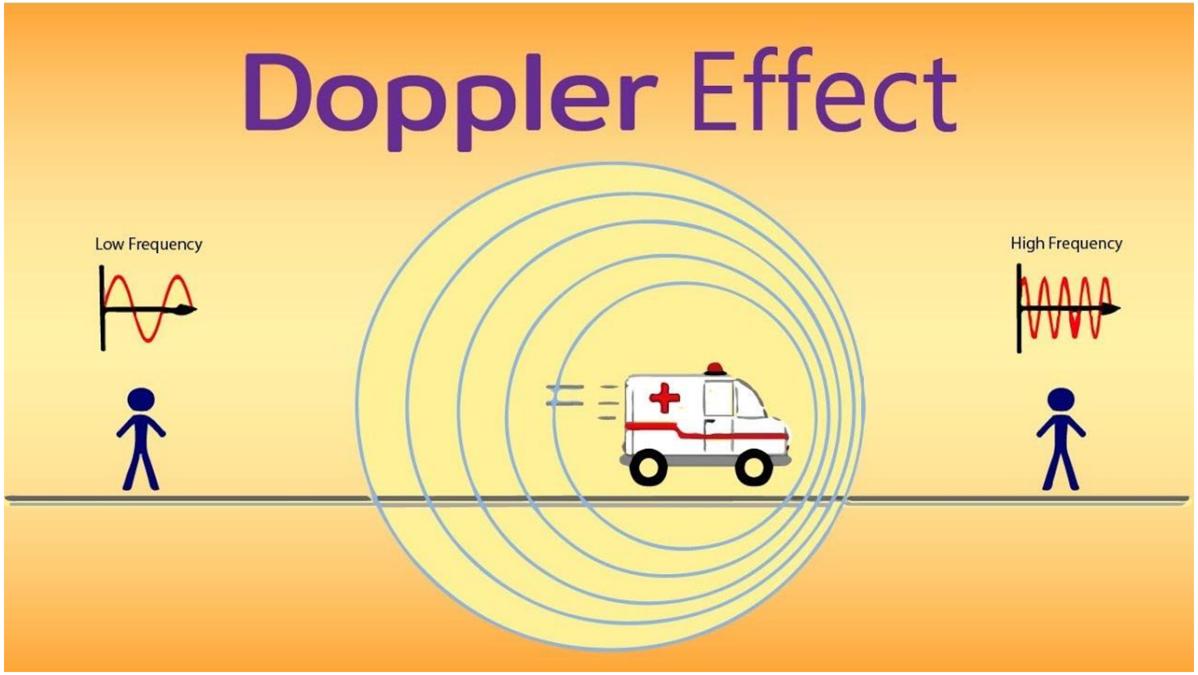
$$|\mathrm{f1} - \mathrm{f2}| \geq Bc \ \rightarrow H(f1)\ and\ H(f2)\ are\ uncorrelated$$

Multipath Fading

Doppler Spread

Doppler effect

an increase (or decrease) in the frequency of sound, light, or other waves as the source and observer move towards (or away from) each other.



Multipath Fading

Doppler Spread

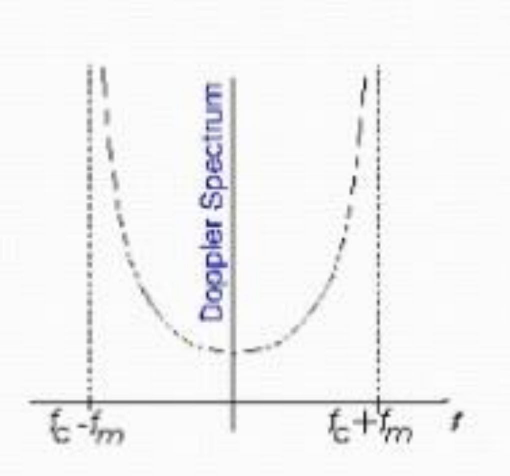
- Time varying fading due to **motion** of a scatter or the motion of the transmitter or receiver or both result in Doppler spread.

- It is caused by time selective fading

  i.e. for a particular instance of time channel behaves as a **fading** channel and for rest it behaves as **flat** channel.

- When a receiver is moving in a multipath environment, the frequency of the multipath components Rx are heading towards appear to increase; the frequency of the multipath components Rx are heading away from appear to decrease. **Frequency spreading** of the received signal is called Doppler Spread.

Maximum frequency shift, $f_D = \frac{v}{c} f_c$



Multipath Fading

Coherence time

- Coherence time, T_c , is the time domain dual of the Doppler spread.

- It gives period over which channel is significantly correlated.

- Time selective fading.

$$|\mathrm{t1} - \mathrm{t2}| \leq Tc \ \rightarrow h(t1) \approx h(t2)$$

$$|\mathrm{t1} - \mathrm{t2}| \geq Tc \ \rightarrow h(t1)\ and\ h(t2)\ are\ uncorrelated$$

$$\mathrm{T_c} \approx \frac{1}{f_D}$$

If the transmitter and receiver are moving fast relative to each other and hence Doppler is large the channel will change much more quickly than the transmitter and receiver are stationary.

Multipath Fading

Doppler spread - Coherence time

f_c	***Speed (km/hr)***	***Max. Doppler, f_D (Hz)***	***Coherence time, T_c (msec)***
700 MHz	2	1.3	775
700 MHz	45	29.1	34
700 MHz	350	226.5	4.4
2.5 GHz	2	4.6	200
2.5 GHz	45	104.2	10
2.5 GHz	350	810	1.2

15EC81

Wireless Cellular and LTE 4G Broadband
Module - 2

Robin Singla
Assistant Prof.
Dept. of ECE
BMSIT

Syllabus:-
Module – 2

Multicarrier Modulation: OFDM basics, OFDM in LTE, Timing and Frequency Synchronization, PAR, SC-FDE (Sec 3.2 – 3.6 of Text).

OFDMA and SC-FDMA:OFDM with FDMA,TDMA,CDMA, OFDMA, SC-FDMA, OFDMA and SC-FDMA in LTE (Sec 4.1 – 4.3, 4.5 of Text).

Multiple Antenna Transmission and Reception: Spatial Diversity overview, Receive Diversity, Transmit Diversity, Interference cancellation and signal enhancement, Spatial Multiplexing, Choice between Diversity, Interference suppression and Spatial Multiplexing (Sec 5.1 – 5.6 of Text).

Orthogonal Frequency Division Multiplexing (OFDM)

OFDM - Basics

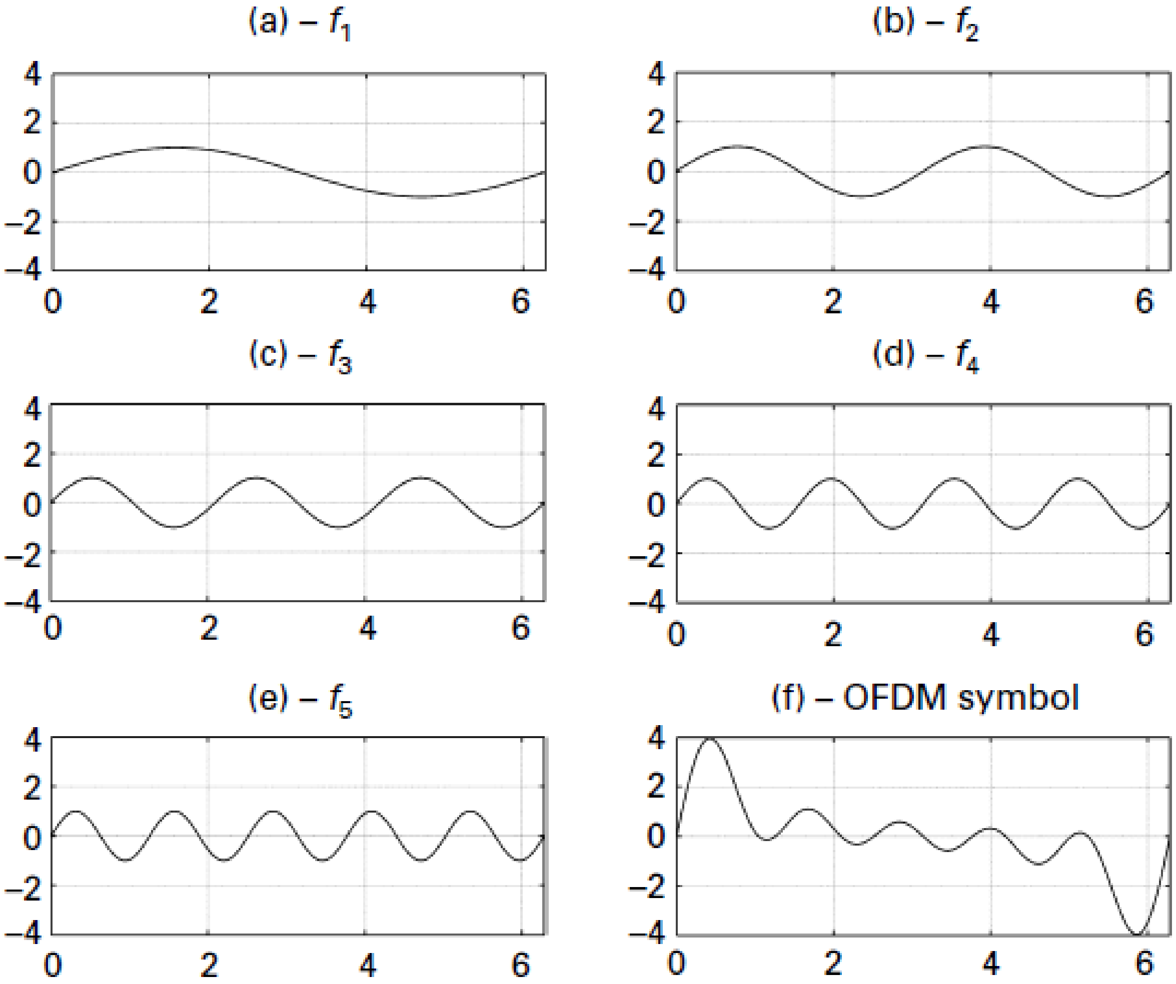
- The technique used for radio transmission and reception in LTE is known as orthogonal frequency division multiplexing (OFDM).
- It is also a powerful method to minimize the problems of fading and inter-symbol interference.
- The basic principle of OFDM is to divide the available spectrum into narrowband parallel channels referred to as subcarriers and transmit information on these parallel channels at a reduced signalling rate.
- The goal is to let each channel experience almost flat-fading simplifying the channel equalization process.
- OFDMA carries out the same functions as any other multiple access technique, by allowing the base station to communicate with several different mobiles at the same time.

Orthogonal Frequency Division Multiplexing (OFDM)

OFDM - Basics

The subchannel/subcarrier frequency $f_k = k\Delta f$, where Δf is the subcarrier spacing.
$\Delta f = 15\ kHz$

Each subcarrier is modulated by a data symbol and an OFDM symbol is formed by simply adding the modulated subcarrier signals.



Orthogonal Frequency Division Multiplexing (OFDM)

OFDM - Basics

Multicarrier modulation divides the high rate transit bit stream into L lower rate substreams Where L is chosen such that each of the subcarrier has effective symbol time

$$\mathbf{T_S\, L \gg T_M}$$

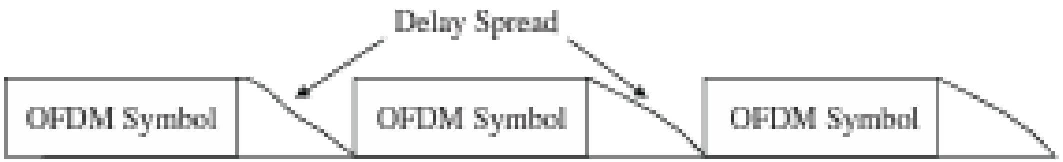
T_S = symbol time
T_M = delay spread (see slide no-38 of module one)

OFDM – Basics

Block transmission with **Guard Intervals**

- Basic idea is to insert a ***guard interval/guard period*** **(GP)** before each symbol, in which nothing is transmitted.

- If the guard period is longer than the delay spread ($T_g > T_m$), then the receiver can be confident of reading information from just one symbol at a time, without any overlap with the symbols that precede or follow.



OFDM – Basics

The Cyclic Prefix (CP)

- The **orthogonality** of OFDM subcarriers can be **lost** when the signal passes through a time-dispersive radio channel due to **inter-OFDM symbol interference**.

- LTE uses a slightly more complex technique, known as **cyclic prefix (CP)** insertion.

- In cyclic prefix extension, the **last part** of the OFDM signal is added as cyclic prefix (**CP**) in the **beginning** of the OFDM signal as shown in figure below.

- Here, the transmitter starts by inserting a guard period before each symbol, as before GP. However, it then copies data from the end of the symbol following, so as to fill up the guard period.

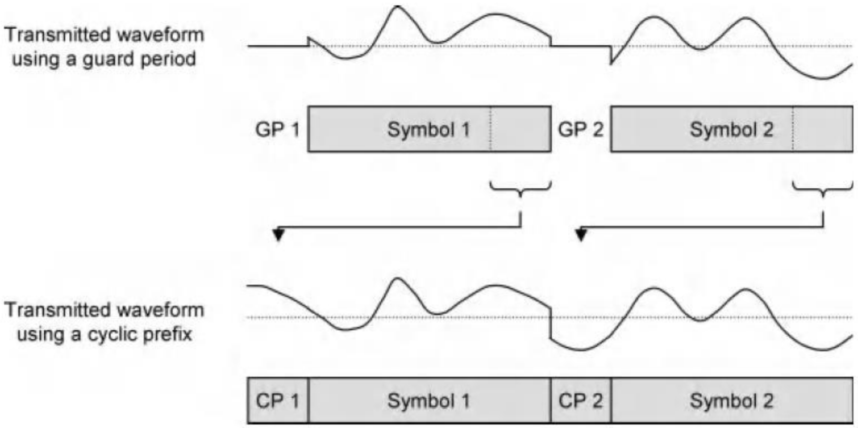
- If the cyclic prefix is longer than the delay spread, then the receiver can still be confident of reading information from just one symbol at a time.

OFDM – Basics

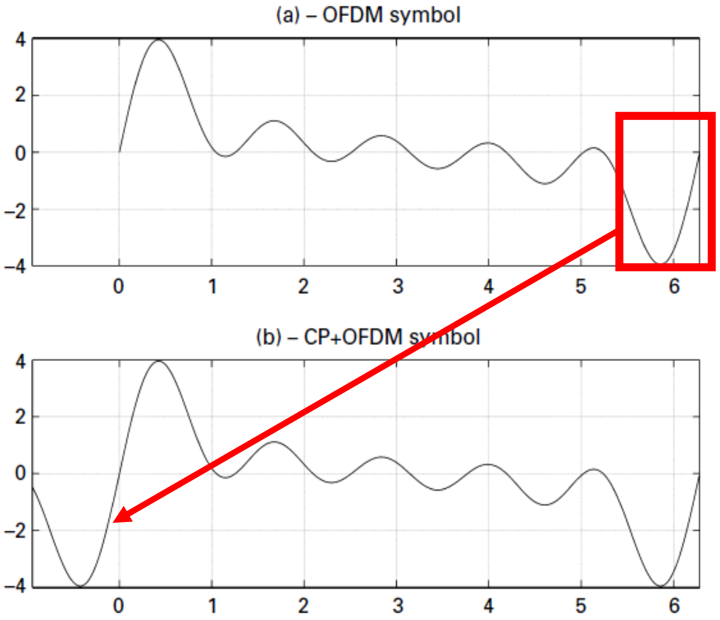
The Cyclic Prefix

An illustration of cyclic prefix extension of OFDM signal.

Schematic - 1



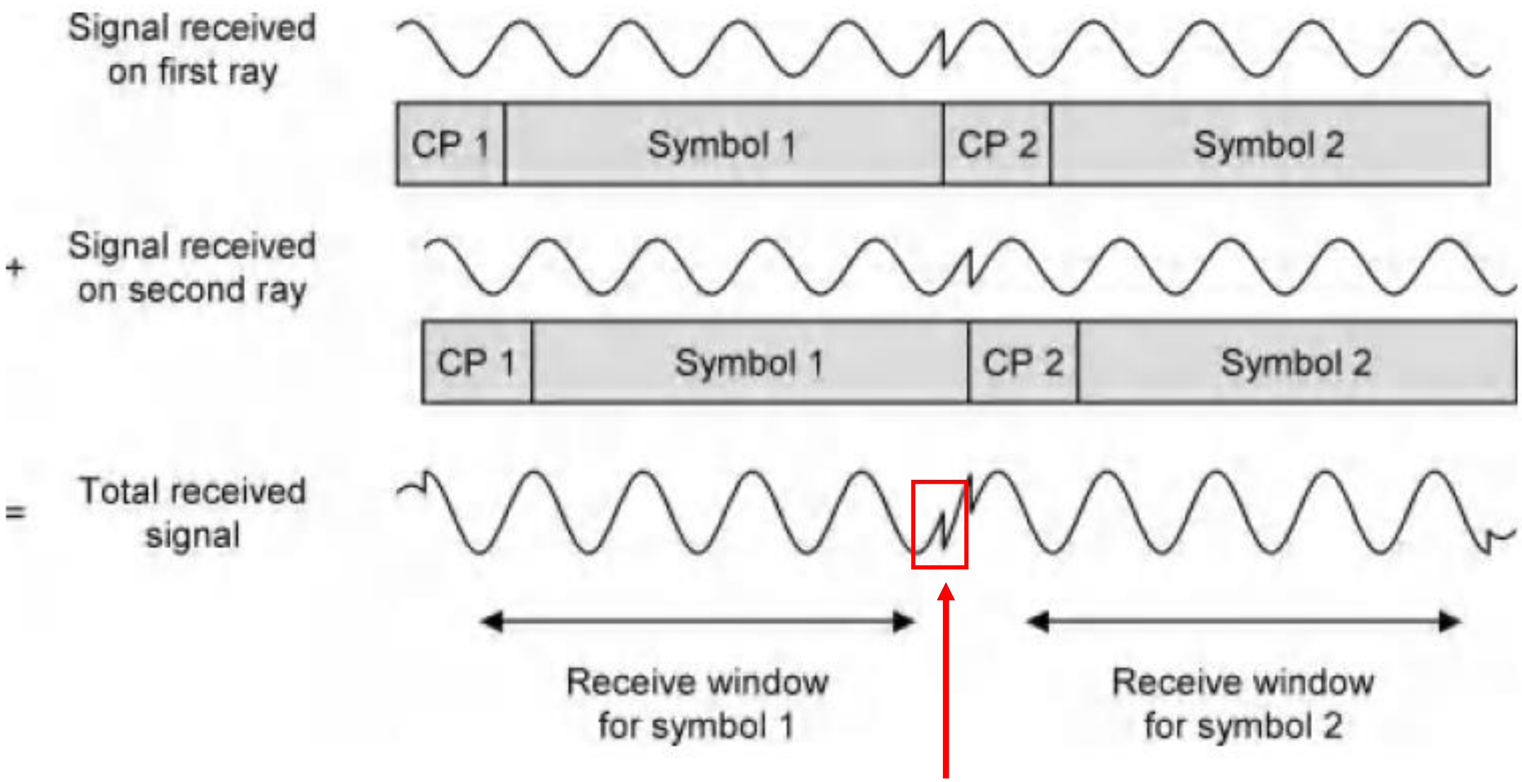
Schematic - 2



Normally, LTE uses a cyclic prefix of about 4.7 μs.

OFDM – Basics

The Cyclic Prefix



Information lost only in this part
And this part is also there in the
starting as CP

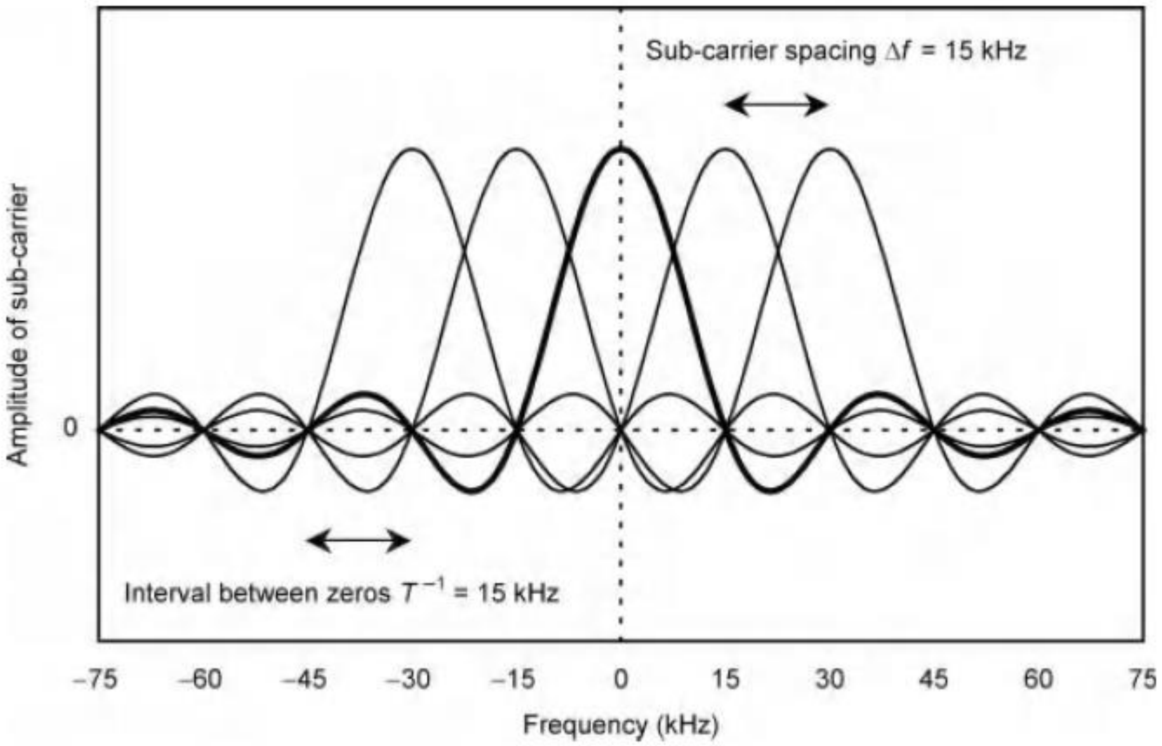
OFDM – Basics

Use of Frequency Domain

Sub-carrier spacing, $\Delta f = 15\ kHz$
Interval between zeros, $T^{-1} = 15\ kHz$

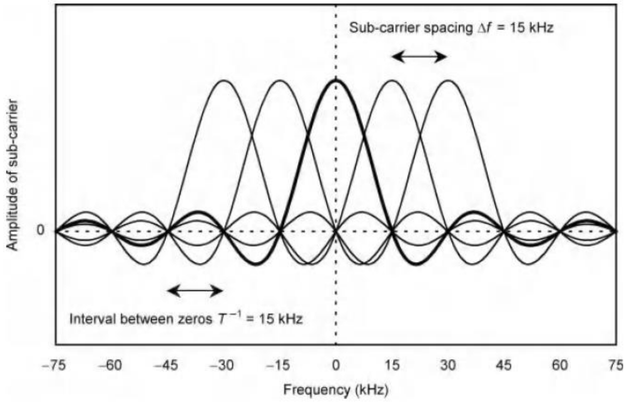
$$T = \frac{1}{15\ kHz} = 66.7\ \mu s$$

At maxima of one sub-carrier, all other sub-carrier has zero amplitude.



Amplitudes of the signals transmitted on neighbouring sub-carriers, as a function of frequency.

OFDM – Basics



Use of Frequency Domain

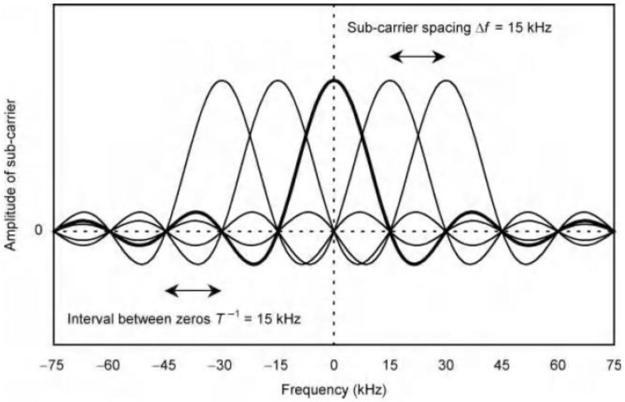
Sub-carrier spacing, $\Delta f = 15\ kHz$
Interval between zeros, $T^{-1} = 15\ kHz$

- In **time domain**, each sub-carrier starts life as a sine wave, but the modulation process makes its ***amplitude and phase change*** at intervals of the symbol duration T, which equals 66.7 µs.
- This broadens the signal in the frequency domain, to a bandwidth of about T^{-1}.
- In the **frequency domain**, the amplitude of each sub-carrier oscillates either side of zero and crosses through zero at regular intervals of T^{-1} (see in figure). (Mathematicians will recognize this response as a sinc function $(x^{-1} \sin x)$.).
- If $\Delta f = T^{-1}$, then the sub-carriers overlap in the frequency domain, but the peak response of one sub-carrier coincides with zeros of all the others. As a result, the mobile can sample one sub-carrier and can measure its amplitude and phase without any interference from the others, despite the fact that they are closely packed together. Sub-carriers with this property are said to be ***orthogonal***.
- This property means that OFDMA uses the frequency domain in a very efficient way and is one of the reasons why the spectral efficiency of LTE is so much greater than that of previous mobile telecommunication systems.

OFDM – Basics

Use of Frequency Domain

Sub-carrier spacing, $\Delta f = 15\ kHz$
Interval between zeros, $T^{-1} = 15\ kHz$



In a multipath environment, a mobile can be moving towards some rays, which are shifted to higher frequencies, but away from others, whose frequencies move lower. As a result, the sub-carriers are not simply shifted: instead, they are blurred across a range of frequencies. If a mobile tries to measure the peak response of one sub-carrier, then it will now receive interference from all the others. We have therefore **lost the orthogonality property.**

The amount of interference will still be acceptable, however, if the Doppler shift is much less than the sub-carrier spacing. We therefore need to choose the sub-carrier spacing f as follows:

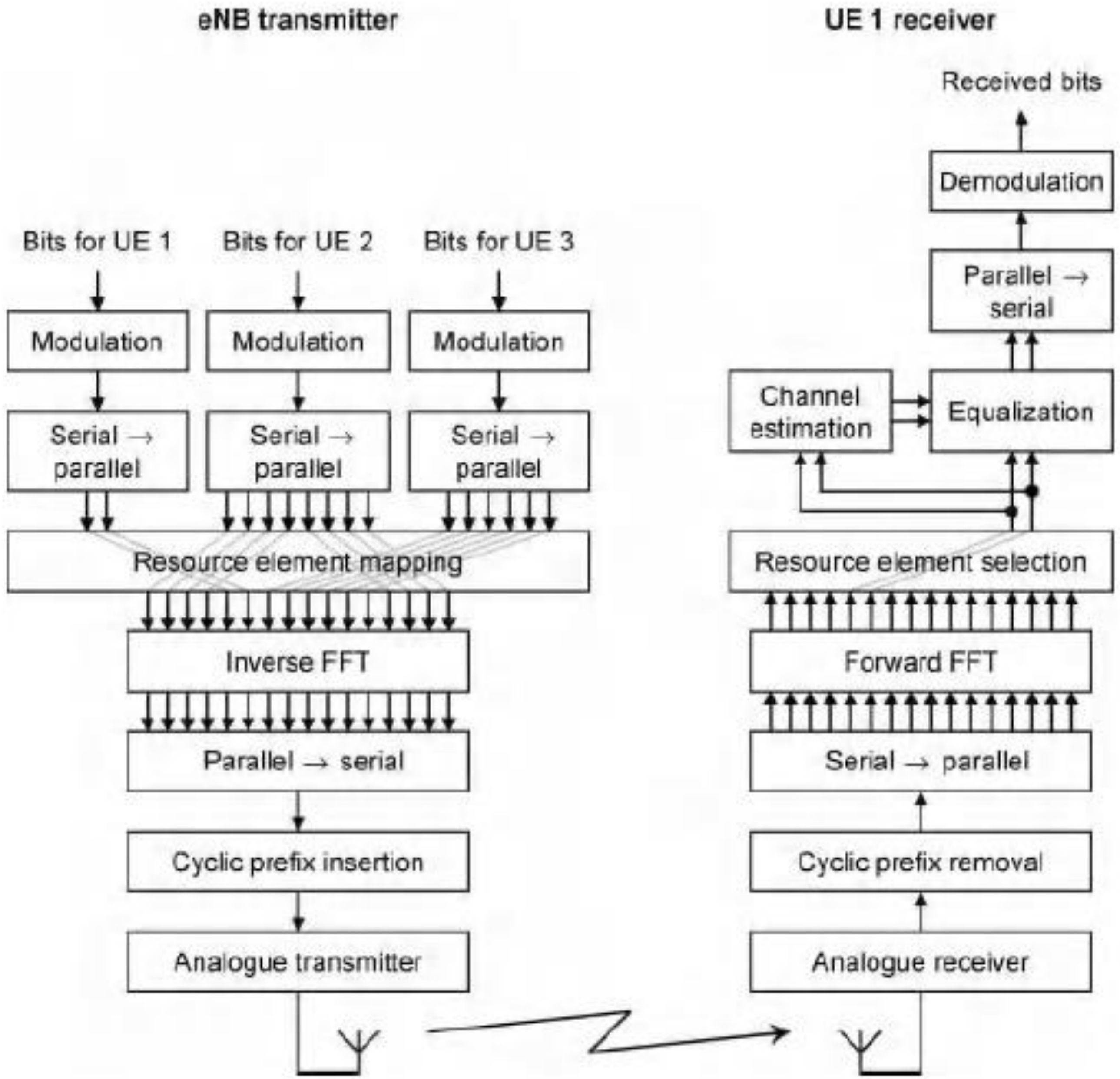
$$\Delta f \gg f_D$$

f_D is the Doppler shift

To minimize the impact of inter-symbol interference, we need to choose the symbol duration T as follows: $T_s \gg T_m$

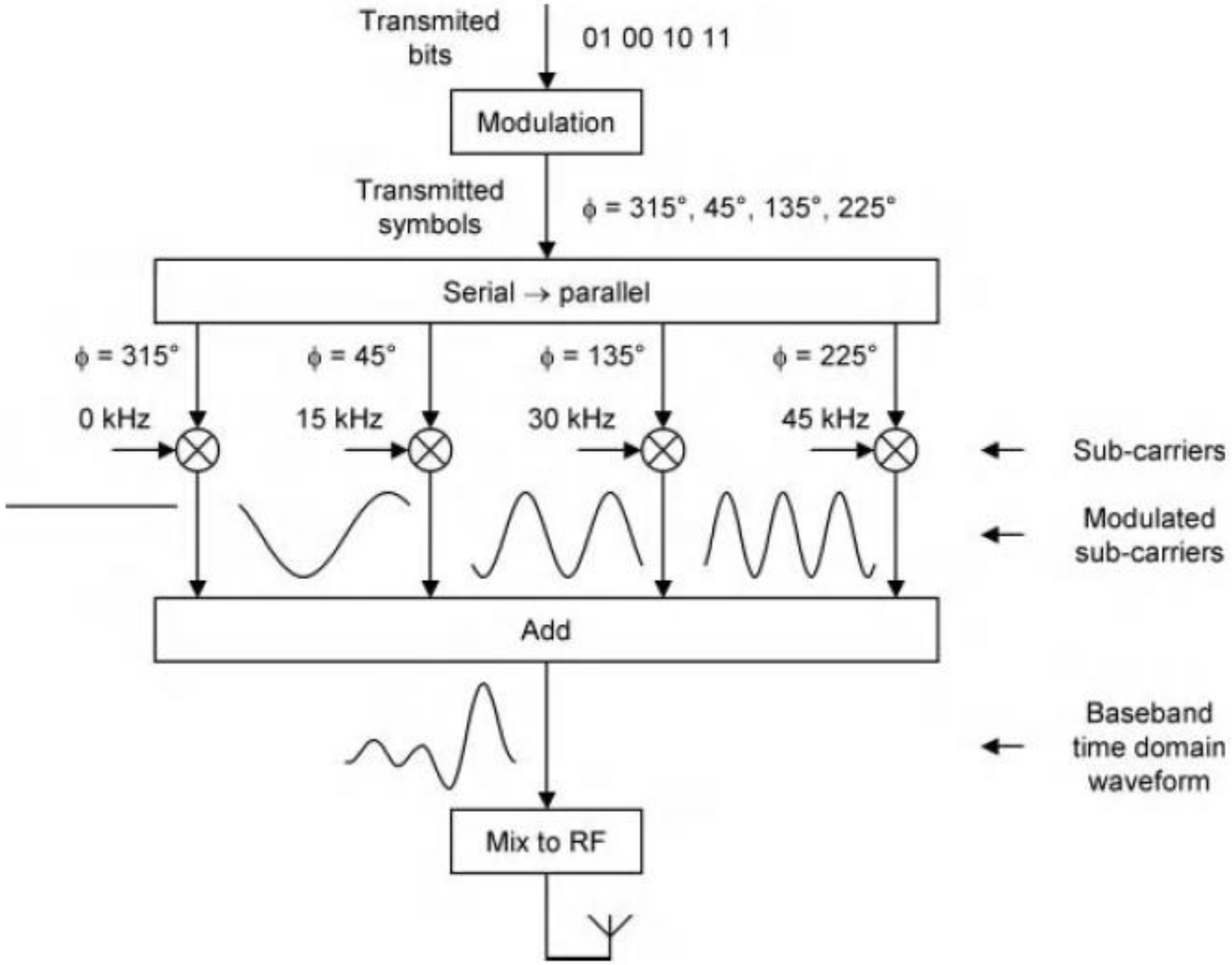
T_m is the delay spread

Complete block diagram of OFDMA in LTE



Complete block diagram of OFDM in LTE

Basic block diagram of OFDM transmitter

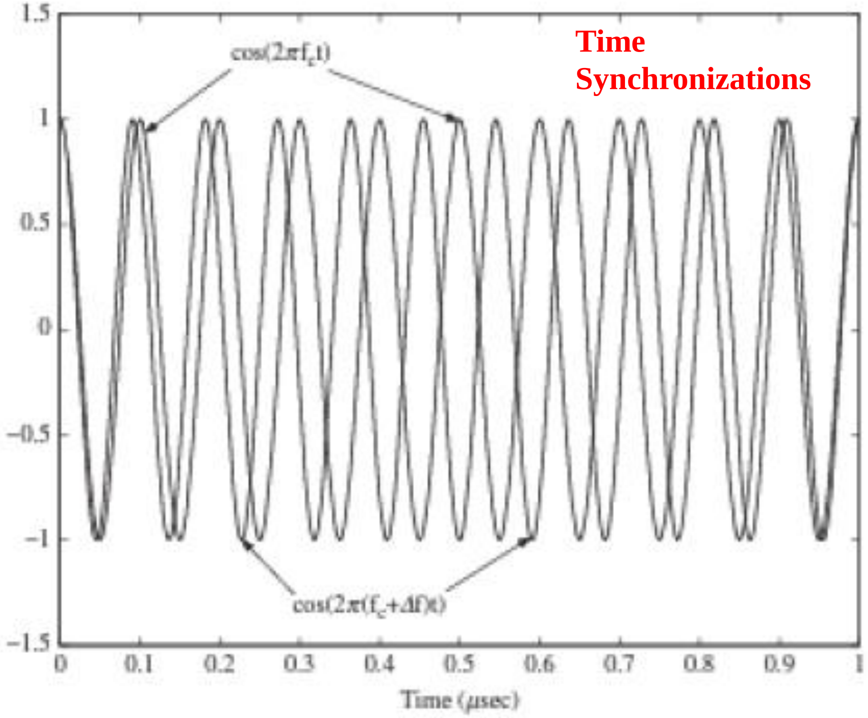


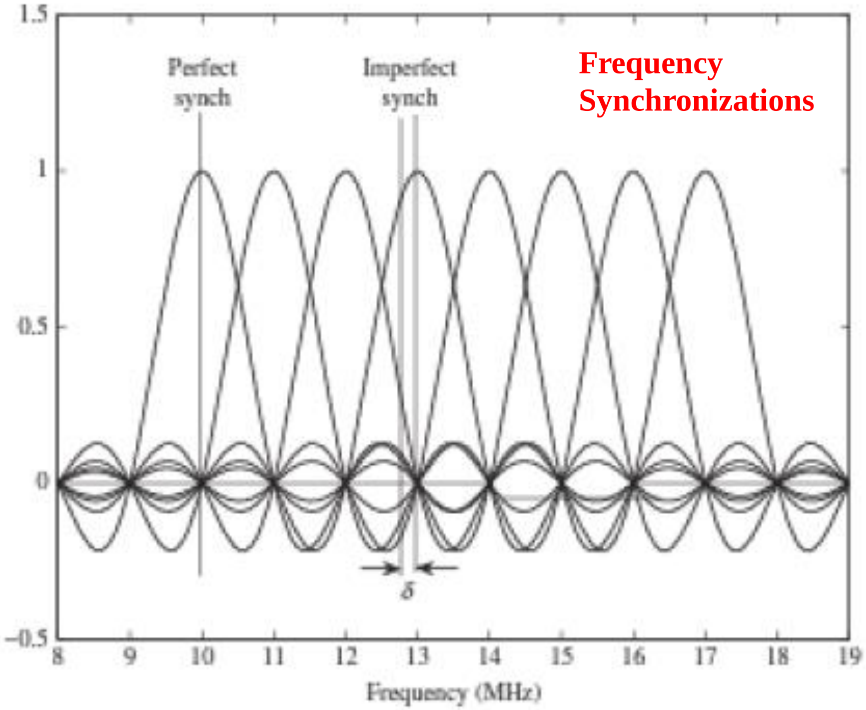
Time and Frequency Synchronizations

- Time synchronization and frequency synchronization are the two important synchronization that need to be performed by the receiver.

- Time synchronization – timing offset the symbols and optimal timing instants need to be determined.

- Frequency synchronization – receiver must align its carrier frequency as closely as possible with the transmitted frequency.





Time Synchronizations

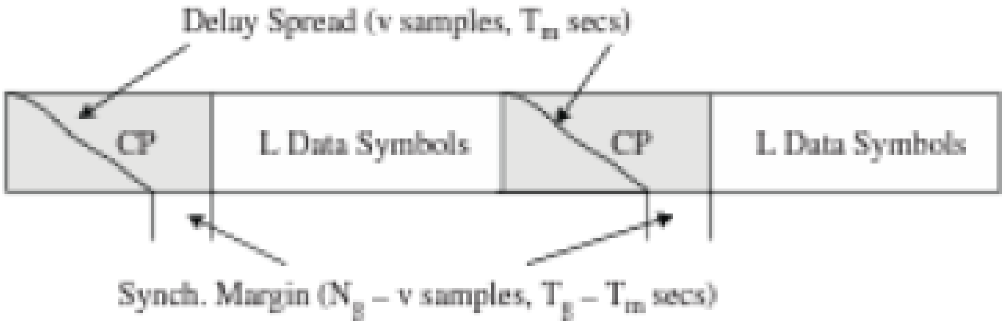
- If timing window slid left or right then a unique phase shift will be introduced to each of the subcarriers.

- The effect of timing error in symbol synchronization is somewhat relaxed in OFDM due to the presence of a cyclic prefix.

- In case of perfect timing synchronization is not maintained, it is still possible to tolerate a timing offset of $\boldsymbol{\tau}$ seconds without any degradation in the performance as long as

$$\mathbf{0} \leq \boldsymbol{\tau} \leq \boldsymbol{T_g} - \boldsymbol{T_m}$$

T_g = guard time
T_m = max. channel delay spread



- Acceptable range of τ is referred as the timing synchronization margin.

- If $\boldsymbol{\tau}$ is not within the window $\mathbf{0} \leq \boldsymbol{\tau} \leq \boldsymbol{T_g} - \boldsymbol{T_m}$, then inter symbol interference (ISI) will occurs.

Time Synchronizations

$$\Delta SNR(\tau) \approx -2\left(\frac{\tau}{LT_s}\right)^2$$

- SNR decreases quadratically with the timing offset.

- Longer OFDM signals are increasingly immune from timing offset, that is, more subcarriers helps.

- Since in general $\tau \ll LT_S$, timing synchronization errors are not that critical, as long s induced phase change is corrected.

- To minimize the SNR loss due to imperfect timing synchronization, the timing error should be kept small compared to the guard interval and a small margin in the cyclic prefix length is helpful.

Frequency Synchronizations

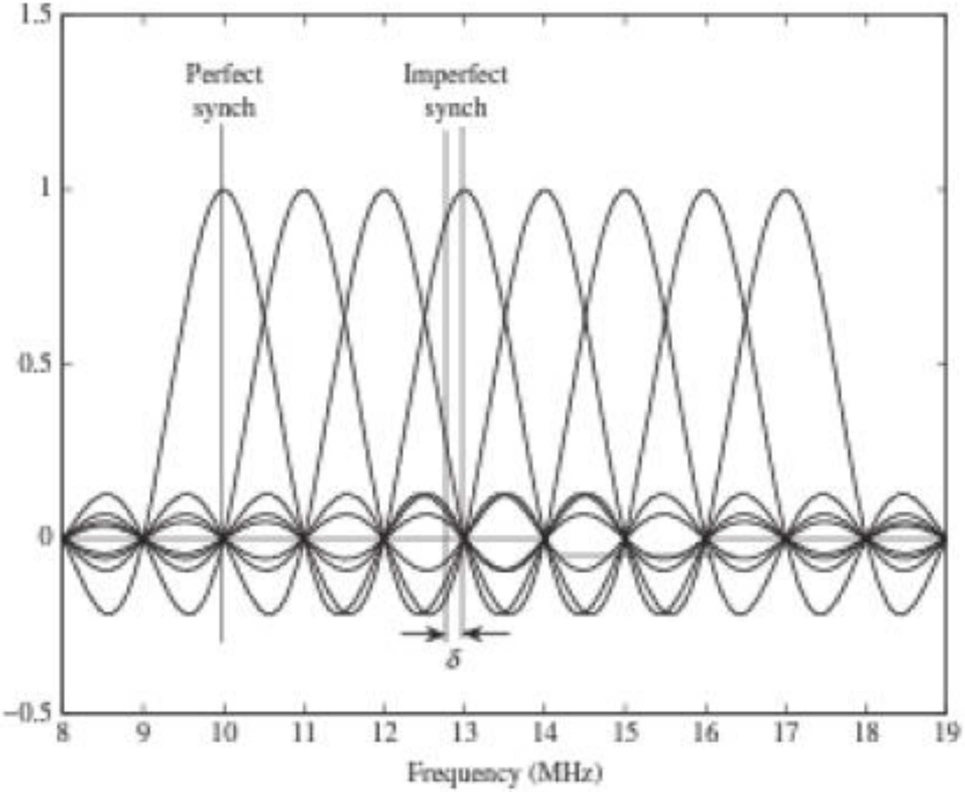
- Frequency synchronization – receiver must align its carrier frequency as closely as possible with the transmitted frequency.

- OFDM achieved a high degree of bandwidth efficiency compared to other wideband systems.

- The subcarrier packing is extremely tight compared to conventional modulation techniques, which required a guard band of the order of 50% or more.

- Multicarrier signal is very sensitive to frequency offsets due to the fact that subcarrier overlap, rather than having each carrier truly spectrally isolated.

- ***Case-1*** – frequency offset = zero
  - Since the zero crossing of frequency domain sinc pulses all line up, as long as frequency offset **δ = 0**, there is **no interference** between the carriers.



Frequency Synchronizations

- ***Case-2*** – frequency offset ≠ zero
  - In practice frequency offset is non-zero.

  - The major causes for this are mismatched oscillator at transmitter and receiver and Doppler frequency shift due to mobility.

For example:-

If a oscillator is accurate to 0.1 part per million (ppm) then

$$f_{offset} \approx (f_c)(0.1\, ppm) = 300\, Hz\ for\ f_c = 3GHz$$

And if Doppler shift = 100 Hz then

$$f_{offset} \approx 300 + 100 \text{ Hz}$$

Which will degrade the orthogonality of the received signal, since now FFT will contain interference from the adjacent subcarriers as well.

Frequency Synchronizations

$$\Delta SNR \approx 1 + C_0 (LT_s \delta)^2 \, SNR$$

- SNR decreases quadratically with the frequency offset.
- SNR decreases quadratically with the number of carriers.
- The loss in SNR is also proportional to the SNR itself.
- In order to keep the loss negligible, say less than o.1 dB, the relative frequency offsets need to be about 1-2% of the subcarrier spacing, or even lower to preserve the high SNRs.

Peak to Average ratio (PAR)

- Peak to average ratio (**PAR**) or peak to average power ratio (**PAPR**) is the relation between the maximum power of a sample in a given OFDM transmit symbol divided by the average power of that OFDM symbol.

- In simple terms, PAPR is the ratio of peak power to the average power of a signal.

- OFDM has high PAPR , because it’s a multicarrier system with each of them are out of phase with each other and output signal is the addition of all subcarriers, and when all the points achieve a maximum value simultaneously, this will cause the output envelope to shoot up suddenly which cause a peak in the output envelope.

How high PAPR is coming:-
In OFDM information symbols loaded to subcarriers and transmitted after performing **IFFT** operation

Let the information symbols are :- X(0) X(1)…….X(N-1) ← to be loaded onto subcarriers
$\pm a$ $\pm a$ $\pm a$

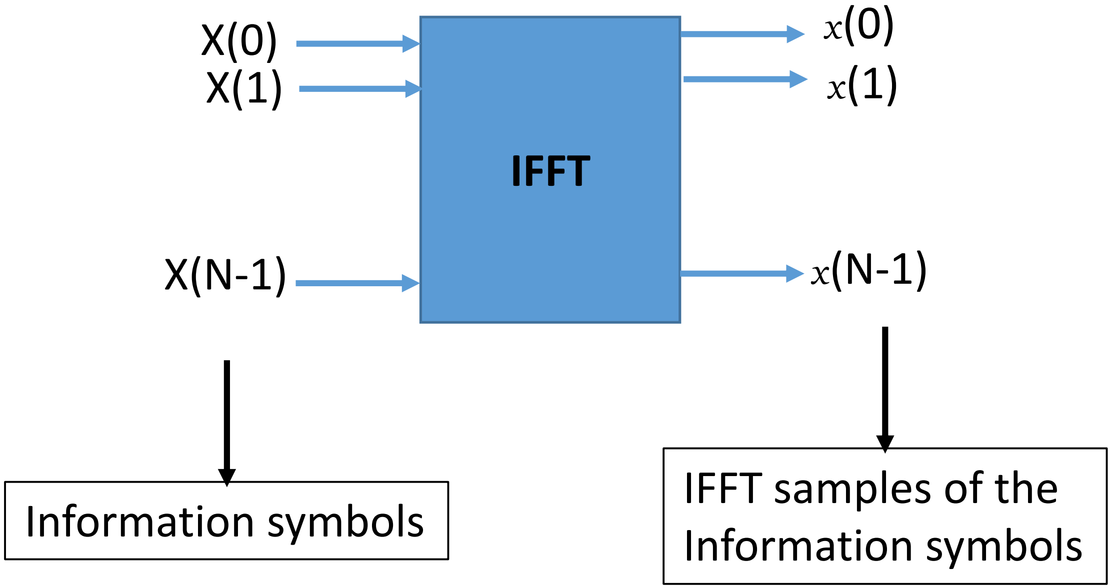
Peak to Average ratio (PAR)

How high PAPR is coming:-

In OFDM information symbols loaded to subcarriers and transmitted after performing **IFFT** operation

Let the information symbols are :- X(0) X(1)……..X(N-1) ← to be loaded onto subcarriers

$\pm a \quad \pm a \qquad\qquad \pm a$



X(0)

X(1)

X(N-1)

IFFT

x(0)

x(1)

x(N-1)

Information symbols

IFFT samples of the Information symbols

Hence the transmitted samples are x(0) x(1) ……… x(N-1)

Peak to Average ratio (PAR)

$$\underbrace{x(k)}_{\boxed{\text{k}^{\text{th}}\text{ IFFT sample}}} = \frac{1}{N}\sum_{i=0}^{N-1} \underbrace{X(i)}_{\boxed{\text{Information symbol}}} e^{j2\pi ki/N}$$

Average power

$$P_{avg} = E\{|x(k)|^2\}$$

$$= \frac{1}{N^2}\sum_{i=0}^{N-1} E\{|X(i)|^2\}\, E\left\{\left|\underbrace{e^{j2\pi ki/N}}_{\boxed{1}}\right|^2\right\}$$

$$= \frac{1}{N^2}\sum_{i=0}^{N-1} E\{|X(i)|^2\} = \frac{1}{N^2}\sum_{i=0}^{N-1} a^2 = \frac{1}{N^2}\,.\,a^2 N = \boldsymbol{\frac{a^2}{N}}$$

Peak to Average ratio (PAR)

$$\underbrace{x(k)}_{k^{th}\text{ IFFT sample}} = \frac{1}{N}\sum_{i=0}^{N-1}\underbrace{X(i)}_{\text{Information symbol}}e^{j2\pi ki/N}$$

Peak power

$$x(0) = \frac{1}{N}\sum_{i=0}^{N-1}X(i)e^{j2\pi i\mathbf{0}/N}$$

$$= \frac{1}{N}\sum_{i=0}^{N-1}X(i)$$

$$\mathrm{X}(0) = X(1)\ldots\ldots\ldots X(N-1) = a$$

$$x(0) = \frac{1}{N}\sum_{i=0}^{N-1}a = \frac{1}{N}aN = a$$

Peak power = $\boldsymbol{a^2}$

Peak to Average ratio (PAR)

Average power = $\frac{\boldsymbol{a}^2}{\boldsymbol{N}}$

Peak power = $\boldsymbol{a}^2$

PAPR = $\frac{\boldsymbol{a}^2}{\frac{\boldsymbol{a}^2}{\boldsymbol{N}}} = N$

N = number of subcarriers which is very high
Hence PAPR in a OFDM system can be significantly higher.

PAPR increases as the number of subcarriers(N) increases.

IFFT pre-processing is enhancing the instantaneous swing of OFDM symbols over the average level – Data symbols across subcarriers can add up to produce a high peak value signal.

For instance in a n OFDM system with 512 subcarriers and BPSK modulation, the PAPR at the output can be as high as 10 dB

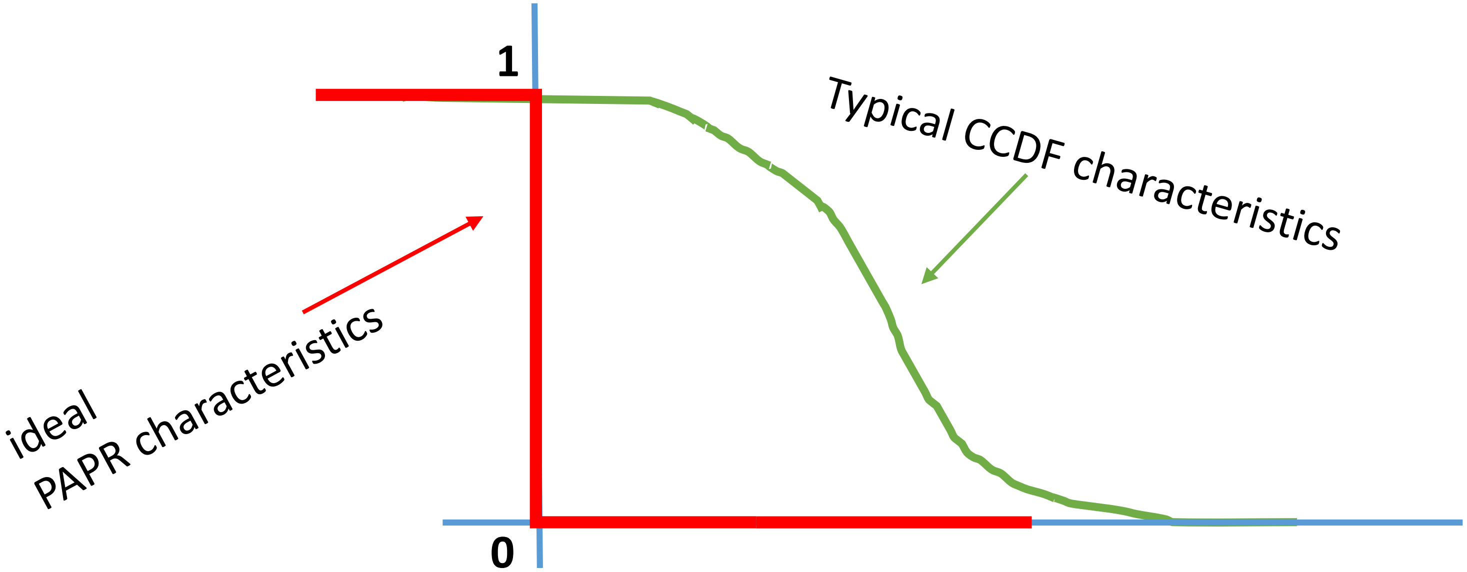
Quantifying the PAPR

PAPR of OFDM system is characterized using the CCDF function.

CCDF- complementary cumulative distribution function

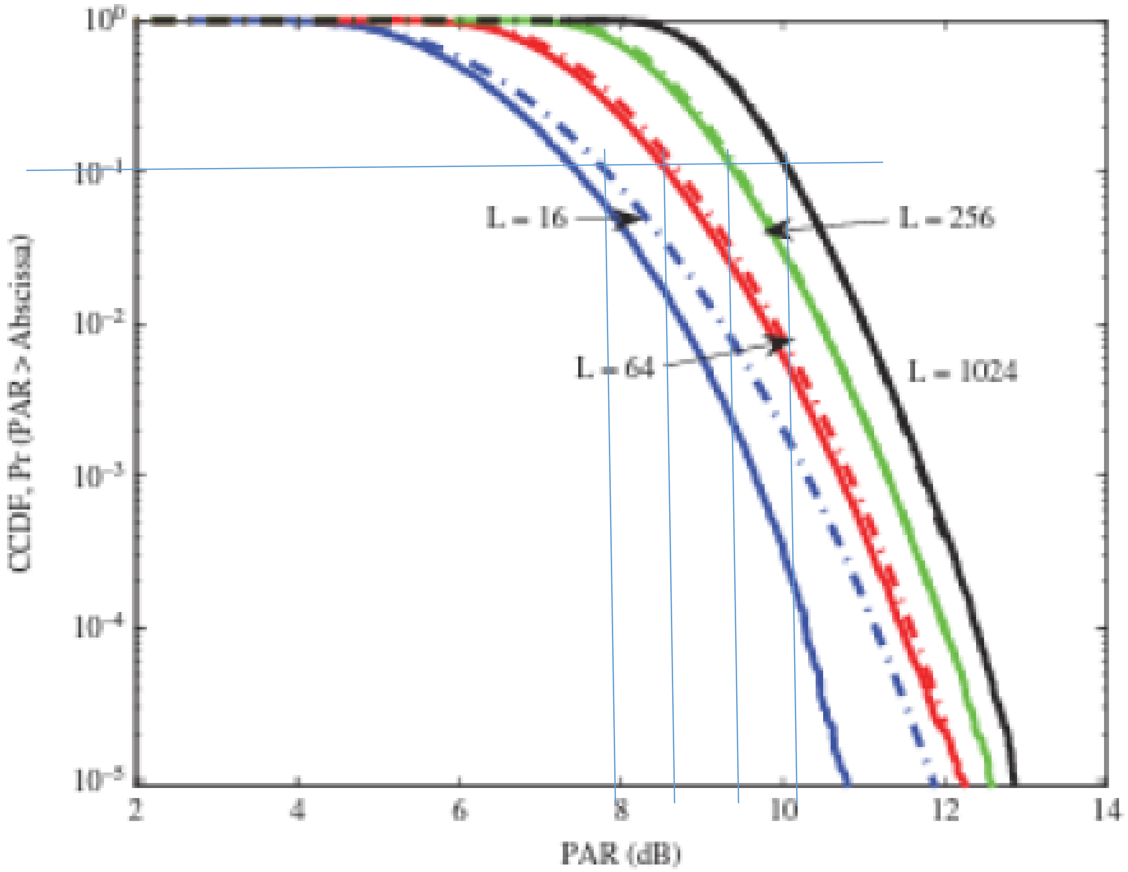
$$\overline{F_X}(x) = P(X > x)$$

X is a random variable and it is PAPR in this case



Quantifying the PAPR

CCDF of PAPR for QPSK OFDM system, L or N = 16, 64, 256, 1024



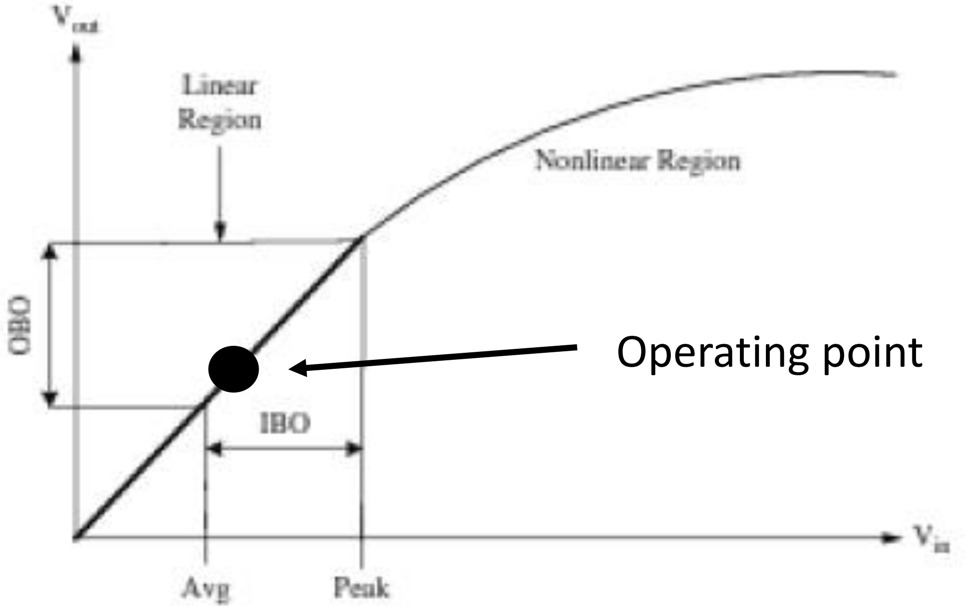
The PAPR problem

What is the affect of PAPR on the OFDM system?

- When a high – peak signal is transmitted through a non-linear device such as a high power amplifier or DAC, it generates out-of-band energy and in-band distortions and these degradations may affect the system performance.

- OFDM work in non-linear region because of high swing in the peak power to average power.

- As the peak swing increases, PA operate in more non-linear region which result in more distortion in signal and inter channel interference.



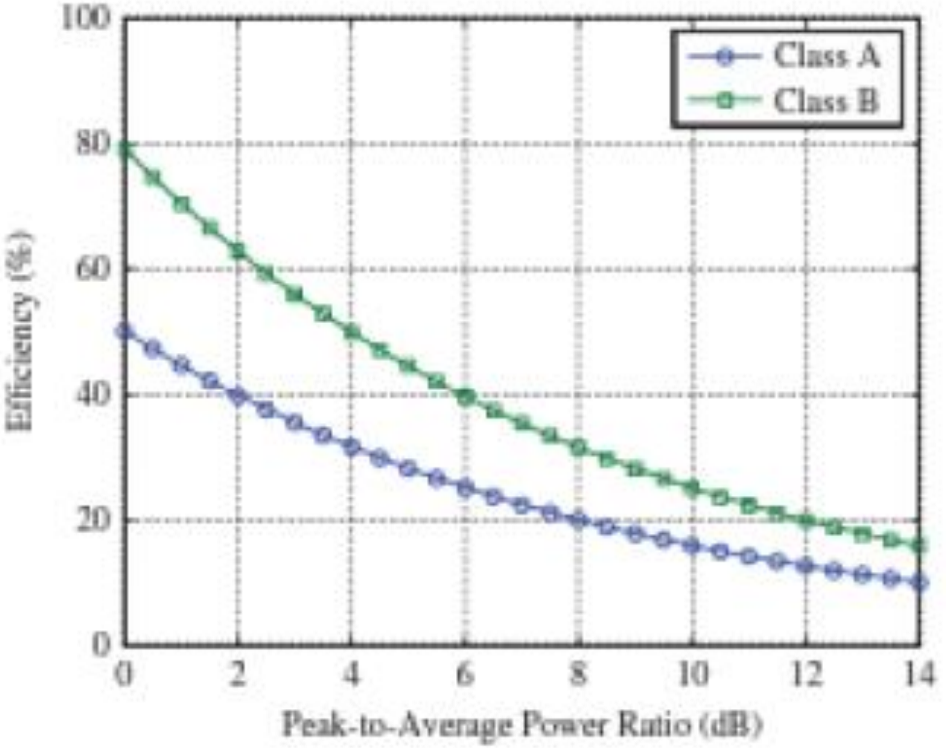
Operating point

The PAPR problem

To avoid the undesirable non-linear effects, a waveform with high peak power must be transmitted in the linear region of HPA by decreasing the average power of the input signal.

The efficiency of HPA can be increased by reducing the PAPR of the transmitted signal

e.g. the efficiency of a class A amplifier is halved when the input PPR is doubled or the operating point is halved.



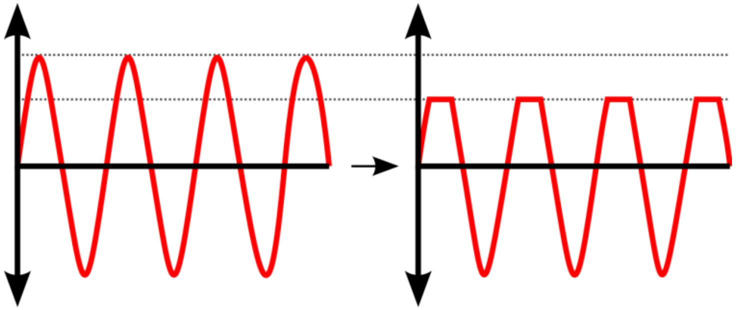
In addition to the large burden placed on HPA, a high PAPR requires high resolutior for both the transmitter's DAC and the receiver's ADC.

High resolution DAC and ADC places an additional complexity, cost and power Burden on the system.

Clipping and other PAPR reduction techniques

Clipping

Clipping in digital electronics/circuits



- In order to avoid operating the power amplifier in non-linear region, the input power can be reduced up to an amount about equal to the PAPR.

- It's a very inefficient and will reduce the range and/or SINR of the system by the same amount.

- Clipping the crop the amplitude of the signals that exceed the clipping level as

$$\breve{x}(n) = \begin{cases} Ae^{j\angle x[n]}, & if\ |x[n]| > A \\ x[n], & if\, |x[n]| < A \end{cases}$$

$x[n]$ = original signal

$\breve{x}(n) =$ output after clipping

A = clipping level, that is the maximum output envelope value

$$\gamma \triangleq \frac{A}{\sqrt{E_x}}, \qquad \gamma\ is\ cliiping\ ratio$$

Clipping and other PAPR reduction techniques

Clipping

Obviously, clipping reduce the PAPR at the expense of (i) distorted the desired signal (ii) spectral regrowth (frequency domain leakage), which cases unacceptable interference to users in neighboring RF channel

PAPR in downlink

In the downlink PAPR is less important because the

- base stations are
  - fewer in number
  - higher in cost
  - not especially sensitive to the exact PAPR.
- So they can avoid the PAPR problem by using expensive power amplifiers that are very close to linear.

PAPR in uplink

In the uplink PAPR is more important because the

- Mobiles are
  - many in number
  - Very sensitive to cost
- So they doesn’t have option of using expensive power amplifiers that are very close to linear.

Single-Carrier Frequency Domain Equalization (SC-FDE)

An alternate approach to OFDM is the less popular but conceptually similar is single carrier frequency domain equalization (SC-FDE) to ISI suppression.

Frequency equalization (FEQ)

$$\hat{X}_l = \frac{Y_l}{H_l}$$

H_l is the complex response of the channel at the frequency $f_c + (\mathrm{l} - 1)\Delta f$

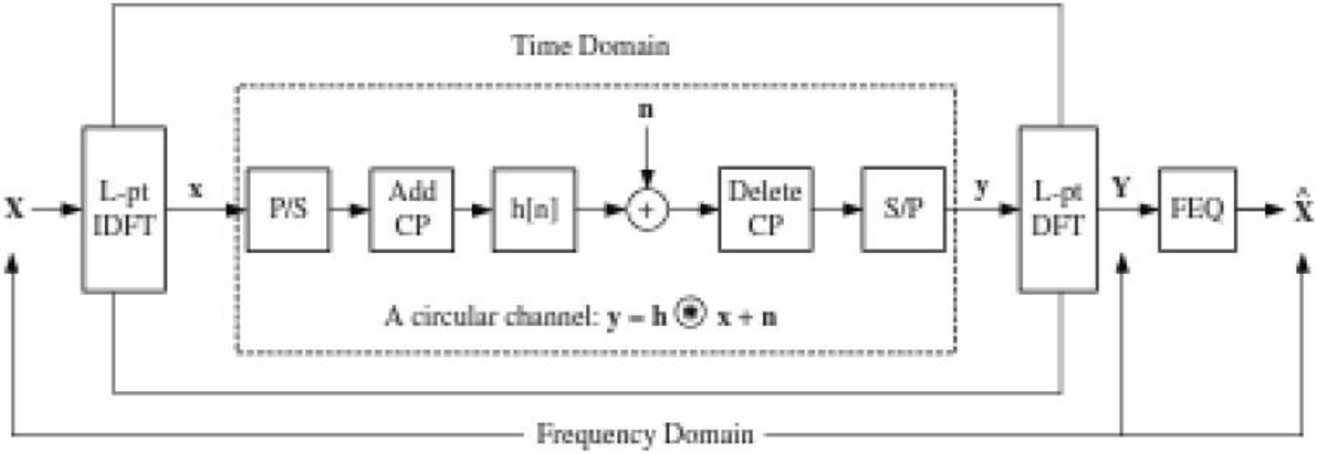
It corrects both the phase and equalizes the amplitude before the decision device.

X is the transmitted data symbols, Y is the received data symbols, $\hat{X}$ is the estimated data symbols.

At receiver CP is discarded, and the L received symbols are demodulated using an FFT operation, which results in L data symbols, each of the form $Y_l = H_l X_l + Nl$

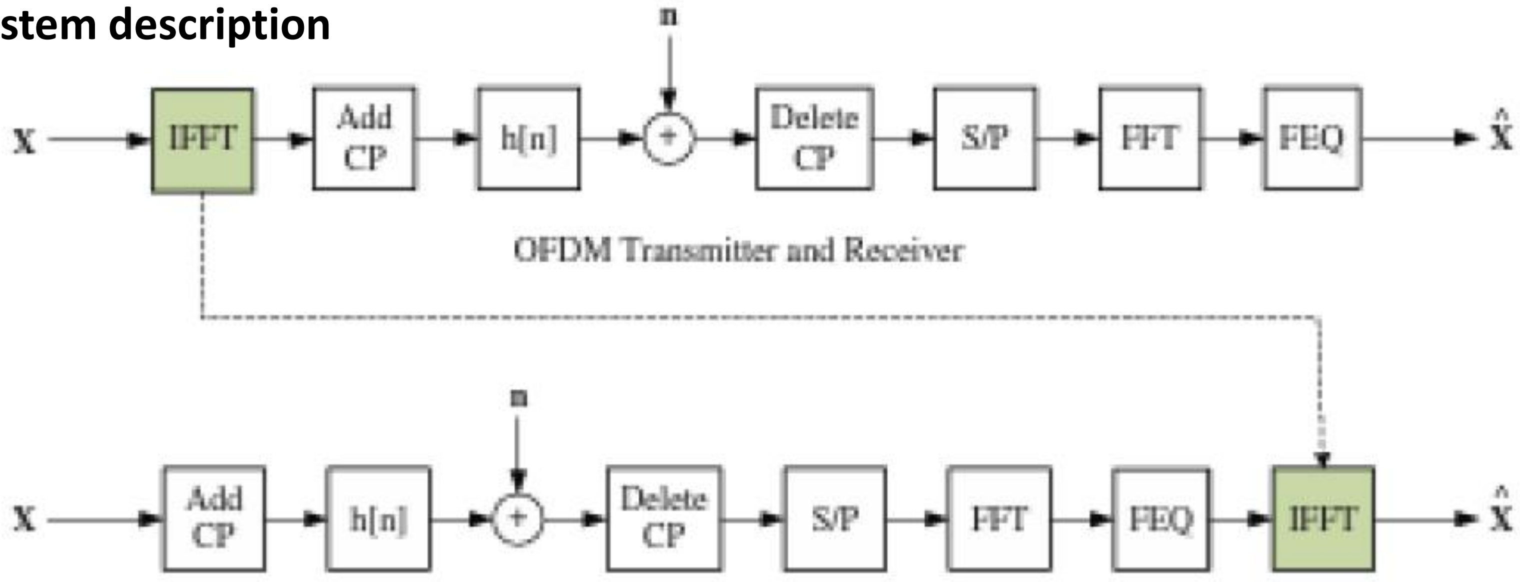
Each subcarrier can then be equalized via an FEQ by simply dividing by the complex channel gain H[i] for that subcarrier.

$$\hat{X}_l = X_l + \frac{N_l}{H_l}$$



Single-Carrier Frequency Domain Equalization (SC-FDE)

SC-FDE system description



OFDM Transmitter and Receiver

SC-FDE Transmitter and Receiver

Now transmitted signal is simply a sequence of QAM symbols, which have low PAPR, on the order of 4-5 dB.

At SC-FDE receiver the FFT operation moves the received signal into frequency domain.

$$y[n] = x[n] \circledast h[n] + w[n], \qquad where\ w[n]\ is\ the\ noise$$

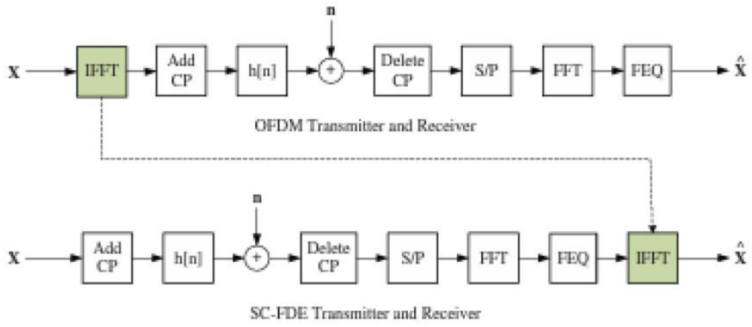
After FFT,

$$FFT\{y[n]\} \triangleq Y[m] = H[m]X[m] + W[m]$$

Now the frequency domain version $X[m]$ is not precisely data symbols , but rather FFT of data symbols $x[n]$

Single-Carrier Frequency Domain Equalization (SC-FDE)

SC-FDE system description



OFDM Transmitter and Receiver

SC-FDE Transmitter and Receiver

After FFT, a simple 1-tap FEQ can be applied that inverts each virtual subcarrier so that

$$\hat{X}[m] = \frac{Y[m]}{H[m]}$$

The resulting signal can then be converted back into the time domain using IFFT operation to give $\hat{x}[n]$, which are the estimates of the desired data symbols.

SC-FDE performance vs OFDM

- **Noise**
  - In OFDM, FEQ doesn’t result in damaging noise enhancement since FEQ is operated on data symbol and SNR of each data symbol will remain unchanged by multiplying by a constant factor. High SNR symbols will remain high and low SNR symbols will remain low.

  - In SC-FDE, FEQ doesn’t operate on data symbols itself but on the frequency domain dual of data symbols. Like in OFDM, SC-FDE FEQ also increase the power of symbol and noise, but unlike in OFDM in SC-FDE when the IFFT is applied to move the signal back into the time domain for detection, the amplified noise is spread by the IFFT operation over all the data symbol. Therefore, although the total noise amplification is same in both OFM and SC-FDE, the noise amplification is not isolated to a single but instead affects all the symbols prior to decoding and detection.

- In some cases OFDM slightly outperform SC-FDE, while in others SC-FDE does a little better.
- OFDM performs a better when the coding is strong and/or the constellation is large, while the opposite is true for SC-FDE.

- Reduced PA backoff of SC-FDE.
- Symmetric complexity of OFDM.

Design consideration for SC-FDE and OFDM

SC-FDE has lower complex transmitter but a highly complex receiver, compared to OFDM. But in OFDM receiver is already more complex then the transmitter due to channel estimation, synchronization, and error correction decoder.

In LTE, uplink utilize SC-FDE and the downlink utilize OFDM. In such a situation, the base station would perform 3 IFFT/FFT operations and the mobile, which is more power and cost sensitive, will perform only a single FFT operation.

Channel estimation and synchronization in OFDM are accomplished via a preamble ok known data symbols (reference symbols) which are inserted at known positions in all subsequent OFDM symbols. Although SC-FDE system would typically also include a preamble, this preamble is in time domain so it not as straightforward to estimate the frequency domain value, H_l.

Another commonly cited disadvantage of SC-FDE is that it has a nominally more dispersive spectrum compared to OFDM. OFDM's sharp spectrum results in less co-channel interference.

On the other hand, OFDM has higher PAPR, it is more subject to clipping that can ause spectral dispersion.

OFDM-FDMA, OFDM-TDMA, OFDM-CDMA

- OFDM is not a multiple access technique, but rather a technique for frequency selectivity.

- OFDM does, however, create many parallel streams of data that can in principle be used by different users.

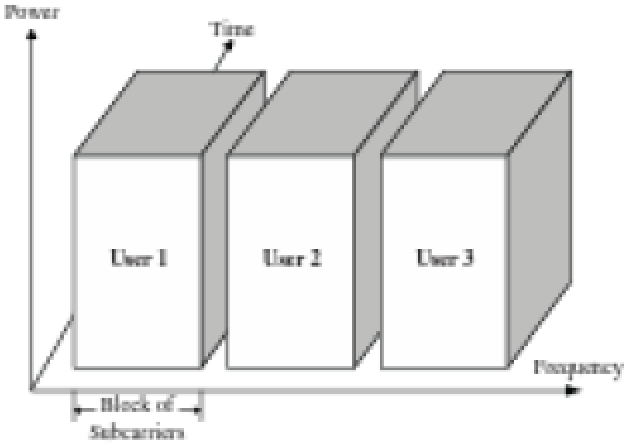
- Single-user OFDM

- Multiple access strategies typically attempt to provide orthogonal, that is, non-interfering communication channels for each active base station-user link.

- The most common ways to divide the available dimensions among the multiple users is through the use of frequency, time, or code division multiplexing.

OFDM-FDMA

- FDMA can be readily implemented in OFDM system by assigning different users their own sets of subcarriers.
- Simplest method is static allocation
- E.g. in a 64 bit subcarrier system, user-1 could take subcarriers 1-16, user 2,3,and 4 using subcarriers 17-32, 33-48, 49-64 respectively.
- Uneven allocation – high data users being allocated more subcarrier than lower data rate users.
- Before OFDMA term was coined and became popular, OFDM-FDMA sometimes used to describe what would now be called as OFDMA.
- OFDMA in LTE, however, has explicit time-sharing and procedure to allow for the dynamic allocation of subcarriers.

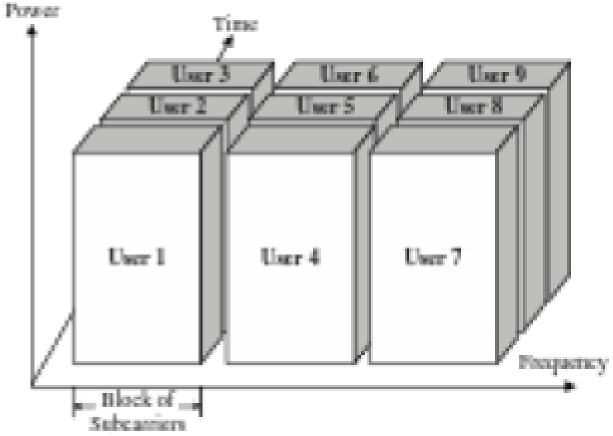


OFDM-TDMA

- In addition to FDMA or instead of FDMA, multiple user can also be accommodated by TDMA.

- In OFDM cellular system, some degree of TDMA is essential since there will generally be more users in the system than can be simultaneously carried on a single OFDM symbol.

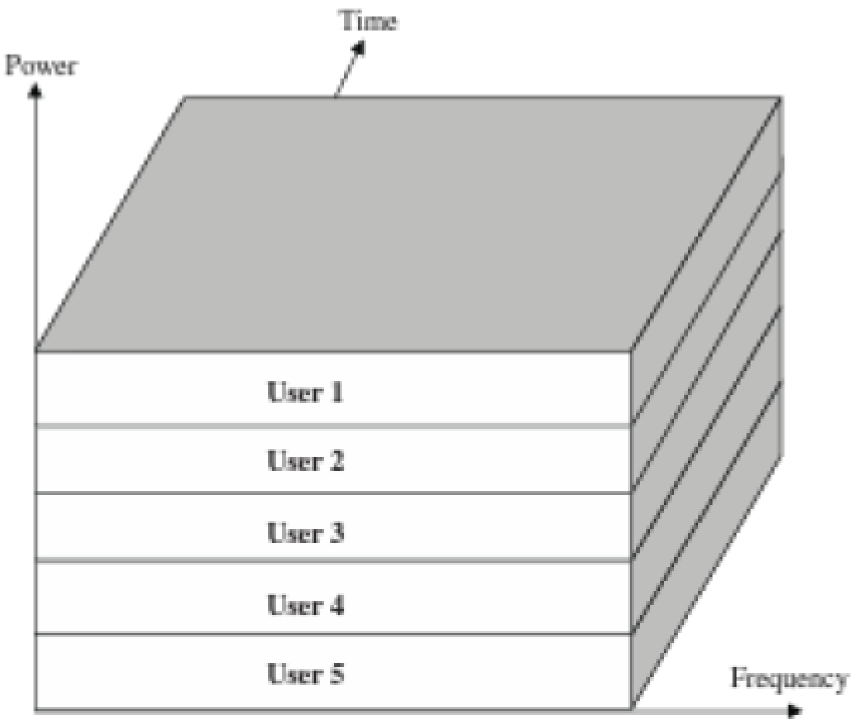
- Furthermore, users often will not have data to send, so it is also important that subcarriers be dynamically allocated in order to avoid waste.



OFDM-CDMA

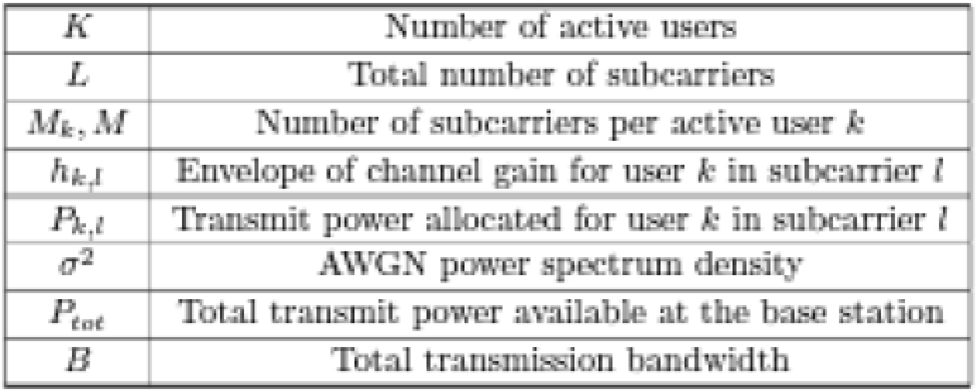
- CDMA was the dominant multiple access technique for 3G cellular system, but not particularly appropriate for high speed data since the entire premise of CDMA is that a bandwidth much larger than data rate is used to suppress the interference.

- OFDM and CDMA are not fundamentally incompatible; they can be combined to create a Multicarrier CDMA (MC-CDMA) waveform.



Orthogonal frequency division multiple access (OFDMA)

Table 4.1 OFDMA Notation

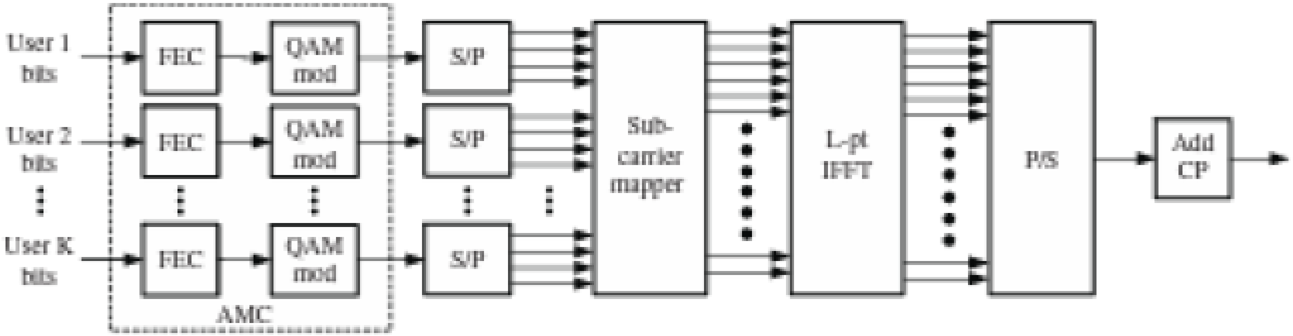


K	Number of active users
L	Total number of subcarriers
M_k, M	Number of subcarriers per active user k
$h_{k,l}$	Envelope of channel gain for user k in subcarrier l
$P_{k,l}$	Transmit power allocated for user k in subcarrier l
σ^2	AWGN power spectrum density
P_{tot}	Total transmit power available at the base station
B	Total transmission bandwidth

Orthogonal frequency division multiple access (OFDMA)

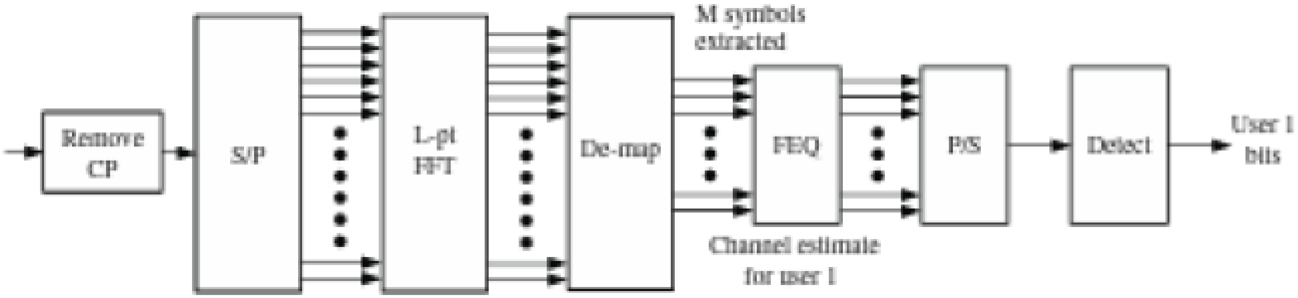
Basic flow is similar to OFDM system except for now K users will share the L subcarriers, where user being allocated M_k subcarriers.

OFDMA downlink transmitter



Adaptive Modulation and Coding

OFDMA downlink receiver

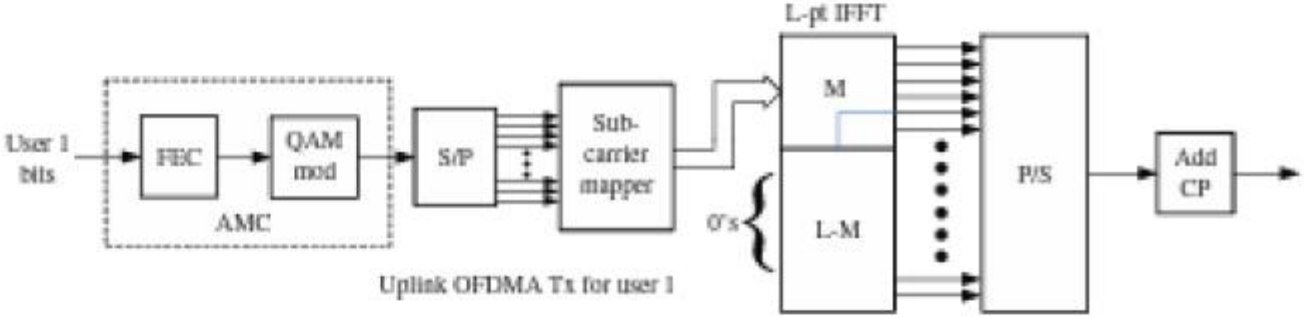


All K active users- who by designed have orthogonal subcarrier assignment- have a different receiver that only detects the Mk subcarriers intended for it.

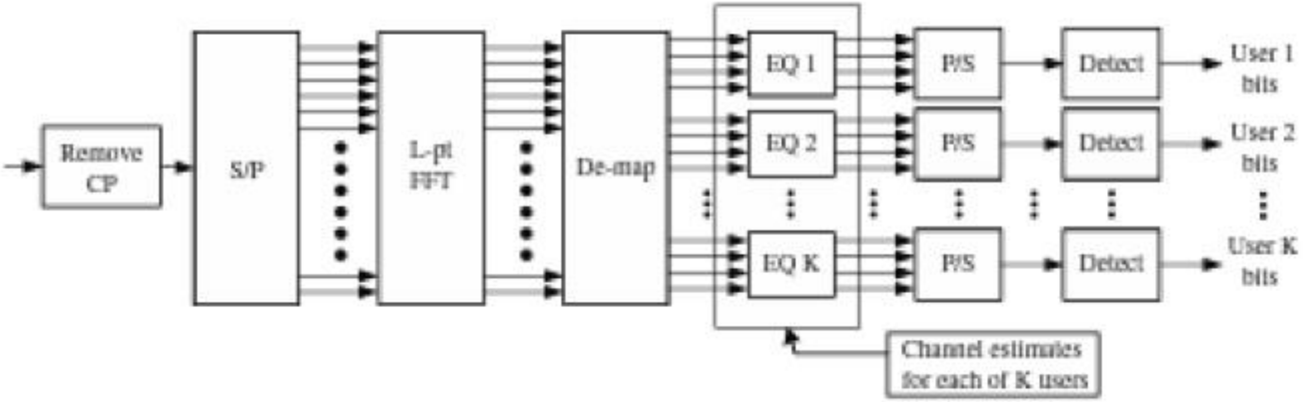
Orthogonal frequency division multiple access (OFDMA)

OFDMA is not used in the LTE uplink.

OFDMA uplink transmitter for user-1 where user-1 is allocated subcarriers 1,2….M out of L subcarriers.



OFDMA uplink receiver



Each of active K users- who by designed have orthogonal subcarrier assignment- are aggregated the receiver and demultiplexed after FFT.

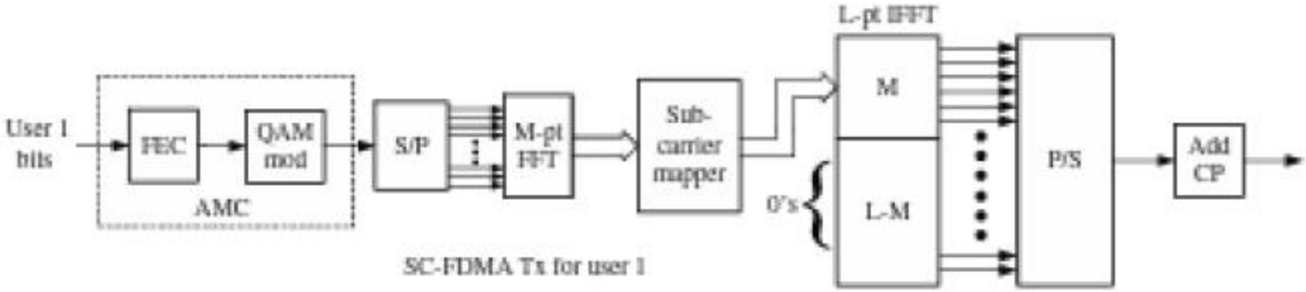
Orthogonal frequency division multiple access (OFDMA) Advantages and disadvantages

homework for students

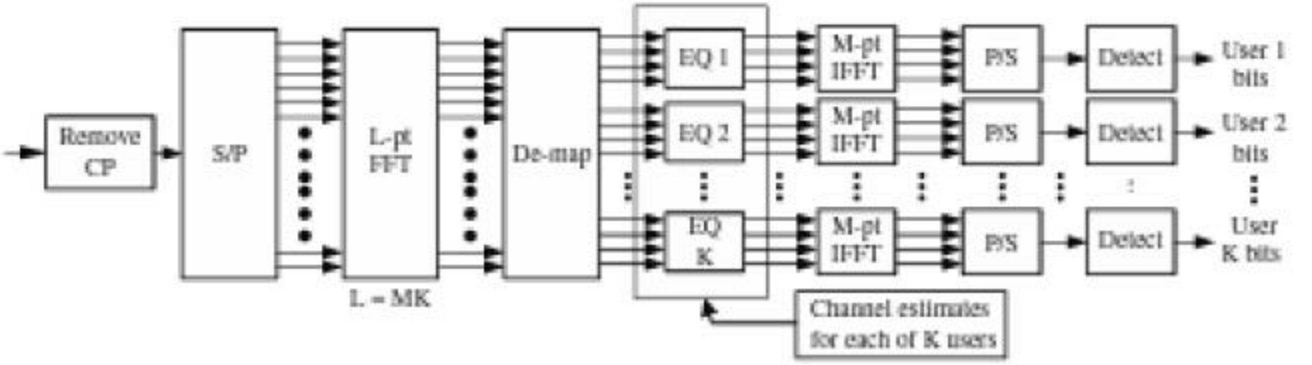
Single carrier frequency division multiple access (SC-FDMA)

SC-FDMA is employed in the LTE uplink.

SCFDMA uplink transmitter



SC-FDMA uplink receiver



Much like OFDMA receiver, difference is that each user's M_k subcarriers an additional small IFFT must be applied prior to detection to bring the received data back into the time domain.

Single carrier frequency division multiple access (SC-FDMA) Advantage and disadvantages

homework for students

OFDMA and SC-FDMA in LTE

LTE, like any OFDMA-based standard must specify several things in order for system to work.
(i) it must specify quanta, or units, of time-frequency resources that can be assigned.

(ii) it must specify messaging protocols that allows the mobile unites to request the resources when necessary, and to know what resource they have assigned, both for transmission and reception.

(iii) ranging procedure must be specified so that simultaneous uplink transmission for several mobile unites can be reliably decoded at the base station.

4.5.1 The LTE Time-Frequency Grid – module 3
4.5.2 Allocation Notification and Uplink Feedback - module 3
4.5.3 Power Control – module 4

Multiple Antenna Transmission and Reception

- From the beginning, LTE was designed so that the base station and mobile could both use multiple antennas for radio transmission and reception.

- The expanded and more advanced use of multiple antennas at both transmitter and receiver promises to be among LTE’s largest advantages over incumbent technologies.

- Multiple antenna techniques can be grouped into roughly three different categories: diversity, interference suppression and spatial multiplexing.
    - The most familiar is **diversity processing**, which increases the received signal power and reduces the amount of fading by using multiple antennas at the transmitter, the receiver or both. Spatial diversity allows a number of different versions of signal to be transmitted and/or received, and provide considerable resilience against fading.

    - **Interference suppression** uses the spatial dimensions to reject interference from other uses either through the physical antenna gain pattern or through other forms of array processing.

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

Spatial Diversity Overview

- The primary advantage of spatial diversity relative to most time and frequency diversity is that no additional bandwidth or power is needed in order to take advantages of spatial diversity.

- Spatial diversity is exploited through two or more antennas which are separated by enough distance so that the fading is approximately decorrelated to each other.

- The cost and space consumed by each additional antenna, its RF transmit or receive chain, and the associated signal processing required to modulate or demodulate multiple spatial streams may not be negligible.

- However for a small number of antennas, the gain are significant enough to warrant the space and expense.

- When multiple antennas are used, two forms of gains are available, diversity gain and array gain.
  - Diversity gain results from the creation of multiple independent channels between the transmitter and receiver, and is product of statistical richness of those antennas.
  - Array gain on the other hand doesn’t rely on statistical diversity between the different channels.

Array Gain

- Array gain doesn’t rely on statistical diversity between the different channels.

- Instead it achieves its performance enhancement by coherently combining the energy of each of the antennas to gain an advantage versus the noise signal on each antenna, which is uncorrelated and doesn’t add coherently.

- Even if the channels are completely correlated (LOS system with closely spaced antennas), due to array gain the received SNR increases linearly with the number of receive antennas (N_r).

- For a N_t x N_r system the array gain is N_r

For 1x N_r

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

$$y_i = h_i x + n_i = hx + n_i$$

$h_i = h$, for all antennas since they are perfectly correlated

Hence, the SNR for a single antenna is

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

Noise power is σ^2, and assume unite energy signal ($\varepsilon_x = E|x^2| = 1$)

Array Gain

$$y_i = h_i x + n_i = hx + n_i$$

h_i = h, for all antennas since they are perfectly correlated

Hence, the SNR for a single antenna is

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

Noise power is σ^2, and assume unite energy signal $(\varepsilon_x = E|x^2| = 1)$

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

$$y = \sum_{i=1}^{N_r} y_i = N_r hx + \sum_{i=1}^{N_r} n_i$$

The combine SNR, assuming that just the noise on each branch is uncorrelated, is

$$\gamma = \frac{|N_r h|^2}{N_r \sigma} = \frac{N_r |h|^2}{\sigma^2}$$

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

However, because all channels are correlated in this case, there is no diversity gain.

Diversity Gain

- The main objective of spatial diversity is to improve the communication reliability by decreasing the sensitivity to fading.
- The physical layer reliability is typically measured by the outage probability or average bit error rate.
- In additive noise the bit error probability (BEP) can be written for virtually any modulation scheme as:

$$P_b \approx c_1 e^{-c_2 \gamma} \ldots\ldots\ldots.(1)$$

- c_1 and c_2 are constant and dependent upon modulation type, γ is received SNR
- Because the error probability is exponentially decreasing with SNR, the few instances in a fading channel when the received SNR is low dominate the BEP, since even modestly higher SNR values have dramatically reduced BEP.

- Without diversity the average BEP can be written as: $P_b \approx c_3 \gamma^{-1} \ldots\ldots\ldots.(2)$

- If N_t transmit antenna and N_r receive antennas that are sufficiently spaced are added to the system, it is said that diversity order is $N_d = N_t N_r$, since that is the number of uncorrelated paths between the transmitter and receiver.

- Since the probability of all the N_d uncorrelated channels having low SNR is very small, the diversity order has dramatic effect on the system reliability.
- With diversity the average BEP improves to: $P_b \approx c_4 \gamma^{-Nd} \ldots\ldots\ldots\ldots\ldots.(3)$

Diversity Gain

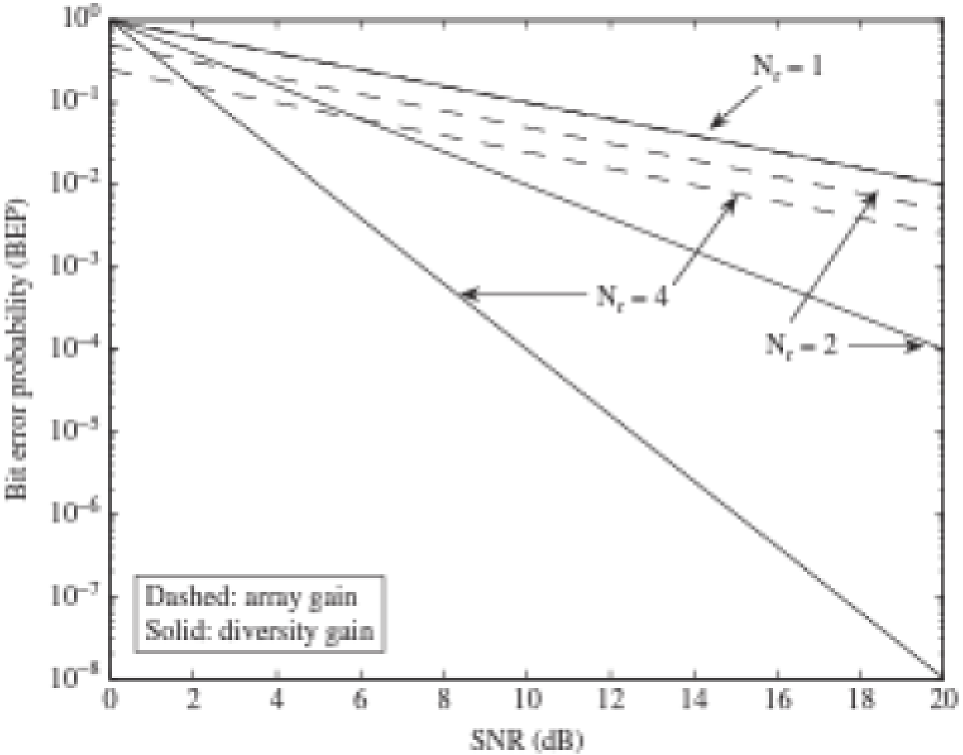
- E.g., id the BEP without any diversity is 1 to 10 – which is awful– the BEP with two antennas at both the transmitter and receiver would be closer to 1 in 10,000. Diversity gain is very powerful.

- On the other hand if only an array gain was possible (e.g. if the antennas are not sufficiently spaced or the channel is LOS, the average BEP would only decrease from eq.2 to

$$P_b \approx c_4(Nd\gamma)^{-1} \ldots\ldots\ldots\ldots (4)$$

BEP curves for N_t =1 and N_r = (1,2,4).

Statistical diversity has a very large impact on BEP, where as array gain only result in fix shift of the curve.



Increased Coverage or Reduced transmit Power

- The benefit of diversity can also harnessed to increase the coverage area and to reduce the required transmit power.

- Assume the there are N_r receive antennas and only one transmit antenna, due to just array gain, the average SNR is approx. $N_r\gamma$

- From path loss model, $P_r = PtPod^{-\alpha}$, it can be found that increase in coverage area is $N_r^{\frac{1}{\alpha}}$ and so the coverage area improvement is $N_r^{\frac{2}{\alpha}}$, without even considering the diversity gain.

- Similar reasoning can be used to show that the required transmit power can be reduced by $10\log_{10} N_r$ dB while maintain a diversity gain of N_t x N_r.

Increased the Data Rate with Spatial Diversity

- Diversity techniques are very effective at averaging out fades in the channel and thus increase the system reliability.

- Receive diversity techniques also increase the average received SNR at best linearly due the array gain.

- Shannon capacity formula give the maximum achievable data rate of a single communication link in adaptive white Gaussian noise (AWGN) as: $C = B\log_2(1+\gamma)$
  C is the capacity or maximum error-free data rate, B is bandwidth and γ is SNR

- Since antenna diversity increase the γ linearly, the diversity technique will increase the C logarithmically w.r.t. the number of antennas.

- When SNR is low, the C also increase close to linear with γ,
  since $\log(1+x) \approx x, for\ small\ x$

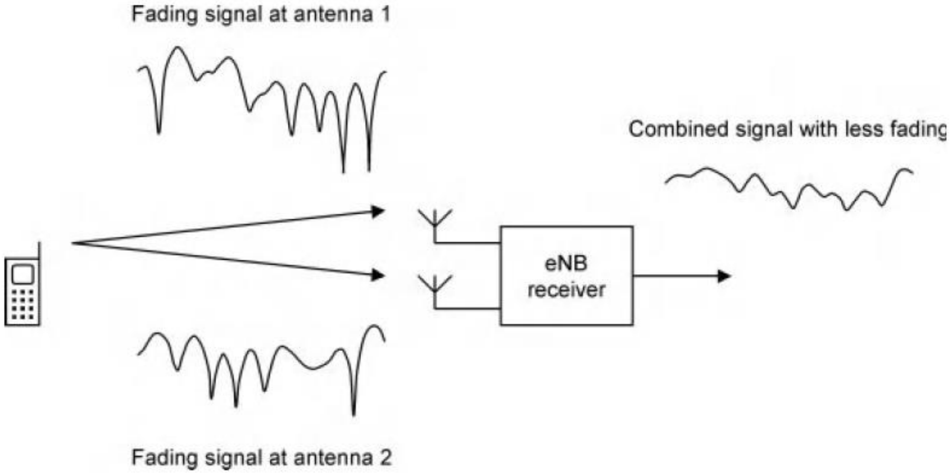
- Hence, in low SNR channels, diversity techniques increase the capacity about linearly.

Receive diversity

- *Receive diversity* is most often used in the uplink.
- Here, the base station uses two antennas to pick up two copies of the received signal
- The signals reach the receive antennas with different phase shifts, but these can be removed by antenna-specific channel estimation.
- The base station can then add the signals together in phase, without any risk of destructive interference between them.
- The signals are both made up from several smaller rays, so they are both subject to fading. If the two individual signals undergo fades at the same time, then the power of the combined signal will be low. But if the antennas are far enough apart (a few wavelengths of the carrier frequency), then the two sets of fading geometries will be very different, so the signals will be far more likely to undergo fades at completely different times. We have therefore reduced the amount of fading in the combined signal, which in turn reduces the error rate.

Base stations usually have more than one receive antenna. In LTE, the mobile's test specifications assume that the mobile is using two receive antennas, so LTE systems are expected to use receive diversity on the downlink as well as the uplink.

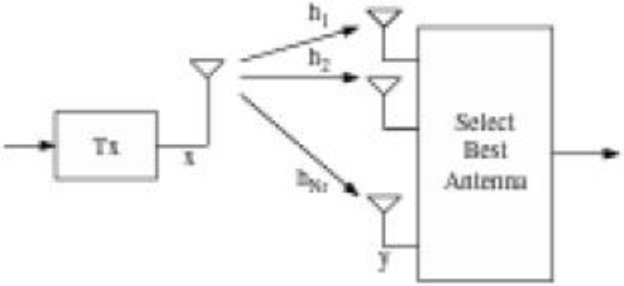
A mobile's antennas are closer together than a base station's, which reduces the benefit of receive diversity,

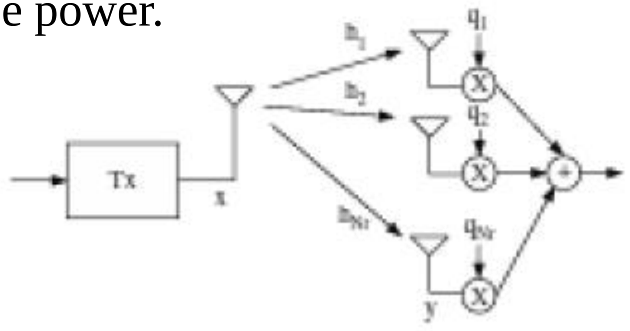


Receive diversity

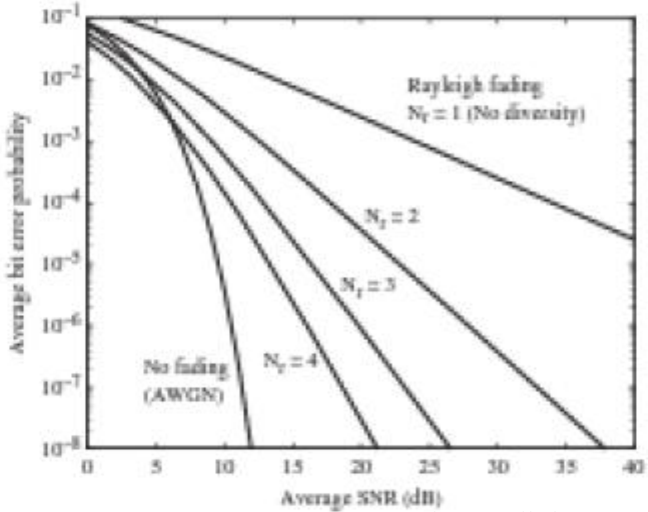
- ***Selection combining (SC)*** is the simplest type of combiner, in that it simply estimate the instantaneous strengths of each of the N_r systems, and selects the highest one.

- ***Maximal ratio combining (MRC)*** combines the information from all the received branches in order to maximize the ratio of signal-to-noise power.

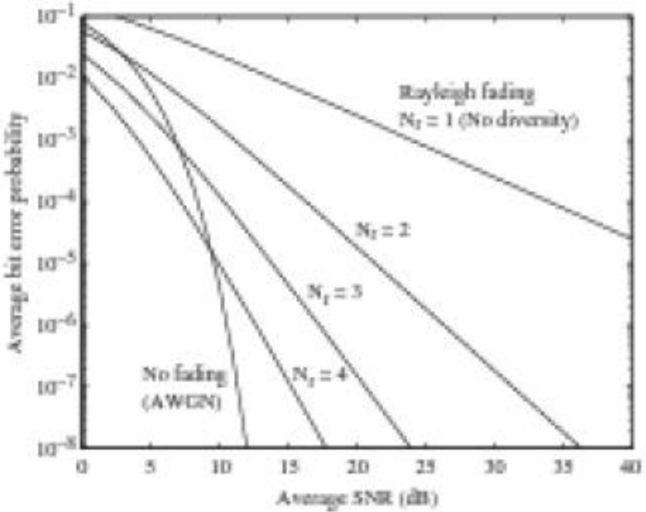




Selection combining



Maximal ratio combining



Transmit Diversity

- *Transmit diversity* reduces the amount of fading by using two or more antennas at the transmitter.
- It is superficially similar to receive diversity, but with a crucial problem: the signals add together at the single receive antenna, which brings a risk of destructive interference.
- There are two ways to solve the problem, the first of which is *closed loop transmit diversity*

Closed Loop Transmit Diversity

- Here, the transmitter sends two copies of the signal in the expected way, but it also applies a phase shift to one or both signals before transmission. By doing this, it can ensure that the two signals reach the receiver in phase, without any risk of destructive interference.

- The phase shift is determined by a *precoding matrix indicator* (PMI), which is calculated by the receiver and fed back to the transmitter. A simple PMI might indicate two options: either transmit both signals without any phase shifts, or transmit the second with a phase shift of 180°.

- If the first option leads to destructive interference, then the second will automatically work.

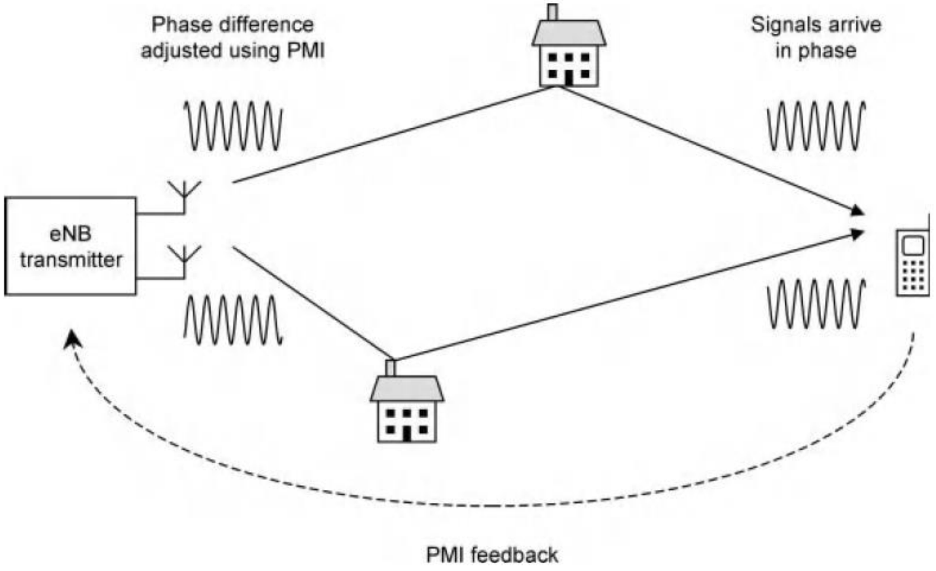
- Once again, the amplitude of the combined signal is only low in the unlikely event that the two received signals undergo fades at the same time.

Closed Loop Transmit Diversity

- The phase shifts introduced by the radio channel depend on the wavelength of the carrier signal and hence on its frequency. This implies that the best choice of PMI is a function of frequency as well.
- However, this is easily handled in an OFDMA system, as the receiver can feed back different PMI values for different sets of sub-carriers.

- The best choice of PMI also depends on the position of the mobile, so a fast moving mobile will have a PMI that frequently changes.

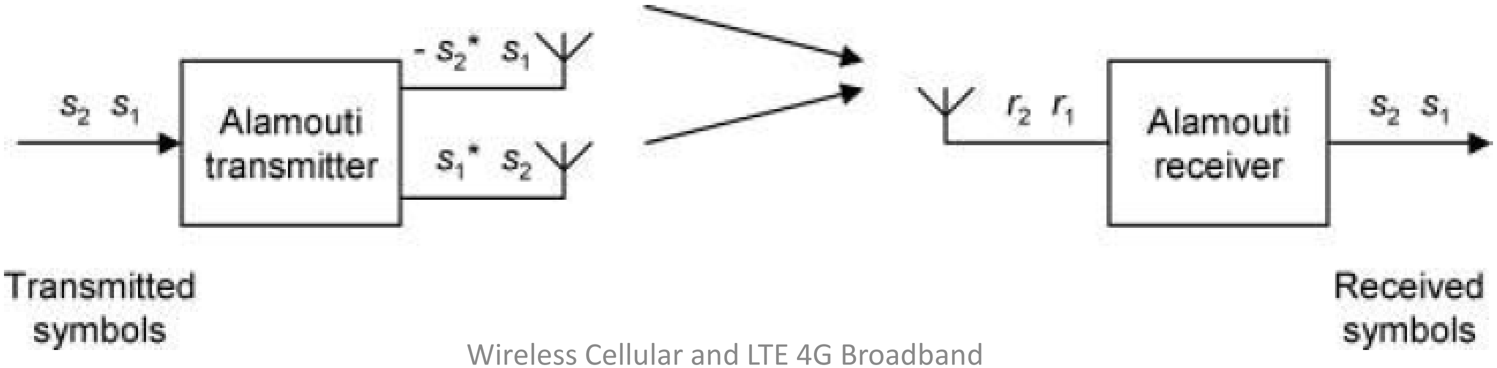
- Unfortunately the feedback loop introduces time delays into the system, so in the case of fast moving mobiles, the PMI may be out of date by the time it is used.
- For this reason, closed loop transmit diversity is only suitable for mobiles that are moving sufficiently slowly. For fast moving mobiles, it is better to use the open loop technique



Open Loop Transmit Diversity

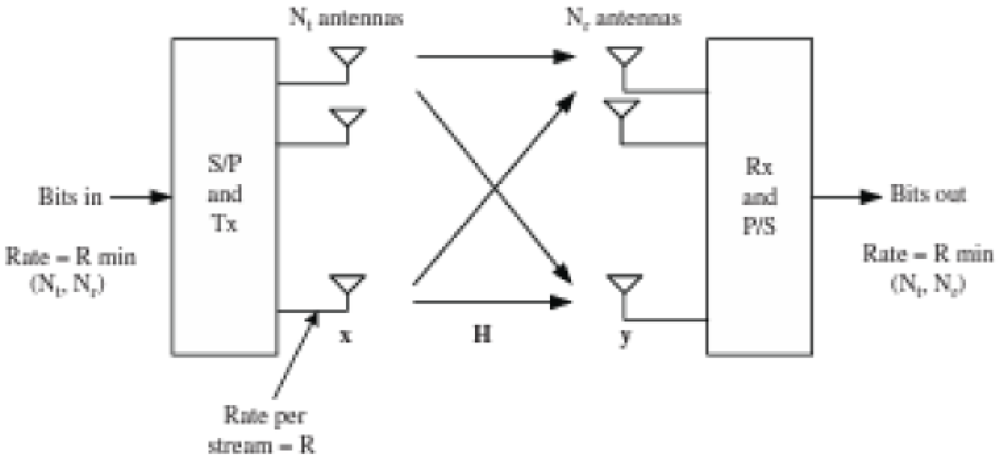
- Figure below shows an implementation of *open loop transmit diversity* that is known as *Alamouti's technique*. Here, the transmitter uses two antennas to send two symbols, denoted s_1 and s_2, in two successive time steps.
- In the first step, the transmitter sends s_1 from the first antenna and s_2 from the second, while in the second step, it sends $-s_2^*$ from the first antenna and $s_1^*$from the second. (The symbol $*$ indicates that the transmitter should change the sign of the quadrature component, in a process known as complex conjugation.)

- The receiver can now make two successive measurements of the received signal, which correspond to two different combinations of s_1 and s_2. It can then solve the resulting equations, so as to recover the two transmitted symbols.
- There are only two requirements: the fading patterns must stay roughly the same between the first time step and the second, and the two signals must not undergo fades at the same time. Both requirements are usually met.



Spatial Multiplexing

- Spatial multiplexing refers to breaking the incoming high data stream into M parallel data streams, for $M = N_T \; and \; N_T \leq NR$
- Assuming that the streams can be successfully decoded, the spectral efficiency is increased by a factor of M.
- It means adding antennas elements can greatly increase the data rate without any increase in bandwidth.
- In a system with N_T transmit and N_R receive antennas, often known as an $N_T \times N_R$ spatial multiplexing system, the peak data rate is proportional to $\min(N_T, N_R)$.

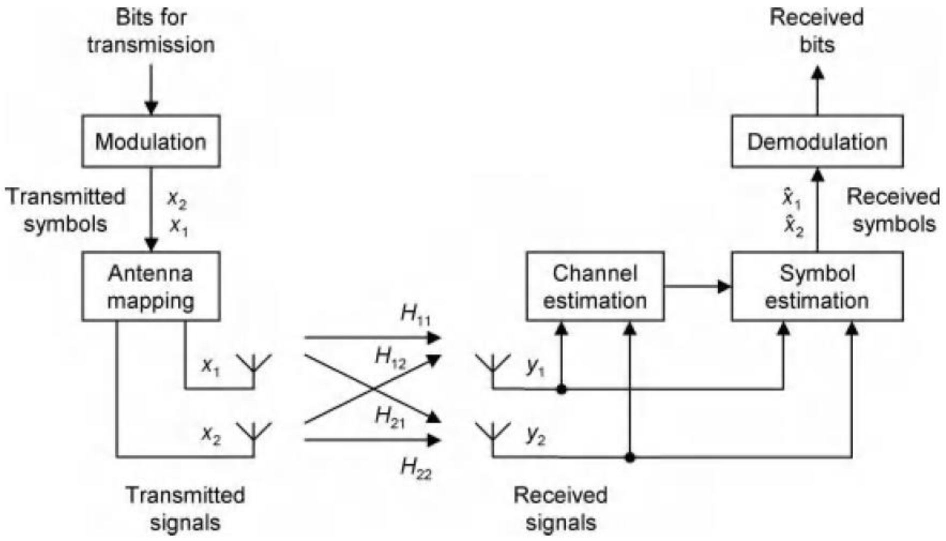


A spatial multiplexing MIMO system transmit multiple substreams to increase the data rate.

Spatial Multiplexing

Principle of operation

- If the transmitter and receiver both have multiple antennas, then we can set up multiple parallel data streams between them, so as to increase the data rate.
- Figure below shows a basic spatial multiplexing system, in which the transmitter and receiver both have two antennas. In the transmitter, the antenna mapper takes symbols from the modulator two at a time, and sends one symbol to each antenna.
- The antennas transmit the two symbols simultaneously, so as to double the transmitted data rate.



Basic principle of a 2 x 2 spatial multiplexing system

Spatial Multiplexing

The symbols travel to the receive antennas by way of four separate radio paths, so the received signals can be written as follows: $(y = Hx + n)$

$$\begin{aligned} y_1 &= H_{11}x_1 + H_{12}\,x_2 + n_1 \\ y_2 &= H_{21}x_1 + H_{22}\,x_2 + n2 \end{aligned}$$

..........eq-S.1

Here, x_1 and x_2 are the signals sent from the two transmit antennas,
y_1 and y_2 are the signals that arrive at the two receive antennas, and
n_1 and n_2 represent the received noise and interference.
H_{ij} expresses the way in which the transmitted symbols are attenuated and phase-shifted, as they travel to receive antenna i from transmit antenna j.

$$H = \begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix}$$

- In general, all the terms in the equation above are complex.
- In the transmitted and received symbols x_j and y_i and the noise terms n_i , the real and imaginary parts are the amplitudes of the in-phase and quadrature components.

- Similarly, in each of the channel elements H_{ij} , the magnitude represents the attenuation of the radio signal, while the phase represents the phase shift.

Spatial Multiplexing

Simple examples by using real numbers alone.

- Lets assume that the transmitter is modulating the bits using binary phase shift keying, so that the in-phase components are +1 and −1, and the quadrature components are zero.

- We will also assume that the radio channel can attenuate or invert the signal, but does not introduce any other phase shifts.

Consistent with these assumptions, let us consider the following example:

$$\begin{aligned} H_{11} &= 0.8 \quad H_{12} = 0.6 \quad x_1 = +1 \quad n_1 = +0.02 \\ H_{21} &= 0.2 \quad H_{22} = 0.4 \quad x_2 = -1 \quad n_2 = -0.02 \end{aligned}$$

Substituting these numbers into Equation (S.1) shows that the received signals are as follows:

$$\begin{aligned} y_1 &= +0.22 \\ y_2 &= -0.22 \end{aligned}$$

- The receiver's first task is to estimate the four channel elements Hij.
- To help it do this, the transmitter broadcasts reference symbols.
- When one antenna transmits a reference symbol, the other antenna keeps quiet and sends nothing at all.
- The receiver can then estimate the channel elements H_{11} and H_{21}, by measuring the two received signals at the times when transmit antenna 1 is sending a reference symbol. It can then wait until transmit antenna 2 sends a reference symbol, before estimating the channel elements H_{12} and H_{22}.

Spatial Multiplexing

The receiver now has enough information to estimate the transmitted symbols x_1 and x_2.

Simplest way to do this is a ***zero-forcing detector***, which operates as follows.

If we ignore the noise and interference, then Equation (S.1) is a pair of simultaneous equations for two unknown quantities, x_1 and x_2. These equations can be inverted as follows:

$$\hat{x}_1 = \frac{\widehat{H}_{22}y_1 - \widehat{H}_{12}y_2}{\widehat{H}_{11}\widehat{H}_{22} - \widehat{H}_{21}\widehat{H}_{12}}$$

$$\hat{x}_2 = \frac{\widehat{H}_{11}y_2 - \widehat{H}_{21}y_1}{\widehat{H}_{11}\widehat{H}_{22} - \widehat{H}_{21}\widehat{H}_{12}}$$

Here, $\widehat{H}_{ij}$ is the receiver's estimate of the channel element Hij .
Similarly, $\hat{x}_1$and $\hat{x}_2$are the receiver's estimates of the transmitted symbols x_1 and x_2.

Substituting the numbers of previous slide from above equation gives the following result:

$$\hat{x}_1 = +1.1$$
$$\hat{x}_2 = -1.1$$

This is consistent with transmitted symbols of +1 and –1.

We have therefore transferred two symbols at the same time using the same sub-carriers, and have doubled the data rate.

Open Loop Spatial Multiplexing

There is a problem with the technique described above.

To illustrate this, let us change one of the channel elements, H_{11}, to give the following example:

$$H_{11} = 0.3 \quad H_{12} = 0.6$$
$$H_{21} = 0.2 \quad H_{22} = 0.4$$

If we try to estimate the transmitted symbols, we find that $H_{11}H_{22} - H_{21}H_{12}$ is zero.
We therefore end up **dividing by zero**, which is nonsense. So, for this choice of channel elements, the technique has **failed**.

We can see what has gone wrong by substituting the channel elements into Equation (S.1), and writing the received signals as follows:

$$y_1 = 0.3(x_1 + 2x_2) + n_1$$
$$y_2 = 0.2(x_1 + 2x_2) + n_2$$

By measuring the received signals y_1 and y_2, we were expecting to measure two different pieces of information, from which we could recover the transmitted data.
This time, however, we have measured the same piece of information, namely $\boldsymbol{x_1 + 2x_2}$, twice.

As a result, we do not have enough information to recover $x_1\, and\, x_2$ independently.
Furthermore, this is not just an isolated special case. If $H_{11}H_{22} - H_{21}H_{12}$ is small but non-zero, then our estimates of *x*1 and *x*2 turn out to be badly corrupted by noise and are completely unusable.

Open Loop Spatial Multiplexing

Solution is that, the receiver measures the channel elements and works out a ***rank indication*** (RI), which indicates the number of symbols that it can successfully receive.

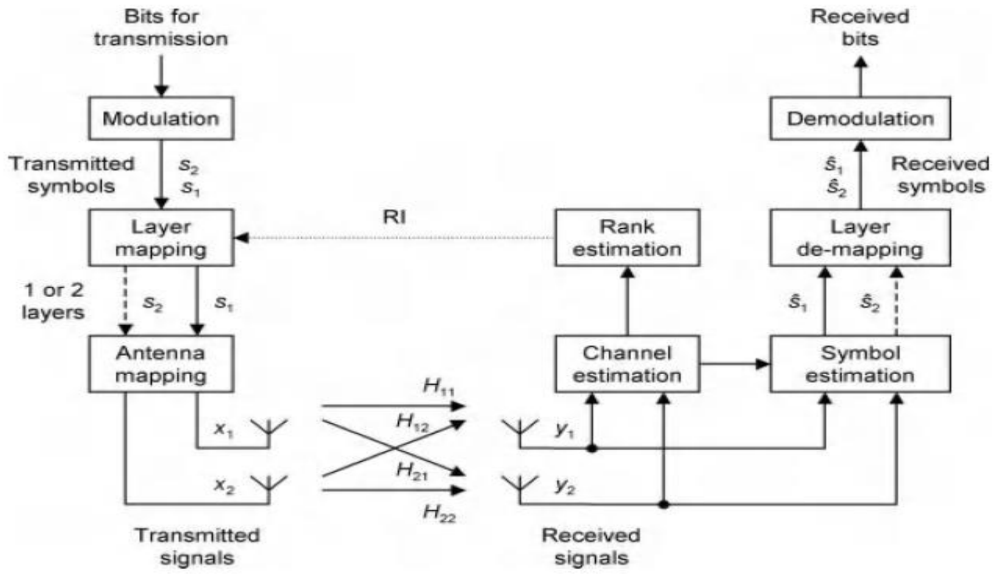
It then feeds the rank indication back to the transmitter.

If the rank indication is two, then the system operates in the same way that we described earlier. The transmitter's *layer mapper* grabs two symbols, s_1 and s_2, from the transmit buffer, so as to create two independent data streams that are known as *layers*.

The ***antenna mapper*** then sends one symbol to each antenna, by a straightforward mapping operation:

$$x_1 = s_1$$
$$x_2 = s_2$$

The receiver measures the incoming signals and recovers the transmitted symbols as before.



Open Loop Spatial Multiplexing

If the **rank indication is one**, then the layer mapper only grabs one symbol, s_1, which the antenna mapper sends to both transmit antennas as follows:

$$\begin{aligned} x_1 &= s_1 \\ x_2 &= s_1 \end{aligned}$$

Under these assumptions, becomes the following:

$$\begin{aligned} y_1 &= 0.9s_1 + n_1 \\ y_2 &= 0.6s_1 + n_2 \end{aligned}$$

The receiver now has two measurements of the transmitted symbol s_1, and can combine these in a diversity receiver so as to recover the transmitted data.

The effect is as follows.
If the channel elements are well behaved, then the transmitter sends two symbols at a time and the receiver recovers them using a spatial multiplexing receiver.
Sometimes this is not possible, in which case the transmitter falls back to sending one symbol at a time and the receiver falls back to diversity reception.

Closed Loop Spatial Multiplexing

There is one remaining problem. To illustrate this, let us change two more of the channel elements, so that:

$$
\begin{aligned}
H_{11} &= 0.3 \qquad & H_{12} &= -0.3 \\
H_{21} &= 0.2 \qquad & H_{22} &= -0.2
\end{aligned}
$$

These channel elements are badly behaved, in that $H_{11}H_{22} - H_{21}H_{12}$ is zero.

But if we try to handle the situation in the manner described above, by sending the same symbol from both transmit antennas, then the received signals are as follows:

$$
\begin{aligned}
y_1 &= 0.3s_1 - 0.3s_1 + n_1 \\
y_2 &= 0.2s_1 - 0.2s_1 + n_2
\end{aligned}
$$

So the transmitted signals cancel out at both receive antennas and we are left with measurements of the incoming noise and interference. We therefore have insufficient information even to recover s_1.

To see the way out, consider what happens if we send one symbol at a time as before, but invert the signal that is sent from the second antenna:

$$
\begin{aligned}
x_1 &= s_1 \\
x_2 &= -s_1
\end{aligned}
$$

The received signal can now be written as follows:

$$
\begin{aligned}
y_1 &= 0.3s_1 + 0.3s_1 + n_1 \\
y_2 &= 0.2s_1 + 0.2s_1 + n_2
\end{aligned}
$$

This time, we can recover the transmitted symbol s_1.

Closed Loop Spatial Multiplexing

So we now require two levels of adaptation. If the rank indication is two, then the transmitter sends two symbols at a time using the antenna mapping of

$$\begin{aligned} x_1 &= s_1 \\ x_2 &= s_2 \end{aligned}$$

If the rank indication is one, then the transmitter falls back to diversity processing and sends one symbol at a time. In doing so, it chooses an antenna mapping such as Equation

$$\begin{aligned} x_1 &= s_1 \\ x_2 &= s_1 \end{aligned}$$

OR

$$\begin{aligned} x_1 &= s_1 \\ x_2 &= -s_1 \end{aligned}$$

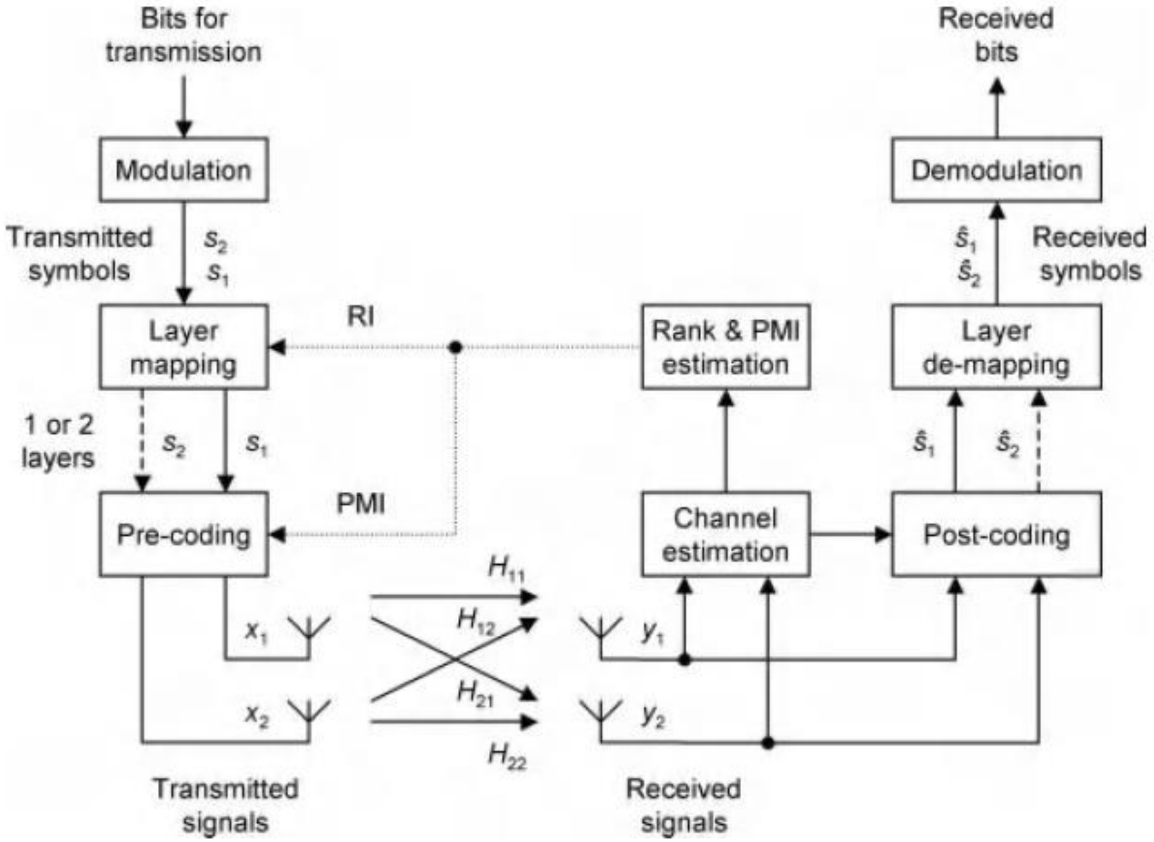
which depends on the exact nature of the channel elements and which guarantees a strong signal at the receiver.

The receiver measures the channel elements as before and uses them to feed back two quantities, namely the rank indication and a precoding matrix indicator (**PMI**).

The PMI controls a *precoding* step in the transmitter, which implements an adaptive antenna mapping using (for example) out of above three equations to ensure that the signals reach the receiver without cancellation.

Closed Loop Spatial Multiplexing

The receiver measures the channel elements as before and uses them to feed back two quantities, namely the rank indication and a precoding matrix indicator (**PMI**). The PMI controls a *precoding* step in the transmitter, which implements an adaptive antenna mapping using (for example) out of above three equations to ensure that the signals reach the receiver without cancellation.



Matrix Representation

We have now covered the basic principles of spatial multiplexing. To go further, we need a more mathematical description in terms of matrices.

In matrix notation, we can write the received signal (Equation S.1) as follows:

$$\boldsymbol{y} = \boldsymbol{H}.\boldsymbol{x} + \boldsymbol{n}$$

Here,

- $\boldsymbol{x}$ is a column vector that contains the signals that are sent from the N_T transmit antennas.
- $\boldsymbol{n}$ and $\boldsymbol{y}$ are column vectors containing the noise and the resulting signals at the N_R receive antennas.
- The *channel matrix* **H** has N_R rows and N_T columns, and expresses the amplitude changes and phase shifts that the air interface introduced.

In the examples we considered earlier, the system had two transmit and two receive antennas, so the matrix equation above could be written as follows:

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix}$$

Now let us assume that the numbers of transmit and receive antennas are equal, so that $N_R = N_T = N$, and let us ignore the noise and interference as before. We can then invert the channel matrix and derive the following estimate of the transmitted symbols:

$$\hat{\boldsymbol{x}} = \hat{\boldsymbol{H}}^{-1}.\boldsymbol{y}$$

Here, $\hat{\boldsymbol{H}}^{-1}$ is the receiver's estimate of the inverse of the channel matrix, while $\hat{\boldsymbol{x}}$ is its estimate of the transmitted signal.

This is the **zero-forcing detector**. The detector runs into problems if the noise and interference are too great, but, in these circumstances, a ***minimum mean square error*** **(MMSE)** detector gives a more accurate answer.

Matrix Representation

If the channel matrix is well behaved, then we can measure the signals that arrive at the N receive antennas and use a suitable detector to estimate the symbols that were transmitted. As a result, we can increase the data rate by a factor N. The channel matrix may, however, be singular , in which case its inverse does not exist. Alternatively, the matrix may be ill conditioned, in which case its inverse is corrupted by noise. Either way, we need to find another solution.

The solution comes from writing the channel matrix H as follows:

$$H = P^{-1}.\Lambda.P$$

Here,

P is a matrix formed from the eigenvectors of H,

while Λ is a diagonal matrix whose elements are the eigenvalues of H.

In the two antenna example, the diagonal matrix is:

$$\Lambda = \begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix}$$

where the eigenvalues are λ_1 and λ_2.

Now let us transmit the symbols in the manner shown in Figure 5.7. At the output from the post-coding stage, the received symbol vector is:

$$\boldsymbol{r} = \boldsymbol{G}.\boldsymbol{H}.\boldsymbol{F}.\boldsymbol{s} + \boldsymbol{G}.\boldsymbol{n}$$

where ***s*** contains the transmitted symbols at the input to the precoding stage, ***F*** is the precoding matrix, ***H*** is the usual channel matrix, and ***G*** is the post-coding matrix. If we now choose the pre- and post-coding matrices so that they are good approximations to the matrices of eigenvectors:

F ≈ ***P***−1

G ≈ ***P***

(

Matrix Representation

Now let us transmit the symbols in the manner shown in figure below. At the output from the post-coding stage, the received symbol vector is:

$$\boldsymbol{r} = \boldsymbol{G}.\boldsymbol{H}.\boldsymbol{F}.\boldsymbol{s} + \boldsymbol{G}.\boldsymbol{n}$$

where ***s*** contains the transmitted symbols at the input to the precoding stage, ***F*** is the precoding matrix, ***H*** is the usual channel matrix, and ***G*** is the post-coding matrix. If we now choose the pre- and post-coding matrices so that they are good approximations to the matrices of eigenvectors:

$$F \approx P^{-1}$$

$$G \approx P$$

then the received symbol vector becomes the following:

$$\boldsymbol{r} \approx \boldsymbol{P}.\boldsymbol{H}.\boldsymbol{P}^{-1}.\boldsymbol{s} + \boldsymbol{P}.\boldsymbol{n}$$

$$\approx \Lambda.\boldsymbol{s} + \boldsymbol{P}.\boldsymbol{n}$$

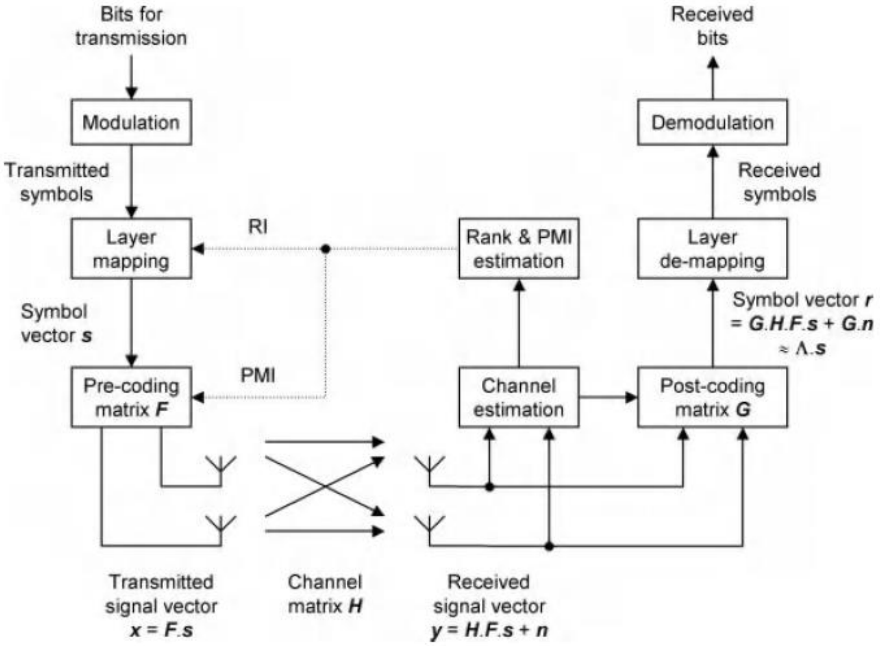
Ignoring the noise, we can now write the received symbols in a two antenna spatial multiplexing system as follows:

$$\begin{bmatrix} r_1 \\ r_2 \end{bmatrix} = \begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix} \cdot \begin{bmatrix} s_1 \\ s_2 \end{bmatrix}$$

We therefore have two independent data streams, without any coupling between them.

It is now trivial for the receiver to recover the transmitted symbols, as follows:

$$\hat{s}_i = \frac{r_i}{\lambda_i}$$



Matrix Representation

So, by a suitable choice of pre- and post-coding matrices, ***F*** and ***G***, we can greatly simplify the design of the receiver.

If the channel matrix ***H*** is singular, then some of its eigenvalues λ_i are zero.
If it is ill-conditioned, then some of the eigenvalues are very small, so that the reconstructed symbols are badly corrupted by noise. The *rank* of ***H*** is the number of usable eigenvalues.

In a two antenna system with a rank of 1, for example, the received symbol vector is as follows:

$$\begin{bmatrix} r_1 \\ r_2 \end{bmatrix} = \begin{bmatrix} \lambda_1 & 0 \\ 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} s_1 \\ s_2 \end{bmatrix}$$

The system can exploit this behaviour in the following way.

The receiver estimates the channel matrix and feeds back the rank indication along with the precoding matrix ***F***.
If the rank indication is two, then the transmitter sends two symbols, s_1 and s_2, and the receiver reconstructs them from Equation of previous slide.
If the rank indication is one, then the transmitter just sends one symbol, s_1, and doesn't bother with s_2 at all.
The receiver can then reconstruct the transmitted symbol from the above equation.

Implementation Issues

Spatial multiplexing is implemented in the downlink of LTE Release 8, using a maximum of four transmit antennas on the base station and four receive antennas on the mobile. There are similar implementation issues :

1. The antennas at the base station and mobile should be reasonably **far apart**, ideally a few wavelengths of the carrier frequency, or should handle different polarizations. If the antennas are too close together, then the channel elements H_{ij} will be very similar. This can easily take us into the situation where spatial multiplexing was unusable and we had to fall back to diversity processing.

2. A similar situation can easily arise in the case of **line-of-sight** transmission and reception. This leads us to an unexpected conclusion: spatial multiplexing actually works best in conditions with no direct line-of-sight and significant multipath, because, in these conditions, the channel elements H_{ij} are uncorrelated with each other. In line-of-sight conditions, we often have to fall back to diversity processing.

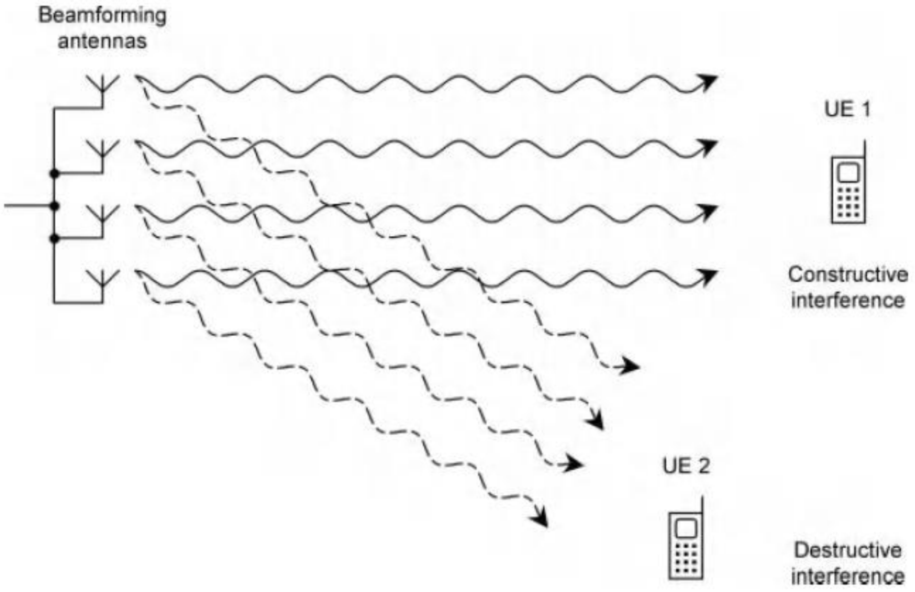
3. As in the case of closed loop transmit diversity, the **PMI** depends on the carrier frequency and the position of the mobile. For **fast moving mobiles**, delays in the feedback loop can make the PMI unreliable by the time the transmitter comes to use it, so open loop spatial multiplexing is often preferred.

Interference Cancellation Suppression and Signal Enhancement Beamforming

Principles of Operation

In beamforming, a base station uses multiple antennas in a completely different way, to increase its coverage. The principles are shown in figure below.
Mobile 1 is a long way from the base station, on a line of sight that is at right angles to the antenna array. The signals from each antenna reach mobile 1 in phase, so they interfere constructively, and the received signal power is high.

Mobile 2 is at an oblique angle, and receives signals from alternate antennas that are 180◦ out of phase. These signals interfere destructively, so the received signal power is low.



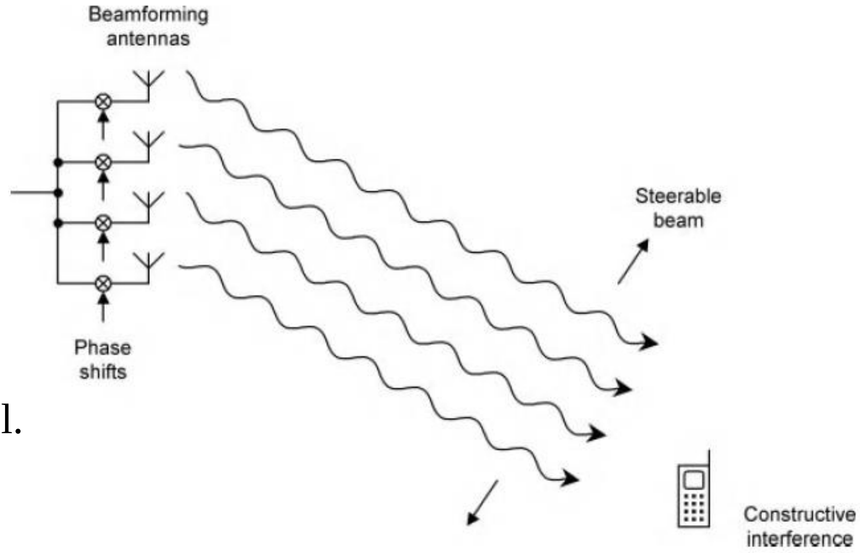
Interference Cancellation Suppression and Signal Enhancement Beamforming

Principles of Operation

As shown in figure below, we can go to a step further. By applying a phase ramp to the transmitted signals, we can change the direction at which constructive interference arises, so we can direct the beam towards any direction we choose. More generally, we can adjust the amplitudes and phases of the transmitted signals, by applying a suitable set of **antenna weights**.

We can use the same technique to construct a synthetic reception beam for the **uplink**. By applying a suitable set of antenna weights at the base station receiver, we can ensure that the received signals **add together in phase and interfere constructively**.

As a result, we can increase the range in the uplink as well.



Beamforming works best if the **antennas are close together**, with a separation comparable with the wavelength of the radio waves. This ensures that the signals sent or received by those antennas are highly correlated.

This is a different situation from diversity processing or spatial multiplexing, which work best if the antennas are far apart, with uncorrelated signals. A base station is therefore likely to use two sets of antennas: a closely spaced set for beamforming and a widely spaced set for diversity and spatial multiplexing.

Interference Cancellation Suppression and Signal Enhancement Beamforming

Beam Steering

How to calculate the antenna weights and steer the beam? How is this done?

For the reception beams on the **uplink**, there are two main techniques.

1. Using the ***reference signal technique***, the base station adjusts the antenna weights so as to reconstruct the mobile's reference symbols with the correct signal phase and the greatest possible signal to interference plus noise ratio (SINR).
2. An alternative is the ***direction of arrival technique***, in which the base station measures the signals that are received by each antenna and estimates the direction of the target mobile. From this quantity, it can estimate the antenna weights that are needed for satisfactory reception.

For the transmission beams on the **downlink**, the answer depends on the base station's mode of operation.

1. In **TDD mode**, the uplink and the downlink use the same carrier frequency, so the base station can use the same antenna weights on the downlink that it calculated for the uplink.

2. In **FDD mode**, the carrier frequencies are different, so the downlink antenna weights are different and are harder to estimate.

For this reason, beamforming is more common in systems that are using TDD rather than FDD.

Interference Cancellation Suppression and Signal Enhancement Beamforming

***Dual layer beamforming* -** Dual layer beamforming takes the idea a step further.

- In this technique, the base station sends two different data streams into its antenna array, instead of just one.
- It then processes the data using two different sets of antenna weights and adds the results together before transmission.
- In doing so, it has created two separate antenna beams, which share the same sub-carriers but carry two different sets of information.

- The base station can then adjust the antenna weights so as to steer the beams to two different mobiles, so that the first mobile receives constructive interference from beam 1 and destructive interference from beam 2 and vice-versa.

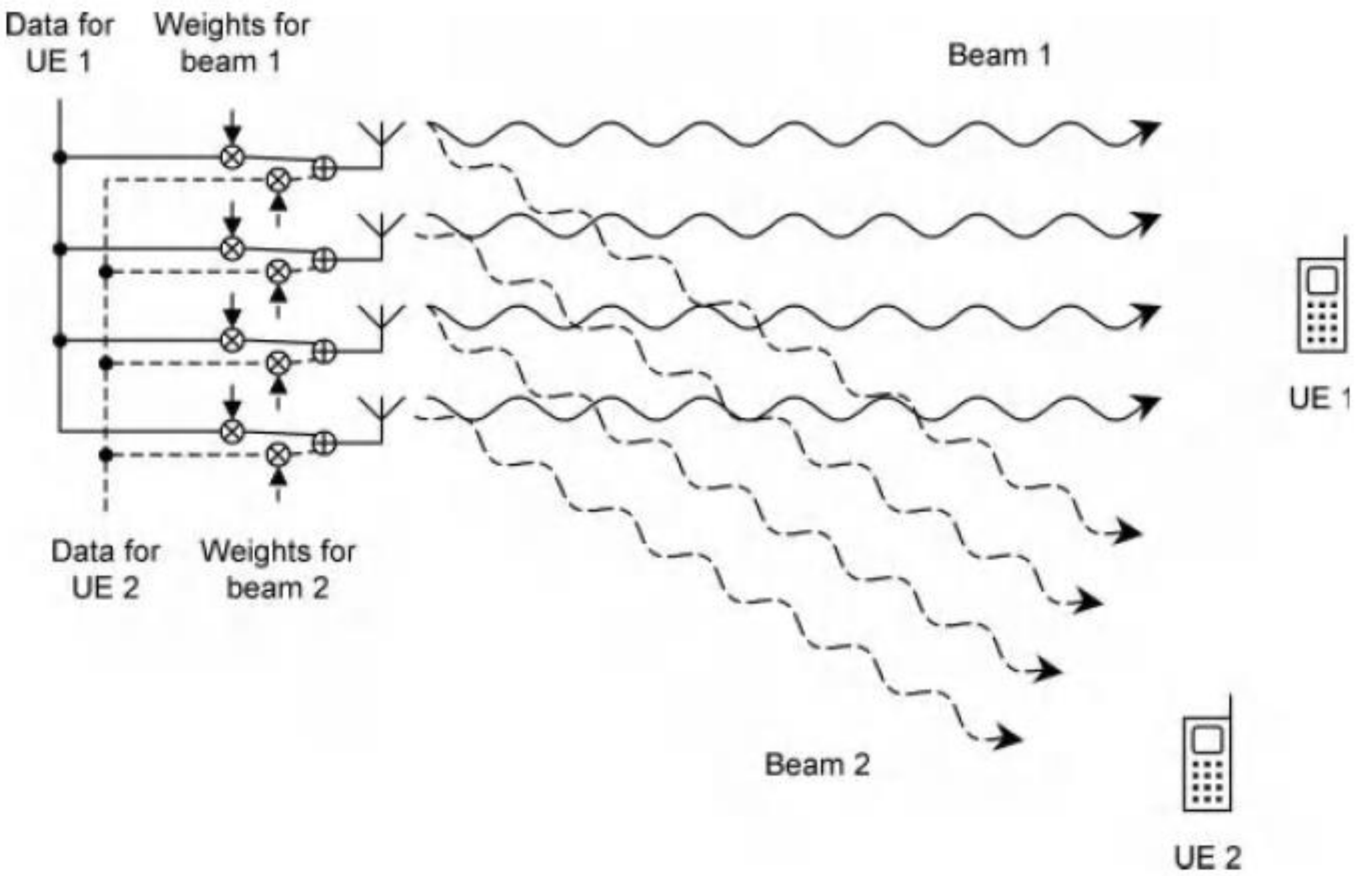
- By doing this, the base station. can double the capacity of the cell. Alternatively, the base station can steer the beams to two different antennas on a single mobile, so as to double that mobile’s instantaneous data rate.

- In ideal conditions, the maximum number of independent data streams is equal to the number of antennas in the array.

- LTE first supports the technique in Release 9 of the 3GPP specifications. In that release, the maximum number of data streams is limited to two, leading to the name of dual layer beamforming.

Interference Cancellation Suppression and Signal Enhancement Beamforming

Dual layer beamforming



Choice between Diversity, Interference suppression and Spatial Multiplexing

Homework

15EC81

Wireless Cellular and LTE 4G Broadband
Module - 3

Robin Singla
Assistant Prof.
Dept. of ECE
BMSIT

Syllabus:-
Module – 3

Overview and Channel Structure of LTE: Introduction to LTE, Channel Structure of LTE, Downlink OFDMA Radio Resource, Uplink SC-FDMA Radio Resource (Sec 6.1 – 6.4 of Text).

Downlink Transport Channel Processing: Overview, Downlink shared channels, Downlink Control Channels, Broadcast channels, Multicast channels, Downlink physical channels, H-ARQ on Downlink(Sec 7.1 – 7.7 of Text).

6.1 Introduction to LTE

6.1.1 Design Consideration

- Network Architecture
- Data Rate Latency
- Performance Requirements
  - Spectrum Efficiency
  - Mobility
  - Coverage
  - MBMS service
- Radio Management
- Deployment Scenario and Co-existence with 3G
- Flexibility of Spectrum and Deployment
- Interoperability with 2G and 3G network

6.1 Introduction to LTE

6.1.2 Network Architecture

- UE
    - MT
    - TE
    - UICC

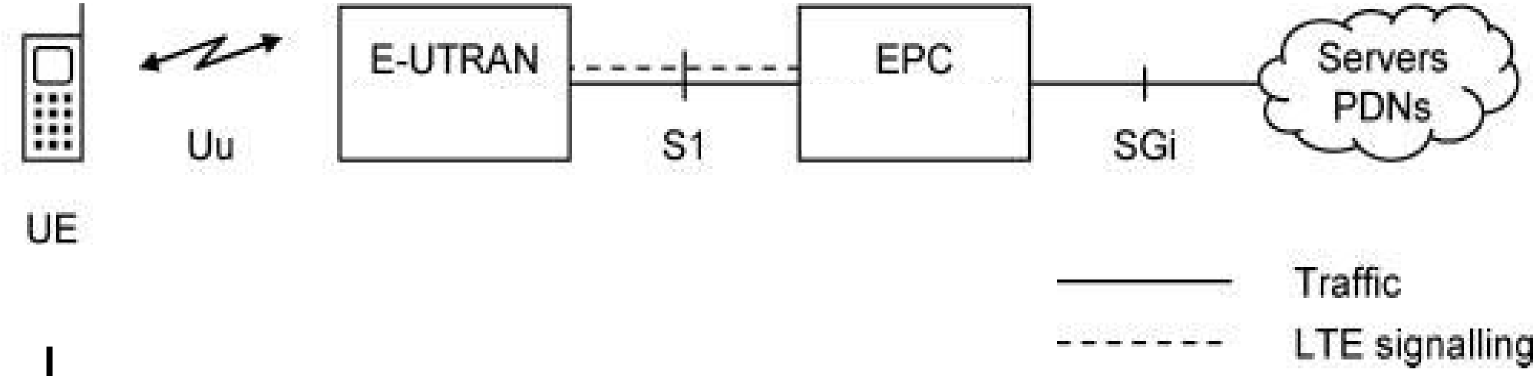
- E-UTRAN
    - e-Node B
- EPC

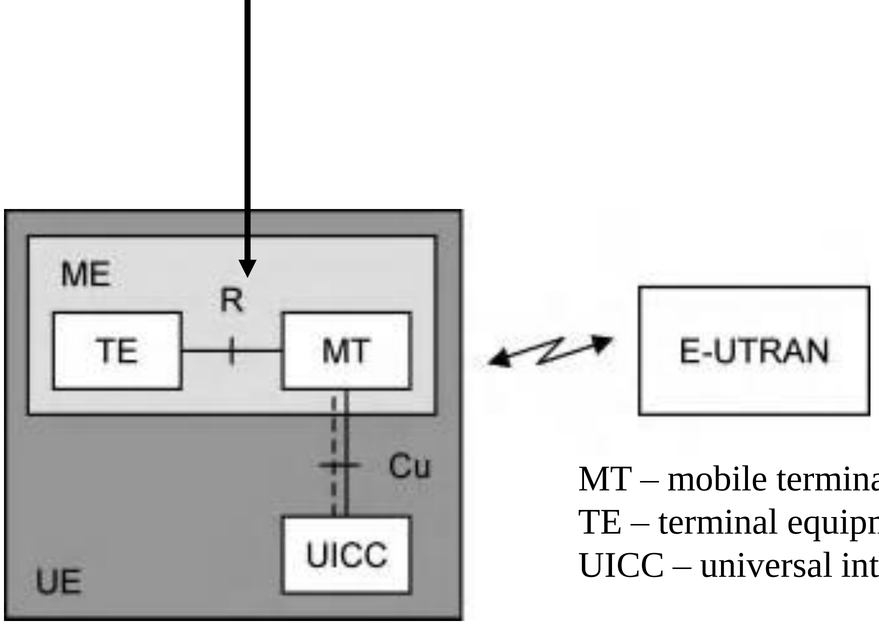
    - HSS
    - S-GW
    - MME

- PDN
- S1 interface
- X2 interface

6.1 Introduction to LTE

6.1.2 Network Architecture





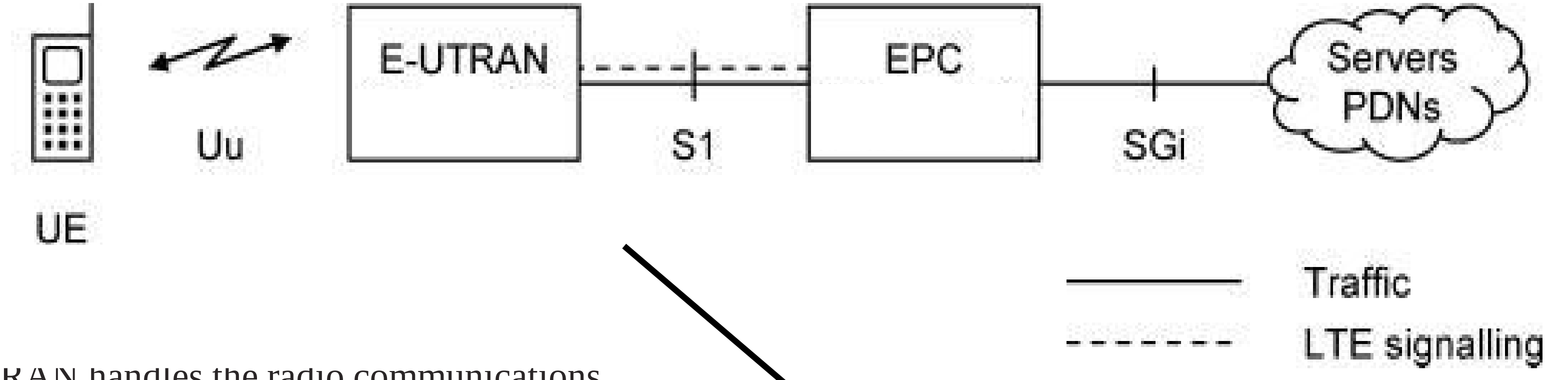
- *LTE supports mobiles that are using IP version 4 (IPv4), IP version 6 (IPv6), or dual stack IP version 4/version 6.*

MT – mobile termination
TE – terminal equipment
UICC – universal integrated circuit card

Architecture of User Equipment

6.1 Introduction to LTE

6.1.2 Network Architecture

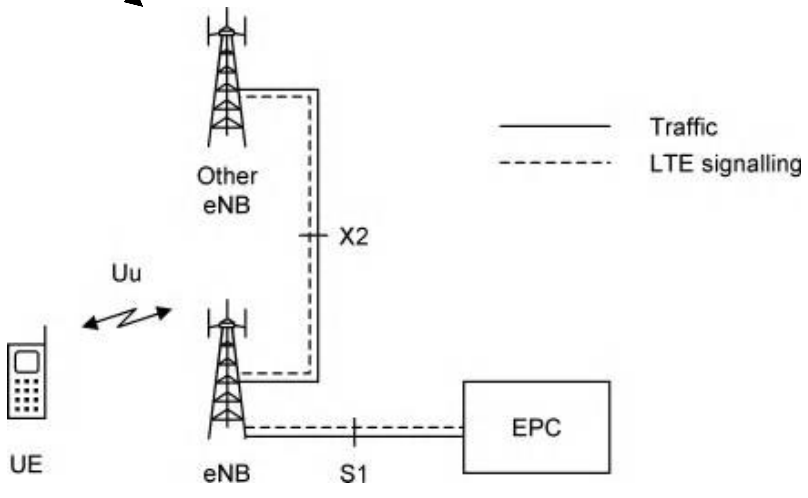


- The E-UTRAN handles the radio communications between the mobile and the evolved packet core and just has one component, the *evolved Node B* (eNB).

- Each eNB is a base station that controls the mobiles in one or more cells. A mobile communicates with just one base station and one cell at a time.

- The base station that is communicating with a mobile is known as its *serving eNB.*

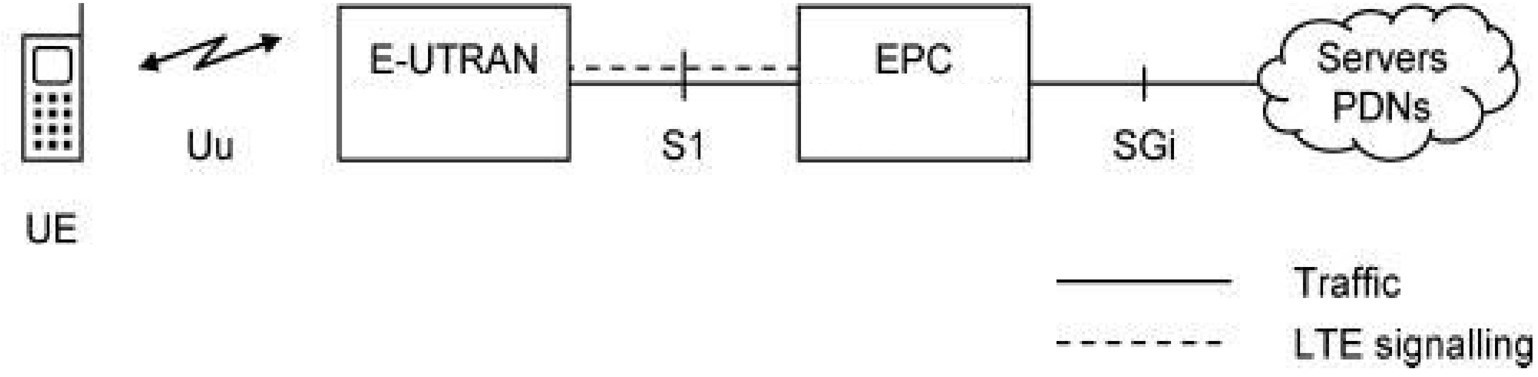
- eNB sends radio transmissions to all its mobiles on the downlink and receives transmissions from them on the uplink, using the analogue and digital signal processing functions of the LTE air interface.



Architecture of the Evolved UMTS terrestrial radio access network (E-UTRAN)

6.1 Introduction to LTE

6.1.2 Network Architecture



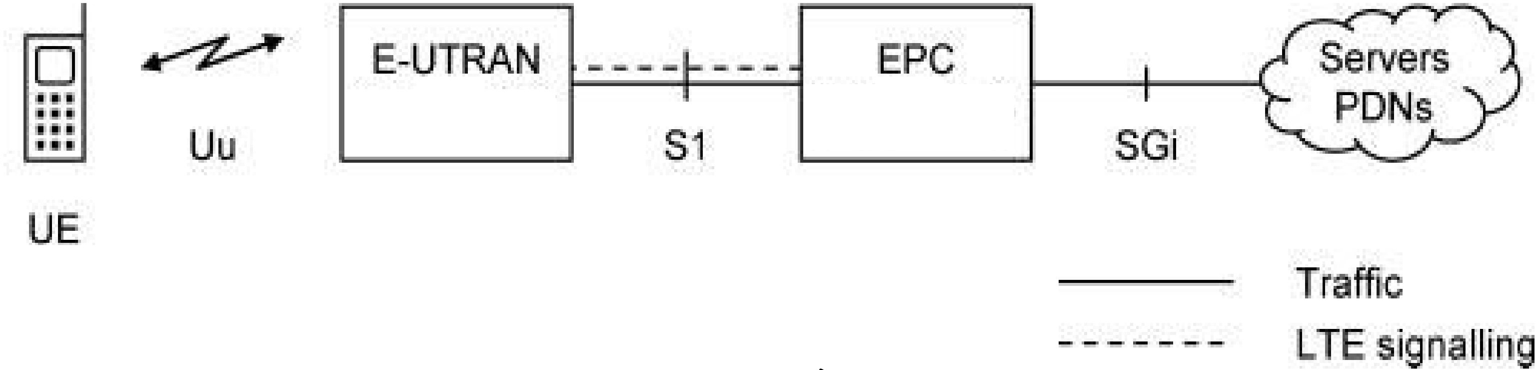
(E-UTRAN)

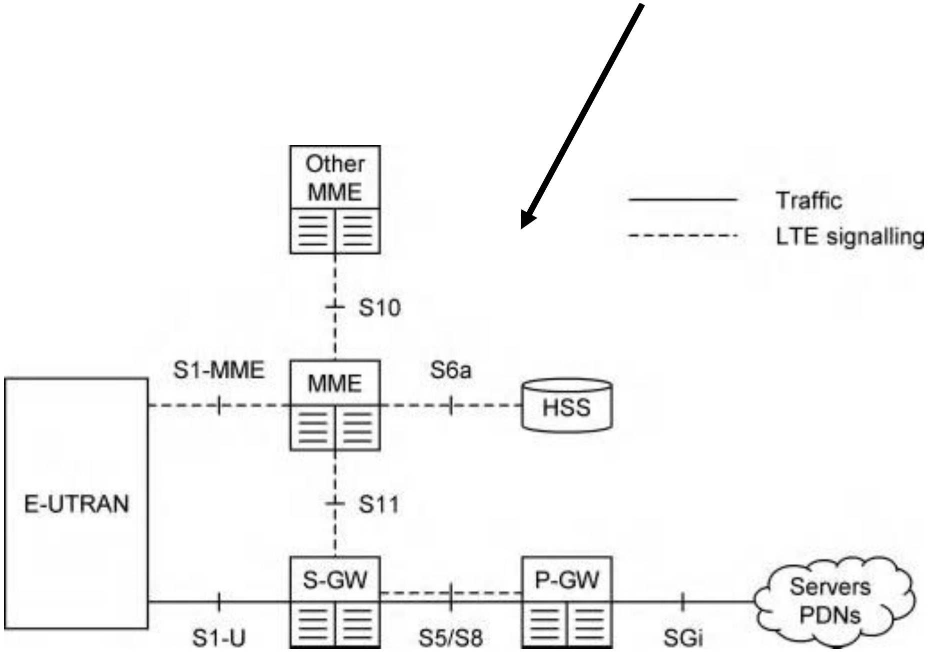
- eNB controls the low-level operation of all its mobiles, by sending them signalling messages such as handover commands that relate to those radio transmissions. In carrying out these functions, the eNB combines the earlier functions of the Node B and the radio network controller, to reduce the latency that arises when the mobile exchanges information with the network.

- Each base station is connected to the EPC by means of the S1 interface. It can also be connected to nearby base stations by the X2 interface, which is mainly used for signalling and packet forwarding during handover.

6.1 Introduction to LTE

6.1.2 Network Architecture



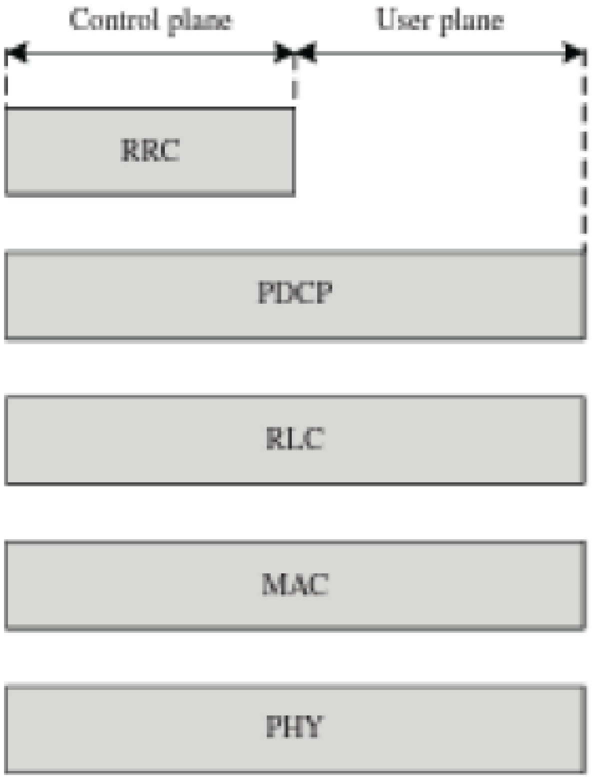


Evolved Packet Core Architecture (EPC)

6.1 Introduction to LTE

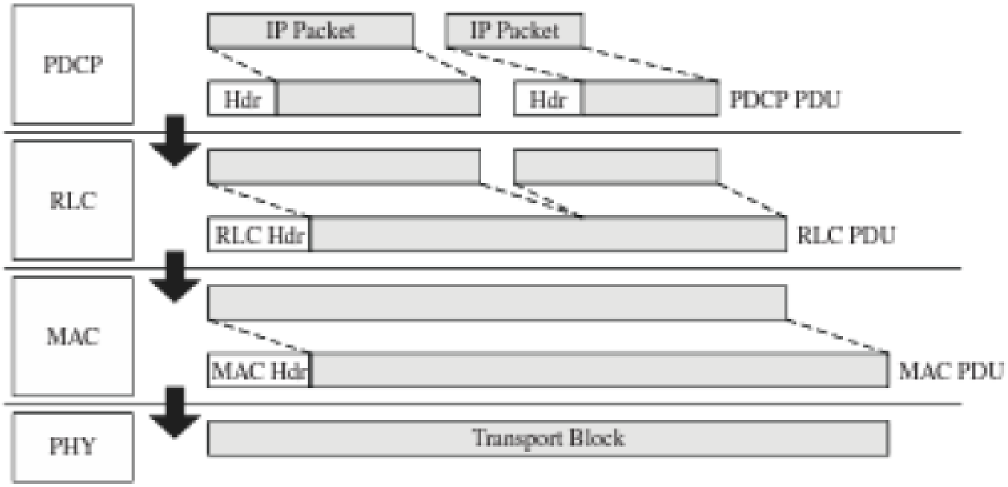
6.1.3 Radio Interface Protocols

LTE radio interface is designed based on a layered protocol stack, which can be divided into control plane and user plane protocol stack.



The LTE radio interface protocol stack

The packet flow in user plane



6.1 Introduction to LTE

6.1.3 Radio Interface Protocols

LTE radio interface is designed based on a layered protocol stack, which can be divided into control plane and user plane protocol stack.

1. Radio Resource Control (RRC) **–** performs the control panel functions

- Paging
- Maintenance and release of an RRC connection
- Security handling
- Mobility management
- QoS management

2. Packet Data Convergence Protocols (PDCP) – main functions of this sublayer include

- IP packet header compression and decompression based on RObust Header Compression (ROHC) protocol
- Ciphering of data and signalling
- Integrity protection of signalling

There is only one PDCP entity per eNode-B and the LTE per bearer.

6.1 Introduction to LTE

6.1.3 Radio Interface Protocols

***3. Radio Link Control (RLC)* –** the main functions of RLC are

- Segmentation and concatenation of data units
- Error correction through Automatic Repeat reQuest (ARQ)
- In-sequence delivery of packets to the higher layers
- Operates in three modes
  - *I. The Transparent Mode (TM)*
  - *II. The Unacknowledged Mode (UM)*
  - *III. The Acknowledged Mode (AM)*

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

4. Medium Access Control (MAC) – main functions of this sublayer include

- Error correction through the Hybrid-ARQ (HARQ)
- 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 handing between UEs by means of dynamic scheduling

There is only one PMAC entity at the eNode-B and one MAC entity at the UE.

6.1 Introduction to LTE

6.1.3 Radio Interface Protocols

***5. Physical Layer (PHY)* –** the main functions of PHY are

- Actual transmission of data in form of transport block
- Signalling of HARQ feedback
- Signalling of schedule allocation
- Channel measurements

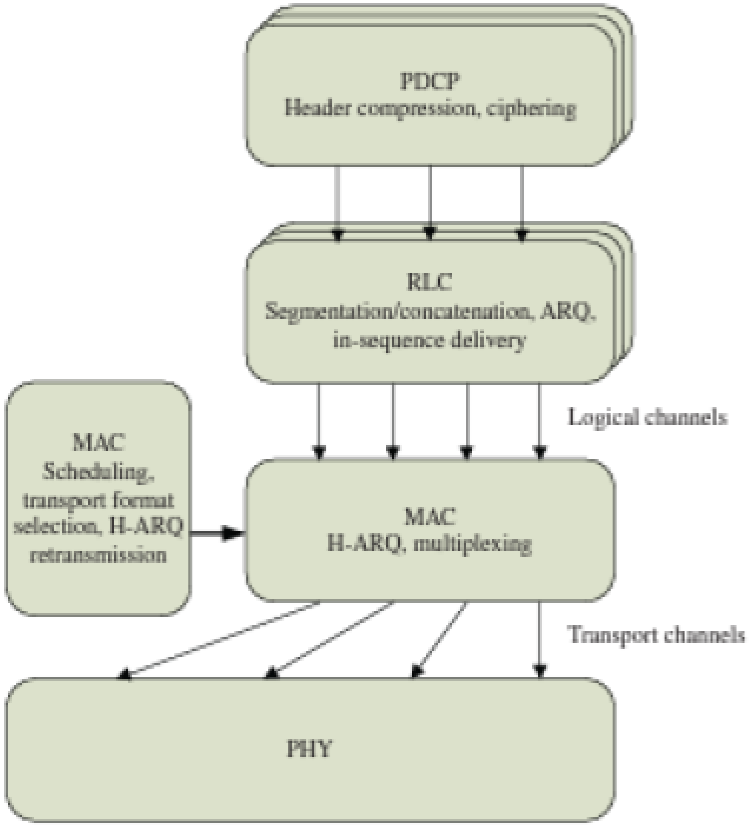
6.2 Hierarchical Channel Structure of LTE

To efficiently supports various QoS classes of services, the LTE adopts a hierarchical channel structure.

In LTE three different channels types are defined

- *a)* ***Logical channels*** – what to transmit
- *b)* ***Transport channels*** – how to transmit
- *c)* ***Physical Channels*** – actual transmission

Each associated with a service access point (SAP) between different layers



Radio interface protocol architecture and the SAPs between different layers

6.2 Hierarchical Channel Structure of LTE

6.2.1 Logical channels – what to transmit

Used by MAC to provide services to the RLC. Each logical channel defined based on the information it carriers.

- Logical Control Channel
- Logical Traffic Channel

Logical control channels, which are used to transfer control plane information

1. ***Broadcast Control Channel (BCCH) –***

downlink common channel used to broadcast system control information to the mobile terminations in the cell,

- downlink system bandwidth
- antenna configuration
- reference signal power

It is mapped to two different transport channels Broadcast channel (BCH) and Downlink Shared Channel (DL-SCH).

6.2 Hierarchical Channel Structure of LTE

6.2.1 Logical channels – what to transmit

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

3. ***Paging Control Channel (PCCH)*** –A downlink channel that transfer paging information to the registered UEs in the cell e.g. in case of mobile terminated communication sessions.

4. ***Common Control Channel (CCCH)*** –A bi-directional channel for transmitting the 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 common CCCH is used during the random access procedure.

5. ***Dedicated Control Channel (DCCH)*** –A point-to-point bi-directional channel that transmit dedicated control information between UEs and network. This channel is used when RRC connection is available, i.e. UE is attached to the network

6.2 Hierarchical Channel Structure of LTE

6.2.1 Logical channels – what to transmit

Logical traffic channels, which are used to transfer user plane information

1. ***Dedicated traffic Channel (DTCH)* –** A point-to-point bi-directional channel used between a given UE and the network. It can exist in both up-link and downlink.

2. ***Multicast traffic Channel (MTCH)* –** A unidirectional, point-to-multipoint data channel that transmit data from the network to the UEs.

6.2 Hierarchical Channel Structure of LTE

6.2.2 Transport channels – how to transmit

Transport channels are used by PHY to offer services to the MAC. A transport channel is basically characterized by how and with what characteristics data is transferred over the radio interface,

- Channel coding scheme
- Modulation scheme
- Antenna mapping

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

Downlink transport channels

1. ***Downlink Shared Channel (DL-SCH)***
2. ***Broadcast Channel (BCH)***
3. ***Multicast Channel (MCH)***
4. ***Paging Channel (PCH)***

6.2 Hierarchical Channel Structure of LTE

6.2.2 Transport channels – how to transmit

Uplink transport channels

1. ***Uplink Shared Channel (UL-SCH)***

2. ***Random access Channel (RACH)***– The *random access channel* (RACH) is a special channel through which the mobile can contact the network without any prior scheduling. Random access transmissions are composed by the mobile's MAC protocol and travel as far as the MAC protocol in the base station, but are completely invisible to higher layers.

6.2 Hierarchical Channel Structure of LTE

6.2.3 Physical channels – actual transmission

Downlink physical channels

1. ***Physical Downlink Control Channel (PDCCH)***
2. ***Physical Downlink Shared Channel (PD-SCH)***
3. ***Physical Broadcast Channel (PBCH)***
4. ***Physical Multicast Channel (PMCH)***
5. ***Physical Hybrid-ARQ Indicator Channel (PHICH)***
6. ***Physical Control Format Indicator Channel (PCFICH)***

6.2 Hierarchical Channel Structure of LTE

6.2.3 Physical channels – actual transmission

Uplink physical channels

1. ***Physical Uplink Control Channel (PUCCH)***
2. ***Physical Uplink Shared Channel (PU-SCH)***
3. ***Physical Random Access Channel (PRACH)***

6.2 Hierarchical Channel Structure of LTE

6.2.2 Transport channels – how to transmit

Besides transport channels, there are different types of **control information** defined in MAC layer, which are important for various physical layer procedures.

1. ***Downlink Control Information (DCI):*** it carries information related to downlink/uplink scheduling assignment, modulation and coding scheme, and transport power control (TPC) command and sent over the PDCCH.

2. **Control Format Indicator (CFI):** it indicate how many symbols the DCI spans in that subframe. It takes values 1,2, or 3 and sent over the PCFICH.

3. **H-ARQ indicator (HI):** it carries H-ARQ acknowledgment in response to up-link transmission and sent over the PHICH. HI = 1 for a positive acknowledgment (ACK) and HI = 0 for negative acknowledgment (NAK).

4. **Uplink Control Information (UCI):** it is measurement indication on the downlink transmission, scheduling request of uplink, and the H-ARQ acknowledgment of downlink transmission. The UCI can be transmitted either on PUCCH or PUSCH.

6.2 Hierarchical Channel Structure of LTE

6.2.3 Physical channels – actual transmission

Besides physical channels, there are signals embedded in the downlink and uplink physical layer, which do not carry information from higher layers.

1. **Reference signal:** It is defined in both uplink and downlink that enables coherent demodulation and for channel quality measurement to assist user scheduling.
    1. Cell specific reference symbol
    2. Multimedia Broadcast multicast service Single Frequency Network (MBSFN) reference symbol
    3. UE-specific reference symbol
2. **Synchronization signal:** it is split into primary and secondary synchronization signal, and is only defined n downlink to enable acquisition of symbol timing and the precise frequency of the downlink signal.

6.2 Hierarchical Channel Structure of LTE

6.2.4 Channel mapping

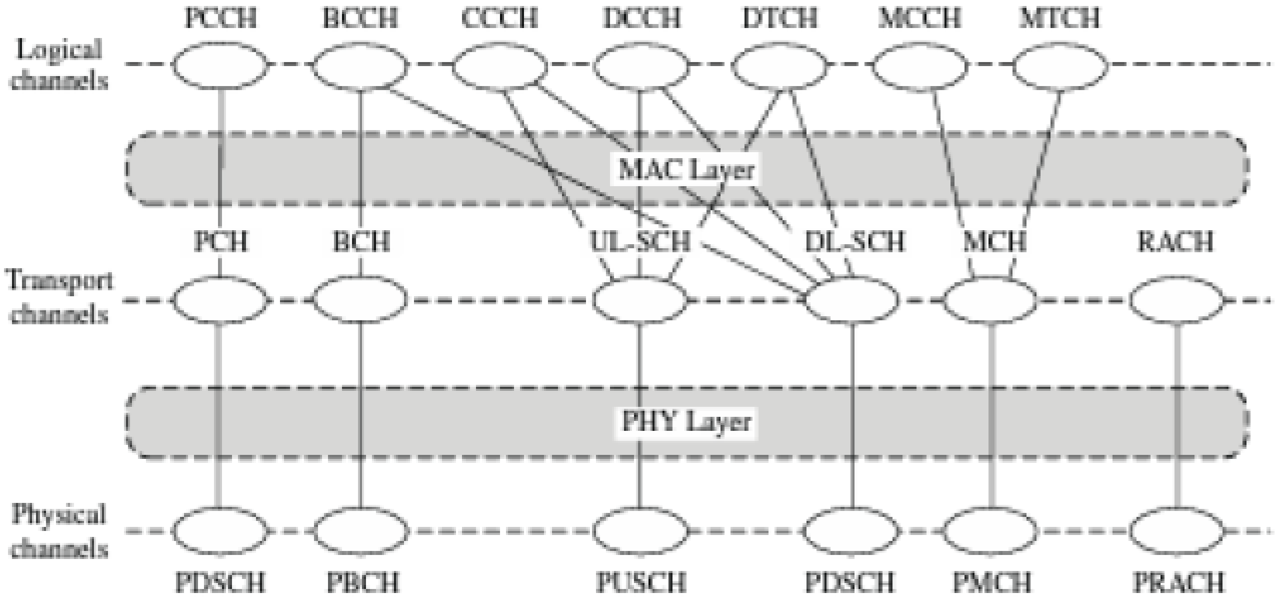


Figure 6.6 Mapping between different channel types.

6.2 Hierarchical Channel Structure of LTE

6.2.4 Channel mapping

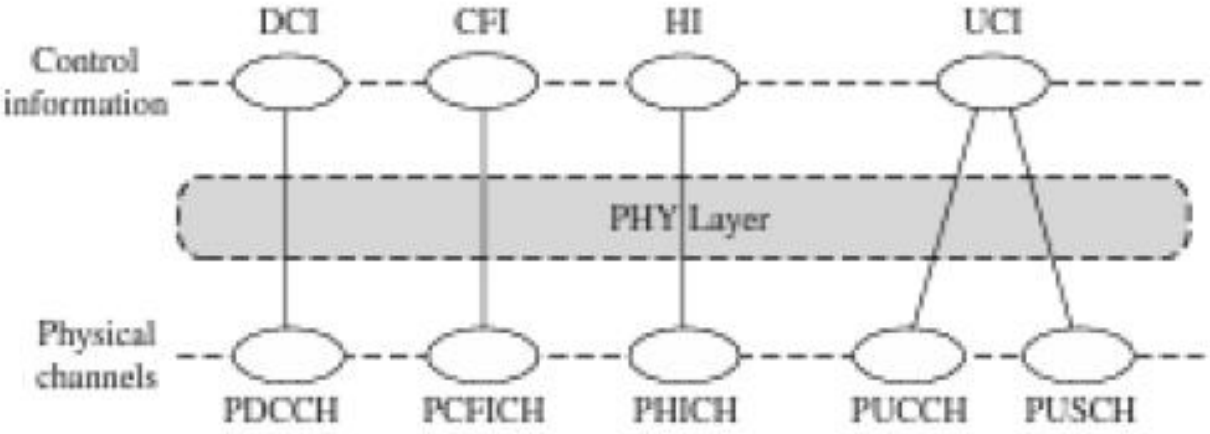


Figure 6.7 Mapping of control information to physical channels.

6.3 Downlink OFDMA Radio Resources

In LTE, the downlink and uplink use different transmission schemes due to different considerations. In the downlink, a scalable OFDM transmission/multi-access technique is used that allows high spectrum efficiency by utilizing multiuser diversity in a frequency selective channel.

6.3.1 Frame Structure

LTE maps the physical channels and physical signals onto the OFDMA symbols and subcarriers that we introduced in module-2.

To understand how it does this, we first need to understand how LTE organizes its symbols and sub-carriers in the time and frequency domains.

First consider the frame stricture in **time domain**, which is a common element shared by both downlink and uplink. The timing of the LTE transmissions is based on a time unit T_s, which is defined as follows:

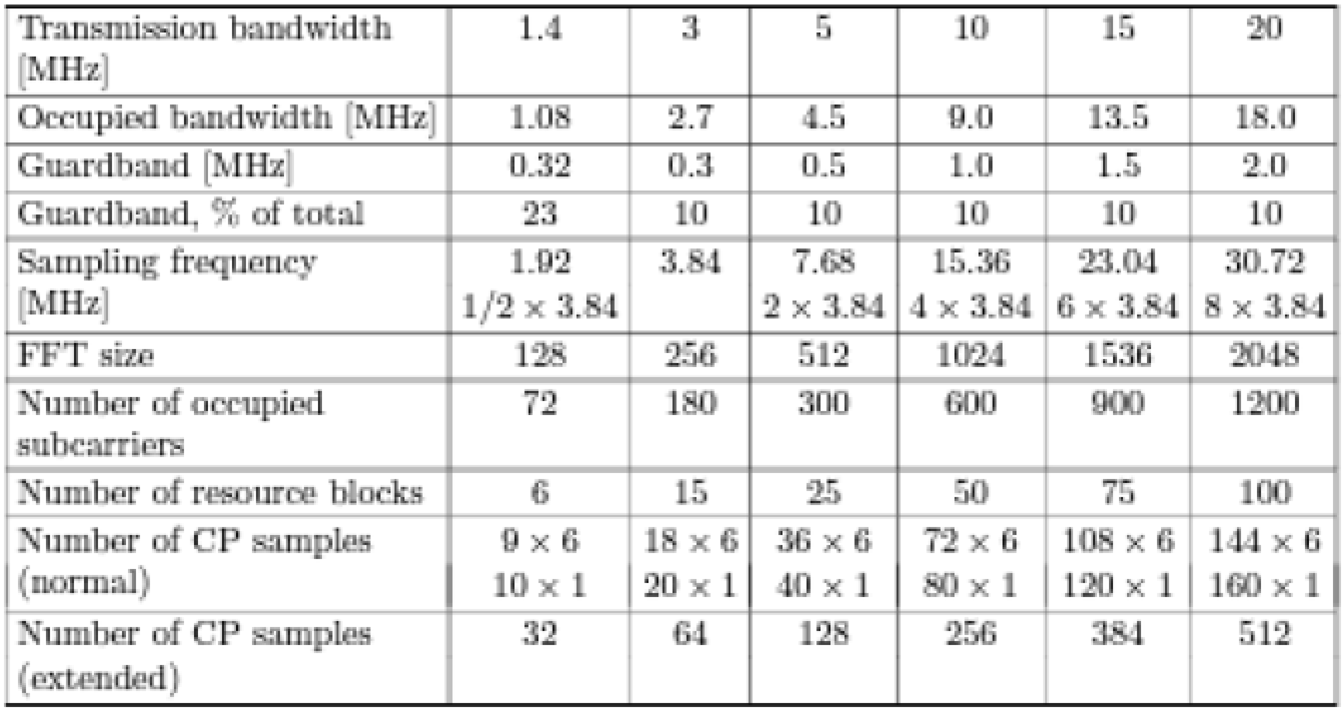
$$T_s = \frac{1}{\underbrace{2048}_{\text{Size of FFT } N_{FFT} = 2048} \times \underbrace{15000}_{\Delta f = 15\ kHz}} \text{ seconds} \approx 32.6 \text{ ns}$$

T_s is the shortest time interval that is of interest to the physical channel processor. T_s can be regarded as the **sampling time** of an FFT-based OFDM transmitter/receiver implementation with FFT size N_{FFT} = 2048.

6.3 Downlink OFDMA Radio Resources

6.3.1 Frame Structure

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

In the time domain, the downlink and uplink multiple Transmission Time Interval (TTIs) are organized into radio frames duration $T_f = 307200.Ts = 10\ ms$.

For flexibility,, LTE supports both TDD and FDD modes.

Accordingly LTE supports two kinds of frames structures: frame structure 1 for FDD and frame structure 2 for TDD.

6.3 Downlink OFDMA Radio Resources

6.3.1 Frame Structure Type-1

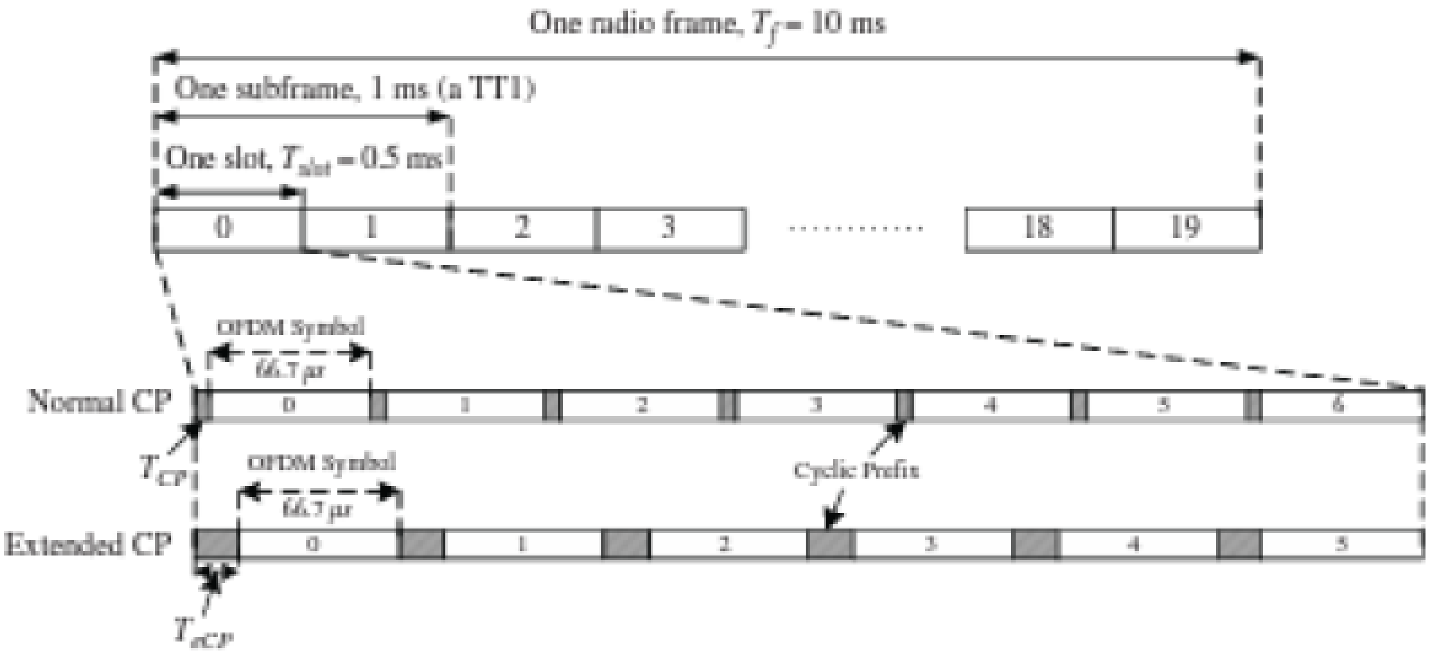


Figure 6.8 Frame structure type 1. For the normal CP, $T_{CP} = 160 \cdot T_s \approx 5.2\mu s$ for the first OFDM symbol, and $T_{CP} = 144 \cdot T_s \approx 4.7\mu s$ for the remaining OFDM symbols, which together fill the entire slot of 0.5 ms. For the extended CP, $T_{eCP} = 512 \cdot T_s \approx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

$$one\ OFDM\ symbol = \frac{1}{\Delta f} = \frac{1}{15\ kHz} = 66.7\ \mu s$$

6.3 Downlink OFDMA Radio Resources

6.3.1 Frame Structure Type-2

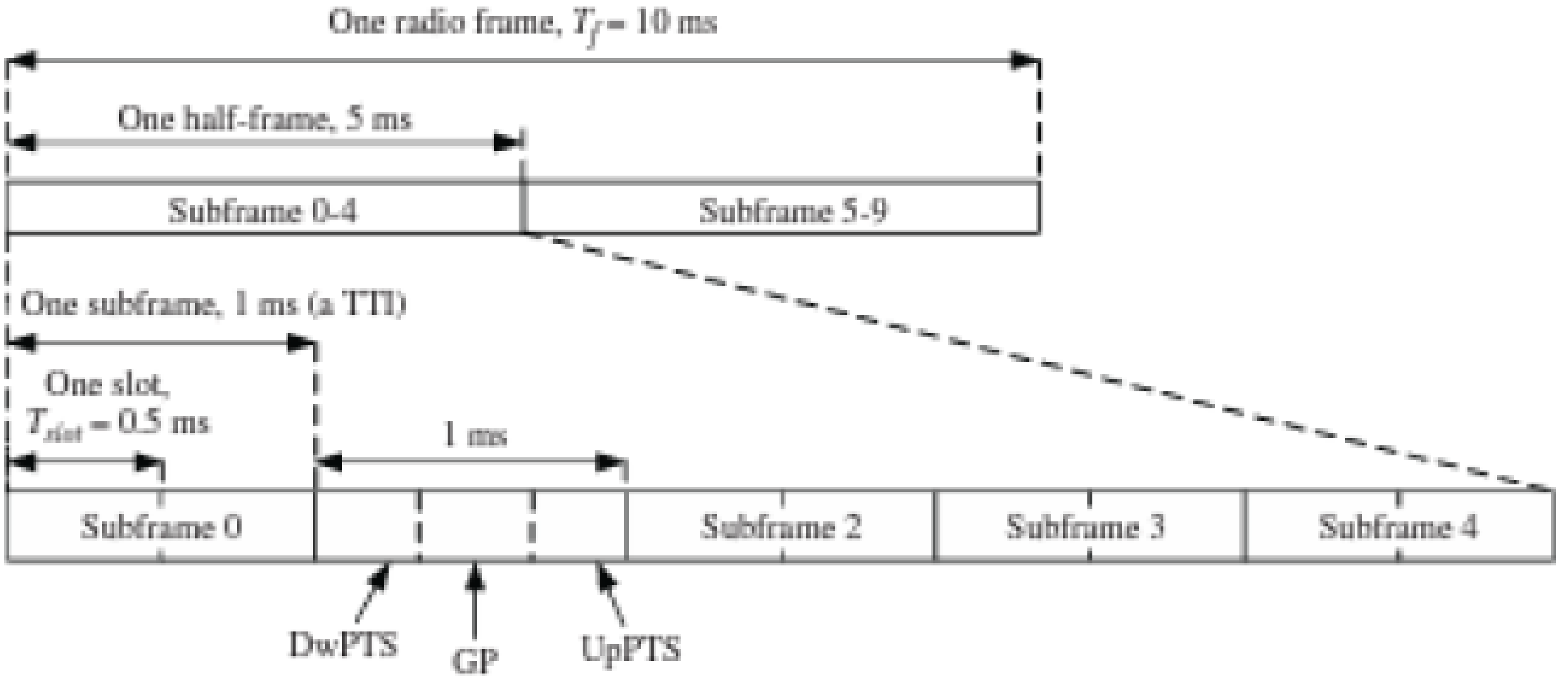


Figure 6.9 Frame structure type 2.

DwPTS – Downlink Pilot time slot
GP – Guard period
UpPTS – Uplink Pilot time slot

6.3 Downlink OFDMA Radio Resources

6.3.2 Physical Resource Block for OFDMA

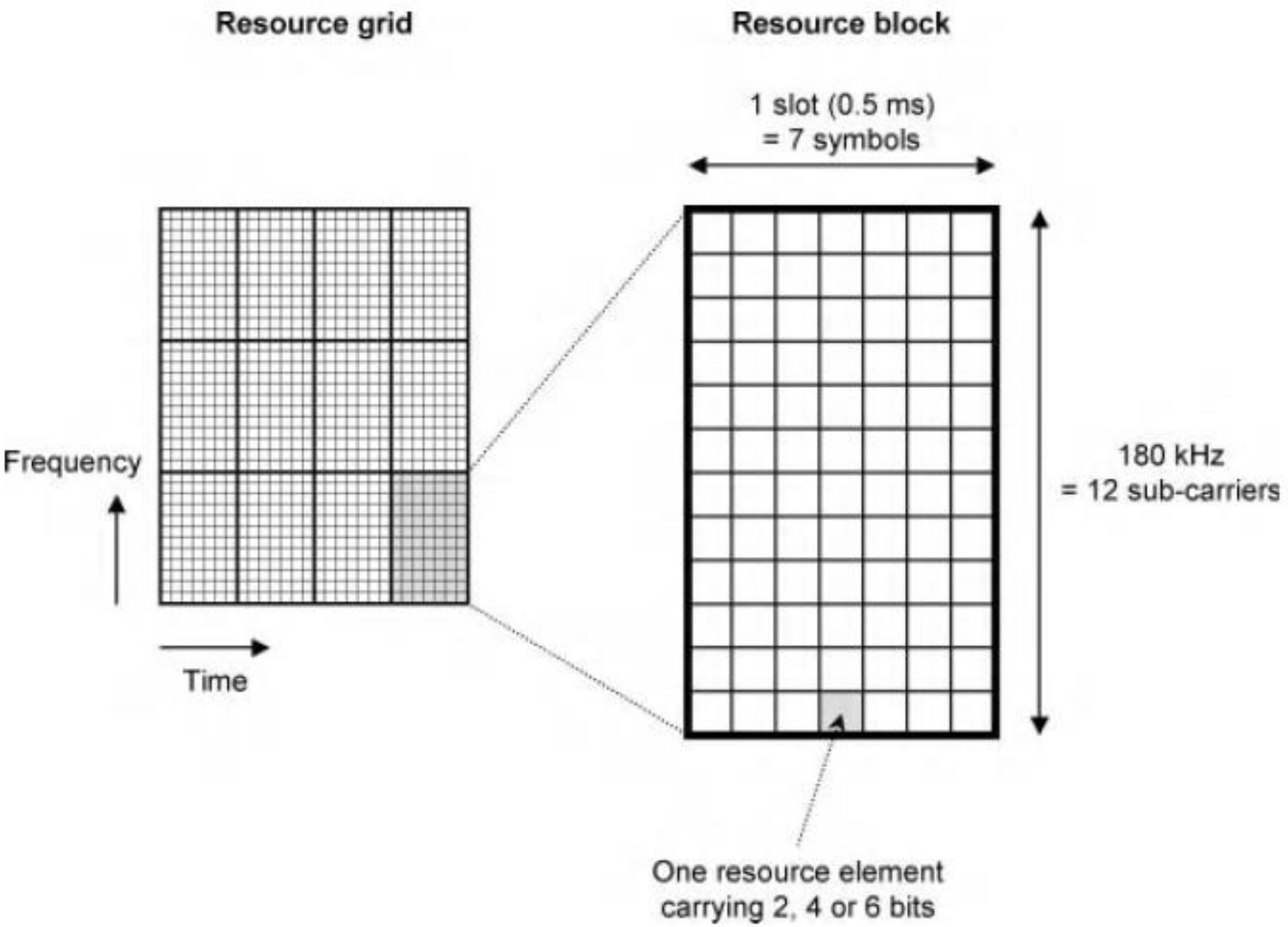
Resource grid – In LTE, information is organized as a function of frequency as well as time, using a *resource grid.*

Resource Element- The basic unit is a *resource element* (RE), which spans one symbol by one subcarrier. Each resource element usually carries two, four or six physical channel bits, depending on whether the modulation scheme is QPSK, 16 QAM or 64-QAM.

Resource Block- Resource elements are grouped into *resource blocks* (RBs), each of which spans 0.5 ms (one slot), by 180 kHz (twelve sub-carriers). The base station uses resource blocks for frequency dependent scheduling, by allocating the symbols and sub-carriers within each subframe in units of resource blocks.

6.3 Downlink OFDMA Radio Resources

6.3.2 Physical Resource Block for OFDMA



Structure of the LTE resource grid in the time and frequency domains, using a normal cyclic prefix.

6.3 Downlink OFDMA Radio Resources

6.3.2 Physical Resource Block for OFDMA

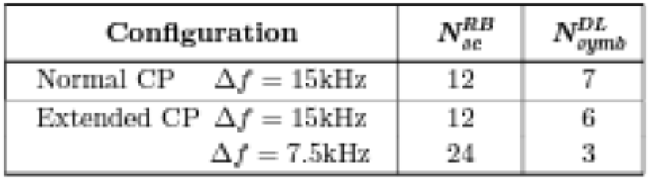
Number of OFDM symbols in each block

$$N^{DL}_{symb}$$

Number of subcarriers in each resource block, N^{RB}_{sc}

$$\Delta f \,.\, N^{RB}_{sc} = 180\ kHz$$

Table 6.4 Physical Resource Block Parameters for the Downlink



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

Number of downlink resource block, N^{DL}_{RB}

$$N^{min,DL}_{RB} \leq N^{DL}_{symb} \leq N^{max,DL}_{RB}$$

$N^{min,DL}_{RB}$ = 6 and $N^{max,,DL}_{RB}$ = 110

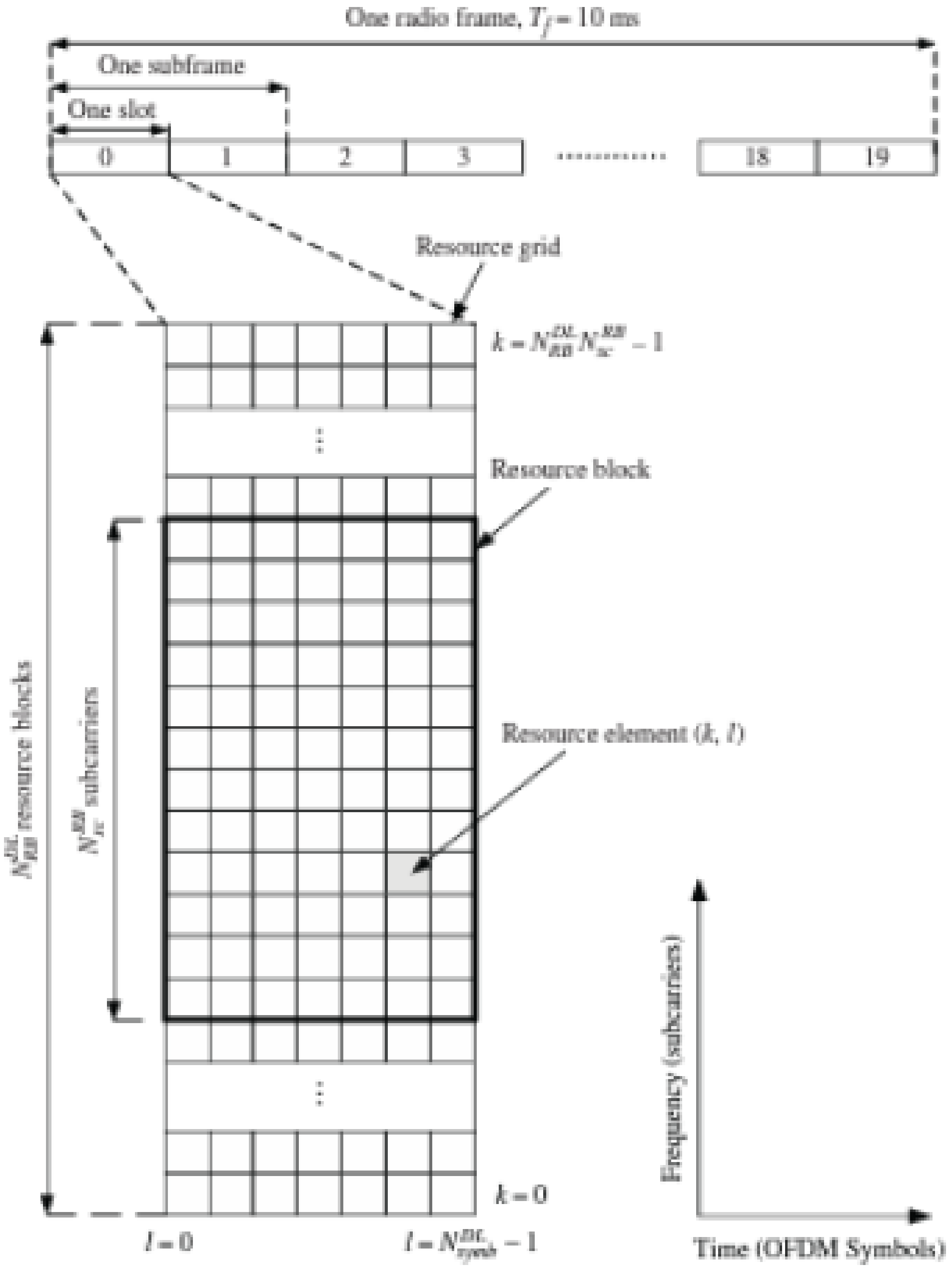


Figure 6.10 The structure of the downlink resource grid.

6.3 Downlink OFDMA Radio Resources

6.3.2 Physical Resource Block for OFDMA

The downlink resource grid has

$N_{RB}^{DL} \times N_{sc}^{RB} \times N_{symb}^{DL}$

resource elements

For example,

with 10 MHz B.W.

$\Delta f = 15\ kHz$

Normal CP

$N_{RB}^{DL} = 50$
$N_{SC}^{RB} = 12$
$N_{symb}^{DL} = 7$

$50 \times 12 \times 7 = 4200\ resource\ elements$

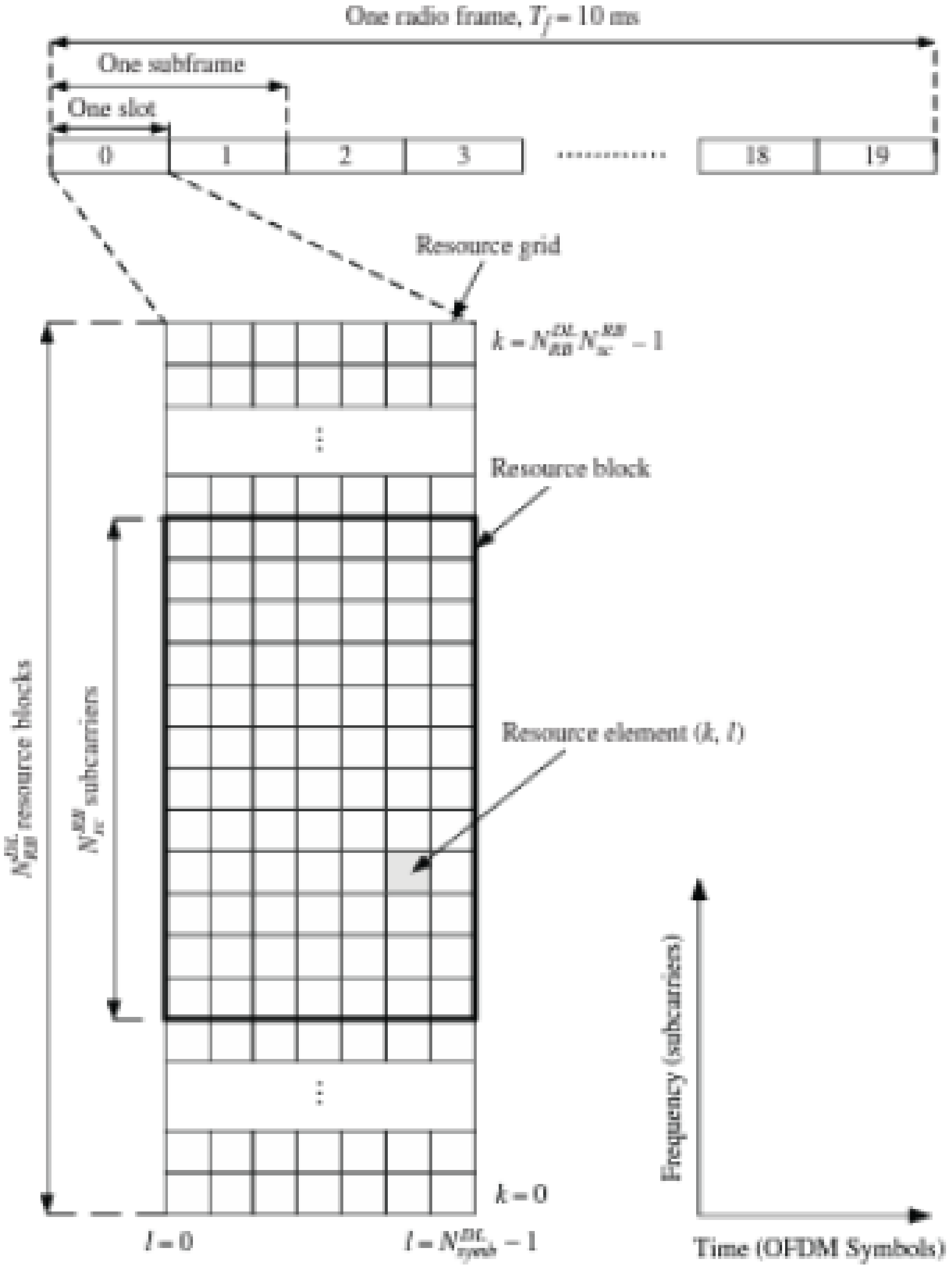


Figure 6.10 The structure of the downlink resource grid.

6.3 Downlink OFDMA Radio Resources

6.3.2 Physical Resource Block for OFDMA

Resource Element- The basic unit is a *resource element* (RE), which spans one symbol by one subcarrier.
identify by index pair (k, l)

$$k = 0,1, \dots \dots \dots, N_{RB}^{DL} \times N_{SC}^{RB} - 1$$

$$l = 0,1, \dots \dots \dots, N_{symb}^{DL} - 1$$

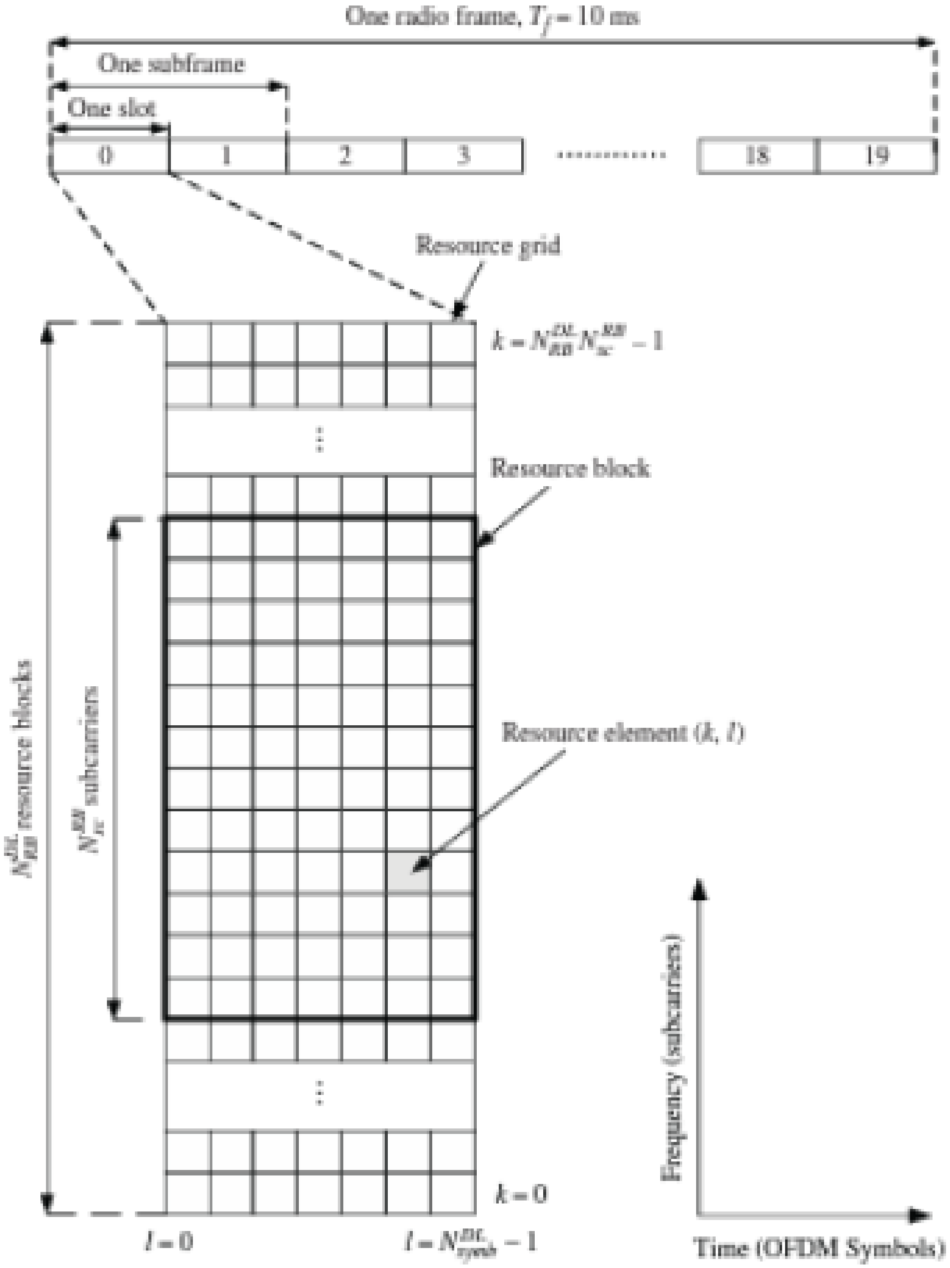


Figure 6.10 The structure of the downlink resource grid.

6.3 Downlink OFDMA Radio Resources

6.3.2 Physical Resource Block for OFDMA

Resource Block- Resource elements are grouped into *resource blocks* (RBs), each of which spans 0.5 ms (one slot), by 180 kHz (twelve sub-carriers). The base station uses resource blocks for frequency dependent scheduling, by allocating the symbols and sub-carriers within each subframe in units of resource blocks.

Resource block is the basic element for the radio resource allocation. There are two kinds of resource block defined in LTE,
Physical resource block (PRB)
Virtual Resource Block (VRB)

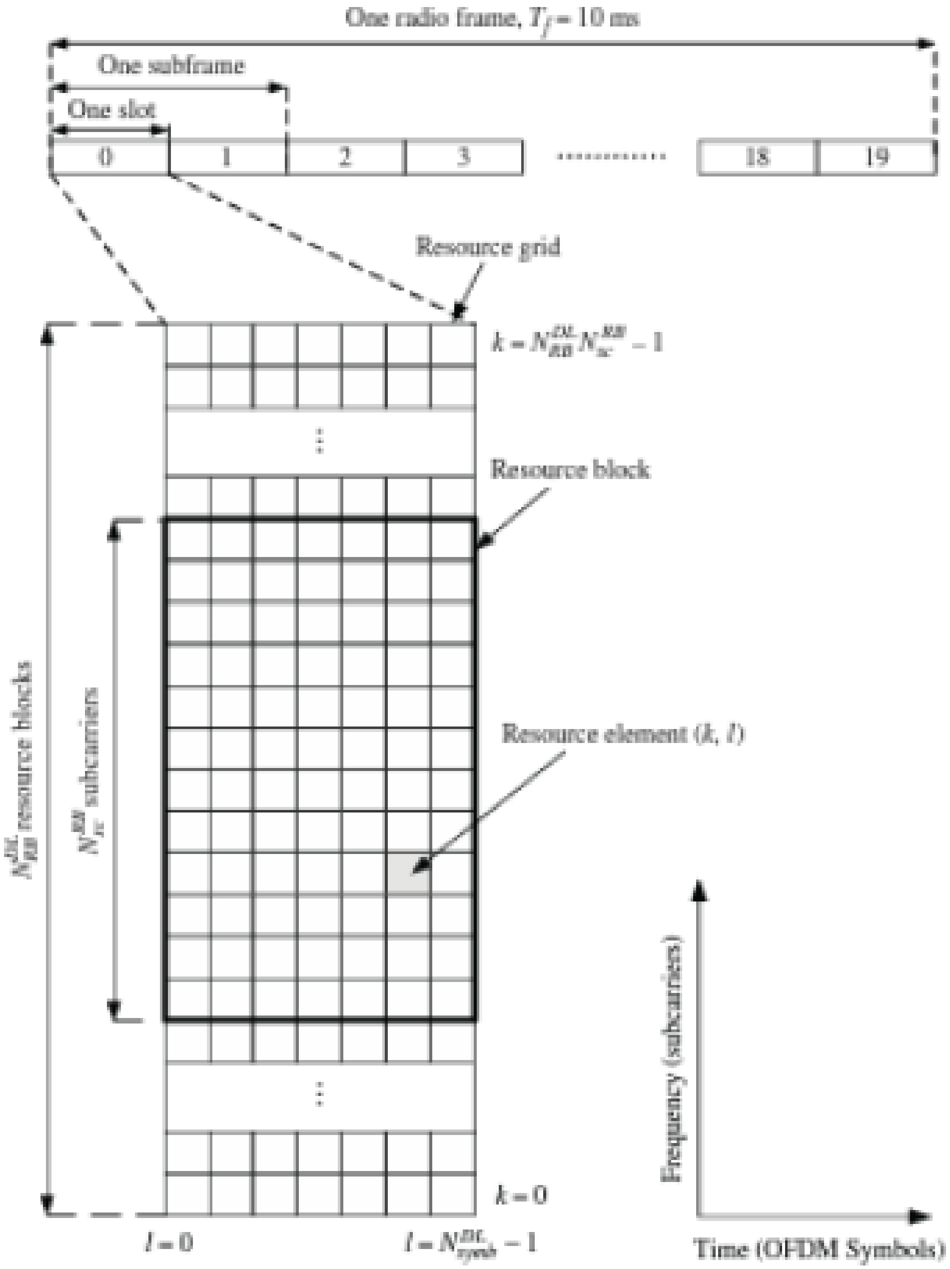


Figure 6.10 The structure of the downlink resource grid.

6.3 Downlink OFDMA Radio Resources

6.3.3 Resource Allocation

- Resource allocation role is to dynamically assign available time-frequency resource block 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.

- Therefore, with resource allocation techniques, multiuser diversity can be exploited by assigning resource blocks to the UEs with favorable channel qualities.

- With OFDMA, the DL resource allocation is characterized by the fact that each scheduled UE occupies number of RB while each RB is assigned exclusively to one UE at a time.

- PRBs and VRBs are defined to support different kinds of resource allocation types.

- In LTE DL supports three different kinds of resource allocations : type-0, type-1, type-2.

- The DL scheduling is performed at eNode-B based on the channel quality information fed back from UEs and the DL resource assignment information is sent to UE on the PDCCH channel.

6.3 Downlink OFDMA Radio Resources

6.3.3 Resource Allocation

- PRB is defined as N_{symb}^{DL} consecutive OFDM symbols in time domain and N_{SC}^{RB} consecutive subcarriers in frequency domain.

- Therefore, each PRB corresponds to one slot in the time domain (0.5 ms) and 180kHz in frequency domain.

- PRBs are numbered from 0 to $N_{RB}^{DL} - 1$ in frequency domain.

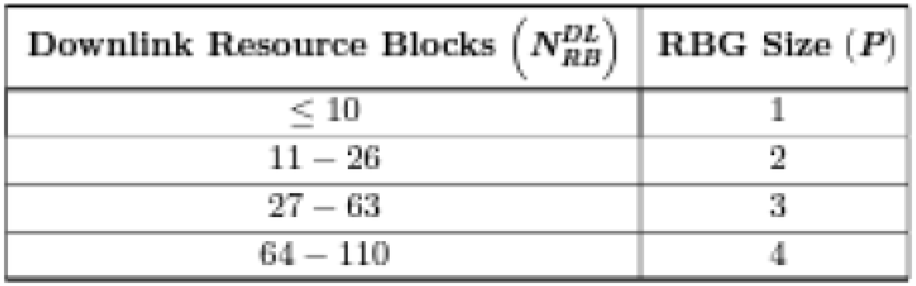
6.3 Downlink OFDMA Radio Resources

6.3.3 Resource Allocation

Type-0 : several consecutive PRBs constitute a resource block group (RBG) and resource allocation is done in the units of RBGs.
The allocated RBGs to a certain UE do not need to be adjacent to each other, which provide frequency diversity.

The RBG size P, that is number of PRBs in each RBG, is depends upon the bandwidth.

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

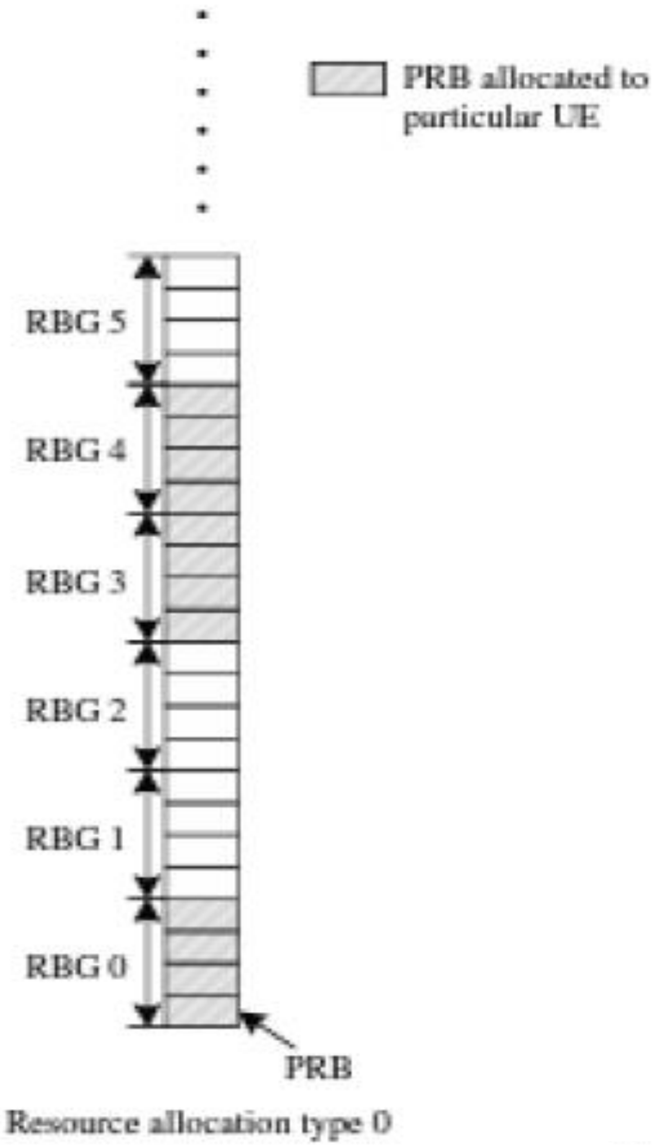


Figure 6.11 Examples of resource allocation type 0

The RBG size P = 4, and RBGs 0,3,4 are allocated to a UE

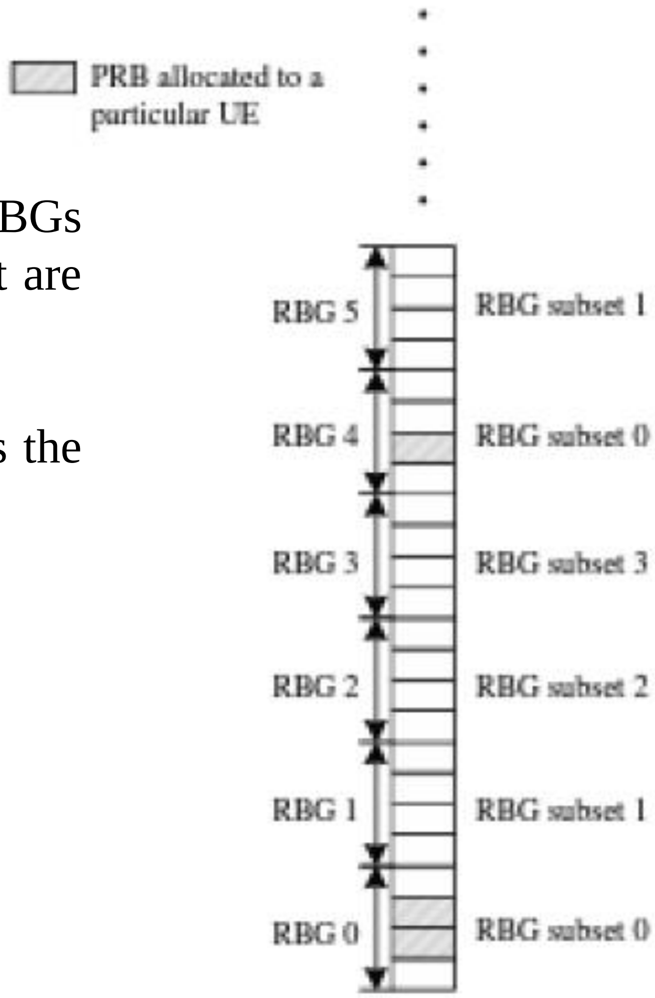
6.3 Downlink OFDMA Radio Resources

6.3.3 Resource Allocation

Type-1 : all the RBGs are grouped into number of RBGs subset and certain PRBs inside a selected RBG subset are allocated to UE.

There are total number of P RBG subsets, where P is the size of RBG

Type-2 : PRBs are not directly allocated, instead VRBs are allocated which are then mapped to PRBs. A VRB is of same size as a PRB.



Resource allocation type 1

The RBG size P = 4, and RBG subset 0 is allocated to a UE

6.3 Downlink OFDMA Radio Resources

6.3.4 Supported MIMO Modes

- Multiantenna transmission and reception (MIMO), is a physical layer technique that can improve both reliability and throughput of the communications over wireless channels.

- The baseline antenna configuration in LTE is two transmit antennas at the cell site and two receive antenna at the UE. The higher order MIMO is also supported with upto 4 transmit and receive antennas.

- The downlink transmission supports both single-user MIMO (SU-MIMO) and multiuser MIMO (MU-MIMO).

- For SU-MIMO one or multiple data streams are transmitted to a single UE through space time processing.

- For MU-MIMO, modulation data streams are transmitted to different UEs using same time-frequency resource.

- The supported Su-MIMO modes are listed below:
  - Transmit diversity with space frequency bock codes (SFBC)
  - Open loop spatial multiplexing supporting four data streams
  - Closed loop spatial multiplexing, with closed loop precoding as a special case when channel rank = 1.
  - Conventional direction of arrival (DOA) – beamforming

- Supported MIMO modes are restricted to UE capabilities.

6.4 Uplink SC-FDMA Radio Resources

- For the LTE uplink transmission, SC-FDMA with a CP is adopted.

6.4.1 Frame structure

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

6.4 Uplink OFDMA Radio Resources

6.4.2 Physical Resource blocks for SC-FDMA

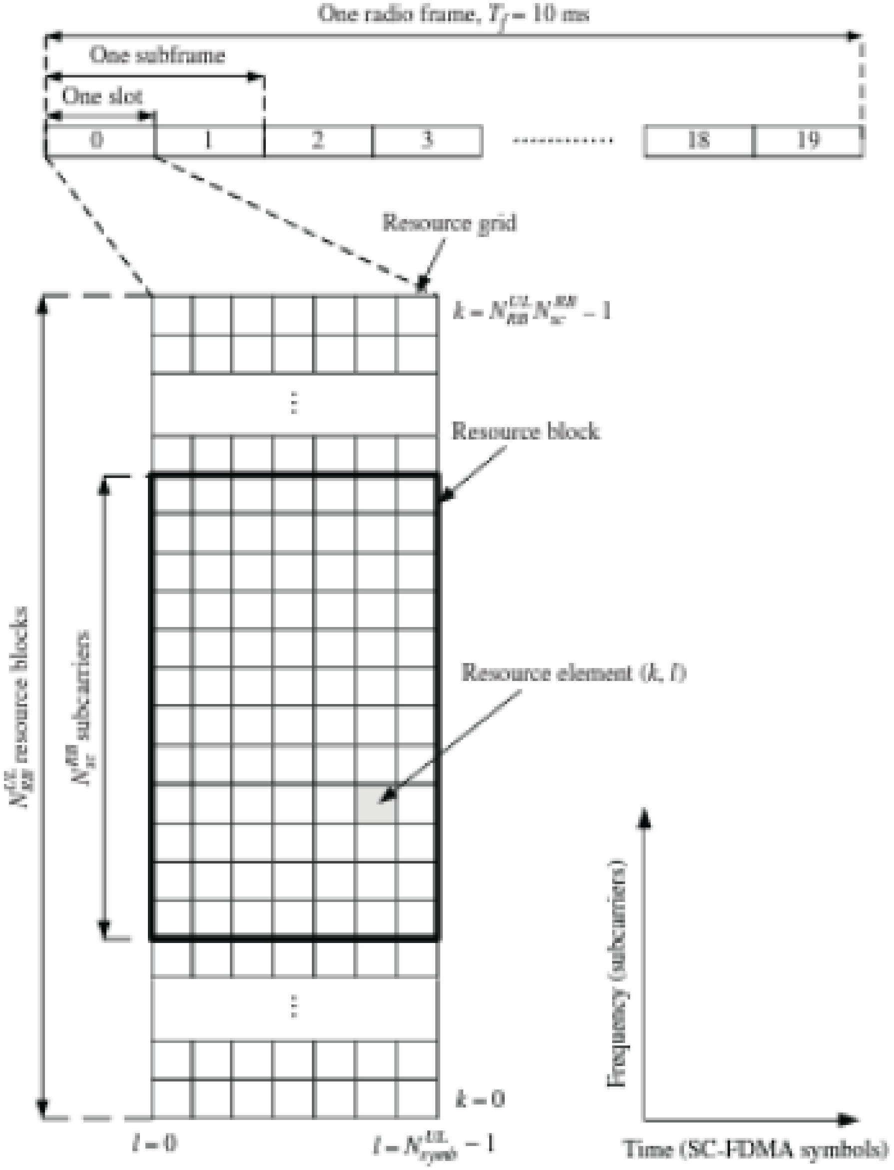


Figure 6.12 The structure of the uplink resource grid.

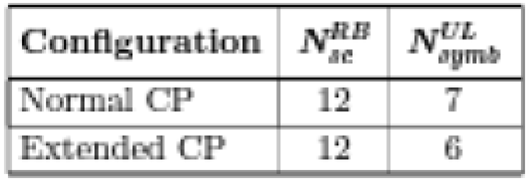
Number of OFDM symbols in each block

$$N_{symb}^{UL}$$

Number of subcarriers in each resource block, N_{sc}^{RB}

$$\Delta f \,.\, N_{sc}^{RB} = 180\ kHz$$

Table 6.6 Physical Resource Block Parameters for Uplink



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

Number of uplink resource block, N_{RB}^{UL}

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

$N_{RB}^{min,UL}$ = 6 and $N_{RB}^{max,,UL}$ = 110

6.4 Uplink OFDMA Radio Resources

6.4.3 Resource allocation

- Similar to downlink

6.4.4 Supported MIMO Modes

- MU-MIMO

7.1 Downlink Transport Channel Processing Overview

- Downlink physical layer processing mainly consists of **channel coding** and **modulation**.
- Channel coding – mapping the incoming transport blocks from MAC layer into different **codewords**.
- Modulation – generates complex valued OFDM baseband signals for each antenna port, which are then **upconverted to carrier frequency**.

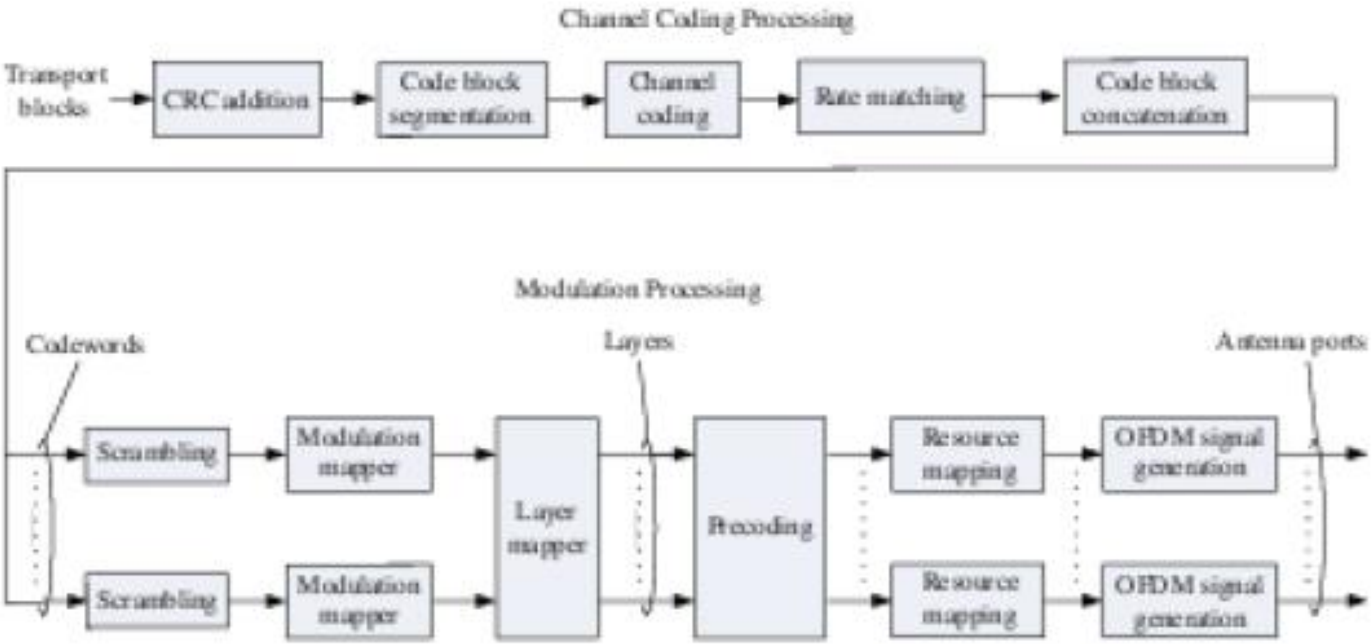


Figure 7.1 Overview of downlink transport channel processing.

7.1 Downlink Transport Channel Processing Overview

7.1.1 Channel Coding Processing

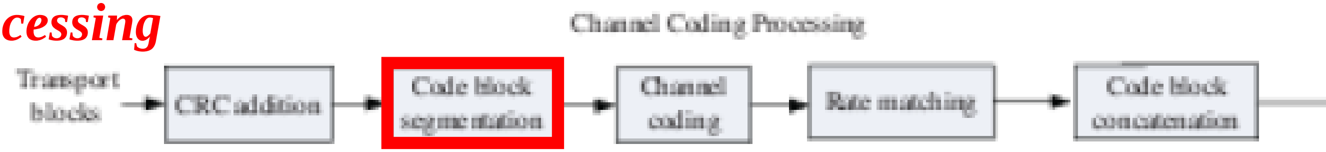
- Channel coding procedure
- Applicable to both downlink and uplink transmission
- Downlink – error detection, error correction, rate matching, interleaving, and transport channel/control information mapping onto physical channel.
- Error control mechanism of data transmission using forward error correction (FEC) code
- Error detection based on cyclic redundancy check (CRC)

7.1.1 Channel Coding Processing

CRC addition

- CRC is used to provide **error detection** on the transport block.
- It generates **parity bits** by a cyclic generator polynomials, which are then **added at the end** of the transport block.
- The number of parity bits can take value 8, 16, or 24.
- The receiver separates the two fields and uses the information bits to compute the **expected CRC** bits.
- If the observed and expected CRC bits are the **same**, then it concludes that the information has been received correctly and sends a **positive acknowledgement** back to the transmitter.
- If the CRC bits are **different,** it concludes that an error has occurred and sends a **negative acknowledgement** to request a re-transmission.
- Positive and negative acknowledgements are often abbreviated to ACK and NACK respectively.

7.1.1 Channel Coding Processing



Code Block Segmentation

- It is preferred when number of bits in the sequence after CRC attachment, B, is larger than the maximum code block size for the turbo encoder, which is Z = 6144.

- It breaks the long sequence into C code blockes and adds an additionl 24-bits CRC sequence to each block

$$C = \begin{cases} 1 & \text{if} \quad B \le Z \\ \lceil B/(Z-L) \rceil & \text{if} \quad B > Z, \end{cases}$$

- L is the number of CRC parity bits.

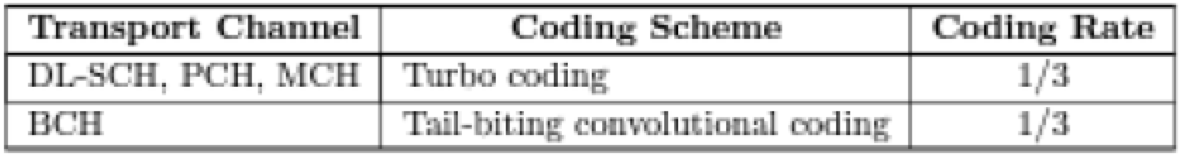
- Each of these C blocks are then encoded independently.

7.1.1 Channel Coding Processing

Channel Coding

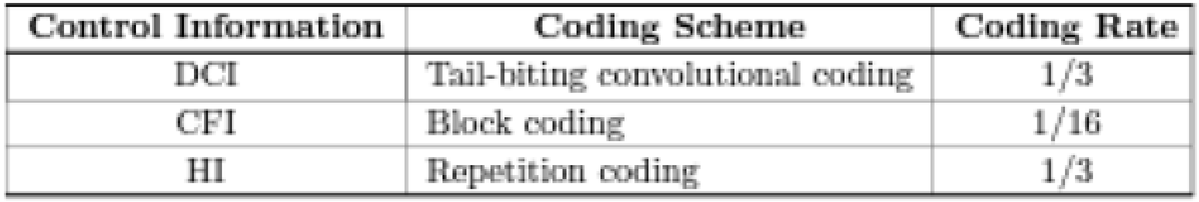
- In LTE the channel encoders applied to transport channels includes **tail-bitting** convolutional coding and convolutional **turbo coding**.

Table 7.1 Channel Coding Schemes and Coding Rates for Downlink Transport Channels



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

Table 7.2 Channel Coding Schemes and Coding Rates for Downlink Control Information



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

7.1.1 Channel Coding Processing

Rate Matching

- Rate matching in LTE performs interleaving, as well as repetition or puncturing, in order to generate a transport block that fits the payload size determined by modulation scheme and the number of resource block allocated for the transport block.

- Rate matching is defined per coded block and consists of following three stages:

- **Interleaving-** performed in order to spread out the occurrence of bursty error across the code block, which improves the overall performance of the decoder.

- **Bit collection** – since the interleaving is performed separately for the symmetric and parity bits, a bit collection stage is required, to place these bits in right order as needed by decoder.

- **Bit selection** – it is need in order to repeat or puncture some of the parity bits to create the required payload.

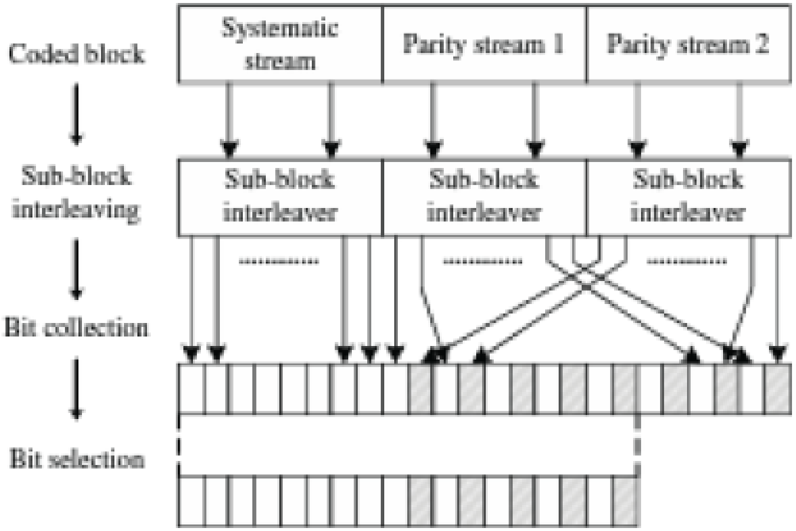
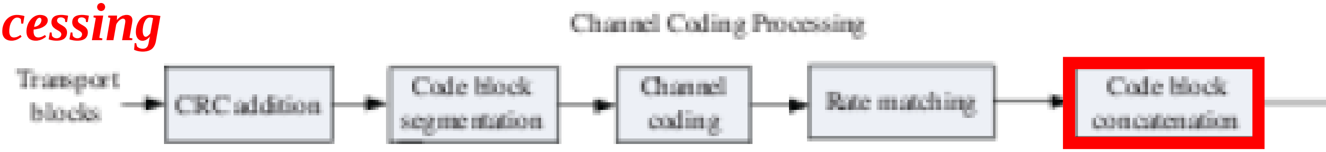


Figure 7.5 Rate matching for coded transport channels.

7.1.1 Channel Coding Processing



Code Block Concatenation

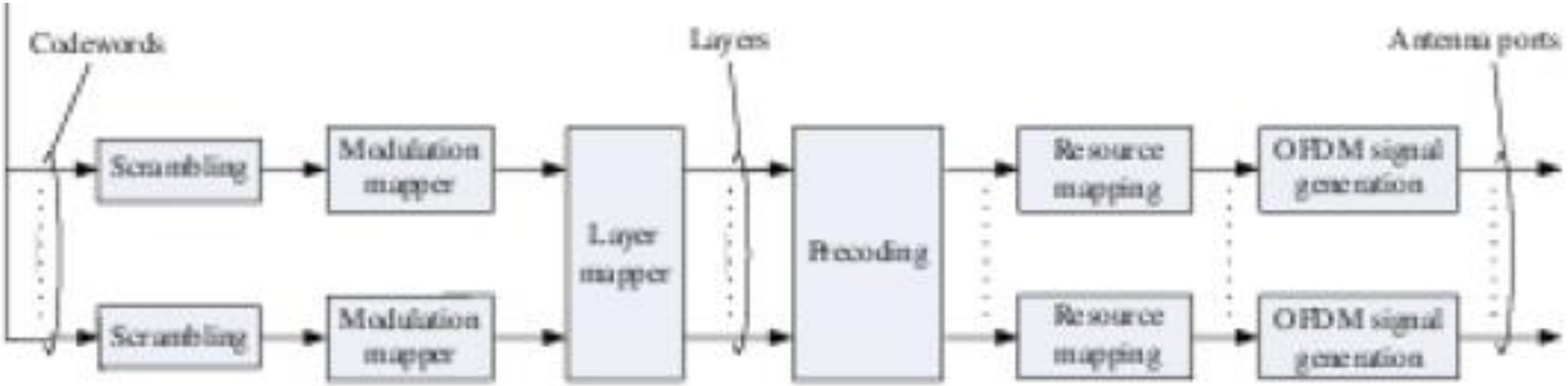
- The code block concatenation consists of sequentially concatenating the rate matching outputs for different code blocks, forming the **codewords** input to the modulation processing.

- It is needed only for turbo coding when the number of code blocks is larger than one.

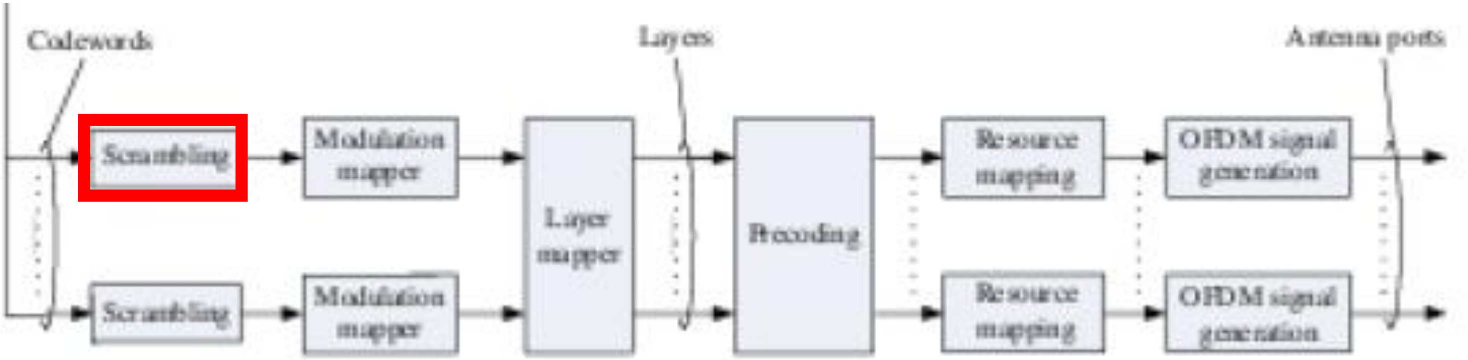
In the downlink, the base station adds a 24 bit CRC to each DL-SCH transport block, segments it into code blocks with a maximum size of 6144 bits and adds another CRC to each one. It then passes the data through a 1/3 rate turbo coder. The rate matching stage stores the resulting bits in a circular buffer and then selects bits from the buffer for transmission. The number of transmitted bits is determined by the size of the resource allocation and the exact choice is determined by the redundancy version. Finally, the base station reassembles the coded transport blocks and sends them to the physical channel processor in the form of codewords

7.1.2 Modulation Processing

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



7.1.2 Modulation Processing



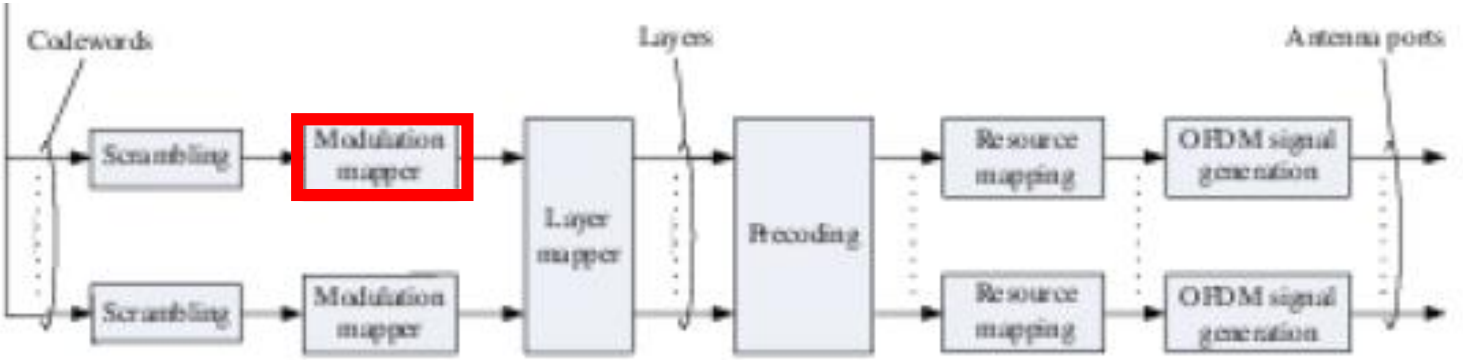
Scrambling

- Before modulation, the codewords generated through channel processing is first scrambled by a bit level scrambling sequence.

- In the downlink, the scrambling stage mixes each codeword with a pseudorandom sequence that depends on the physical cell ID and the target RNTI, to reduce the interference between transmissions from nearby cell.

- Except the multicast channel, for all other downlink transport channels and control information, the scrambling sequence are different for neighbouring cells, so that ICI is randomised.

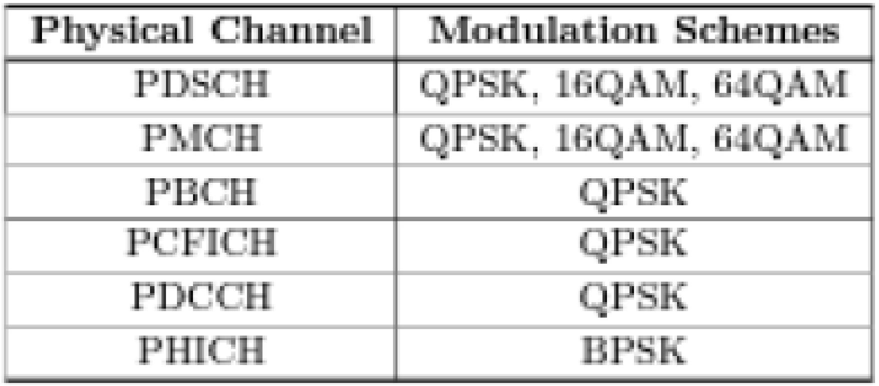
7.1.2 Modulation Processing



Modulation Mapper

The modulation mapper takes the resulting bits from scrambler in groups of two, four or six and maps them onto the in-phase and quadrature components using QPSK, 16-QAM or 64-QAM.

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

7.1.2 Modulation Processing

Layer Mapping and Precoding

- Layer mapping and precoding stages implement the multiple antenna transmission and reception techniques.
- The layer mapping stage takes the codewords and maps them onto one to four independent layers.
- while the precoding stage applies the chosen precoding matrix and maps the layers onto the different antenna ports.
- The layer mapper maps N_c codewords to υ spatial layers, while the precoder maps the υ layers to P antenna ports.

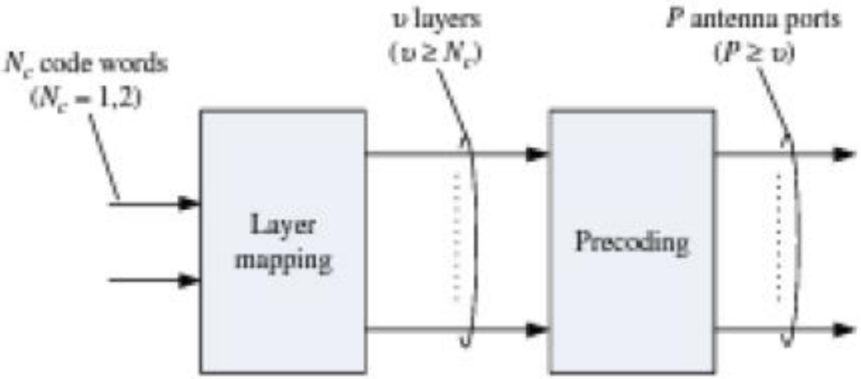


Figure 7.6 Layer mapping and precoding.

7.1.2 Modulation Processing

Codewords

- A codeword is defined as the output of each channel coding/rate matching stage associated with single transport block coming from MAC layer.

- In LTE, although upto 4 transmit/receive antennas are supported, the number of codewords limited to 2.

- This is to limit the uplink feedback overhead, as a separate H-ARQ process is operated for each codeword, which require a separate signalling in the uplink control channel.

Layer

- A layer corresponds to a data stream of the spatial multiplexing channel.

- Each codeword is mapped into one or multiple layers. Therefor the number of layers is at least as many as the number of codeword, i.e., $v \geq Nc$

7.1.2 Modulation Processing

Antenna Ports

- An antenna port is defined by its associated reference signal, which is a logical entity, and may not corresponds to actual physical antennas.

- The number of antenna ports at the e-NodeB is sent to UEs through the PBCH channel, which can be 1,2, or 4 in LTE.

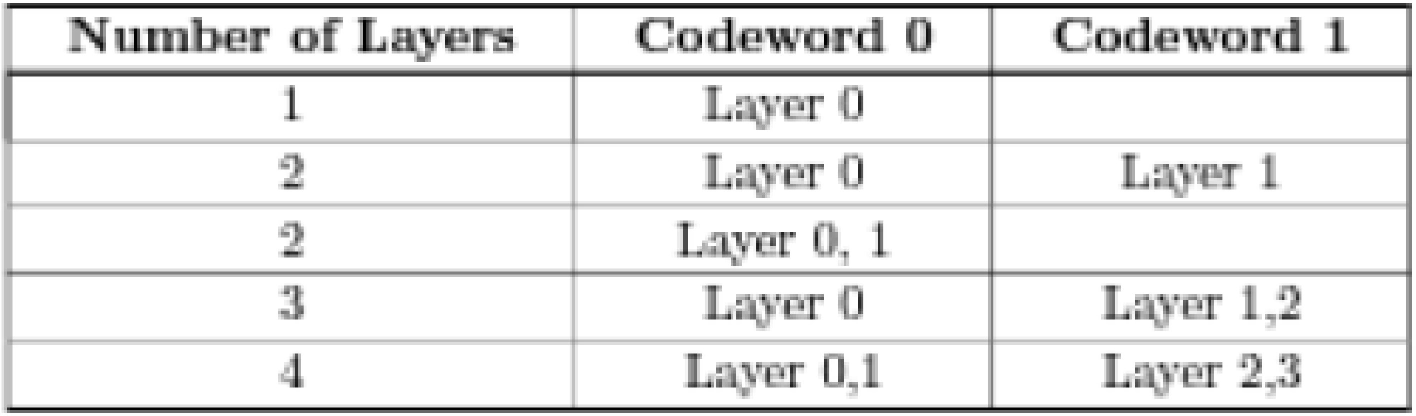
    - Antenna ports 0-3 are cell specific
    - Antenna port 4 is MBSFN specific
    - Antenna port 5 is UE specific
- Cell specific ports and UE specific ports can not be used simultaneously. Different reference symbols are defined for different types of antenna ports.

- Single Antenna Port – one codeword is mapped to a single layer.
- Transmit Diversity – one codeword is mapped to two or four layers. It is an open loop MIMO mode.
- Spatial Multiplexing – N_c codewords are mapped to v layers, where N_c = 1,2 and v = 1,2,3,4 and $v \geq Nc$.

7.1.2 Modulation Processing

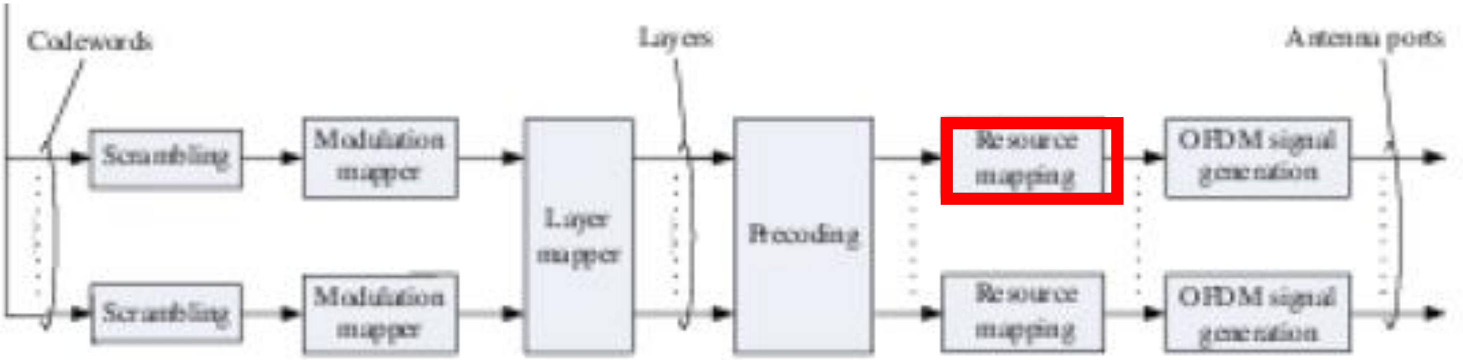
Antenna Ports

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

7.1.2 Modulation Processing

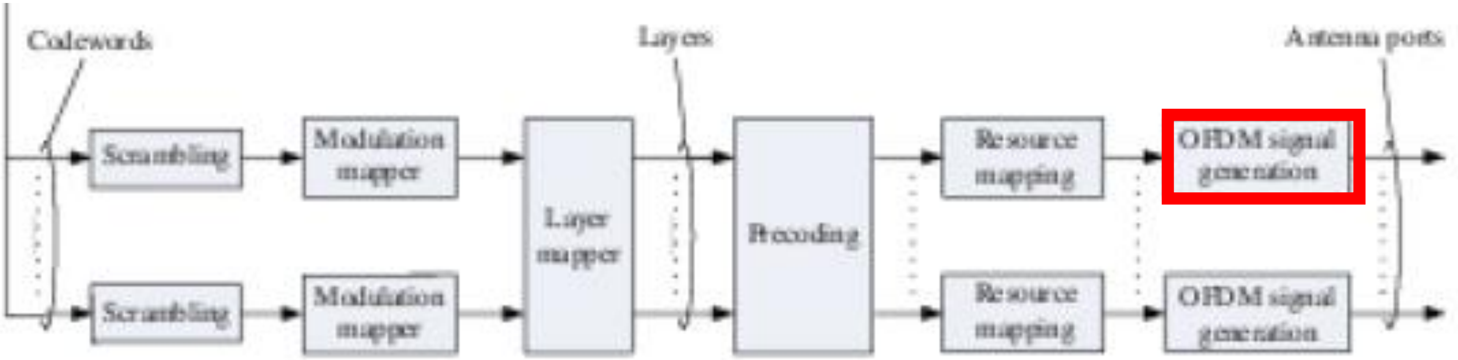


Resource Mapping

- For each antenna ports used for transmission of physical channels, the block of complexed-valued symbols $y_p(0), \ldots, y_p\left(M_s^{ap}-1\right)$ shall be mapped in sequence, starting with $y_p(0)$, to resource block assigned for transmission.

- The mapping to resource element (k, l) on antenna ports p not reserved for other purposes shall be increasing order of first the index k and then index l, starting form the first slot in a subframe.

7.1.2 Modulation Processing



OFDM Signal Generation

- In practice the OFDM signal is generated using IFFT digital processing.
- At receiver FFT processing can be used to convert the time-domain signal back to frequency domain.

7.1.2 Modulation Processing

OFDM Signal Generation

- In practice the OFDM signal is generated using IFFT digital processing.
- At receiver FFT processing can be used to convert the time-domain signal back to frequency domain.

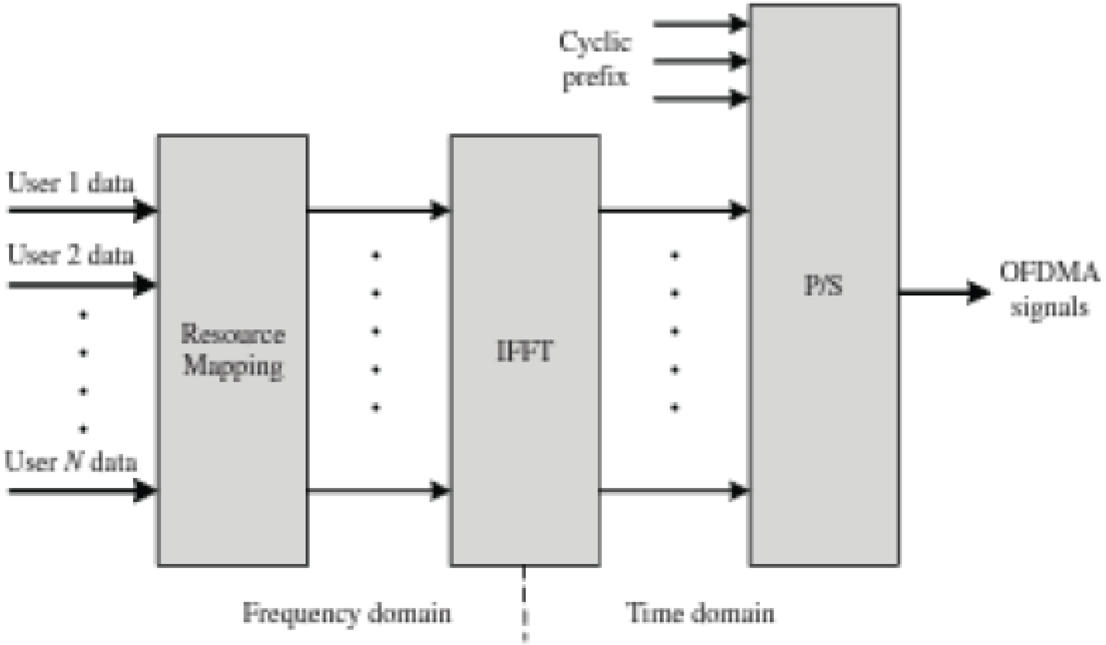


Figure 7.8 OFDMA signal generation with *N* users, where P/S denotes the parallel-to-serial converter.

7.2 Downlink Shared Channel

- DL-SCH is carried on the physical downlink shared channel (PDSCH).

- Data transmission in PDSCH is based on the concept of shared channel transmission, where PHY layer resources, i.e. resource blocks available for PDSCH, is treated as common resource that can be dynamically shared among the different UEs.

- The dynamic multiplexing of UEs on PDSCH is done by a scheduler on a 1 msec interval.

- This way a large portion of radio resource can be allocated to a specific UE, which is suitable for packet-data applications.

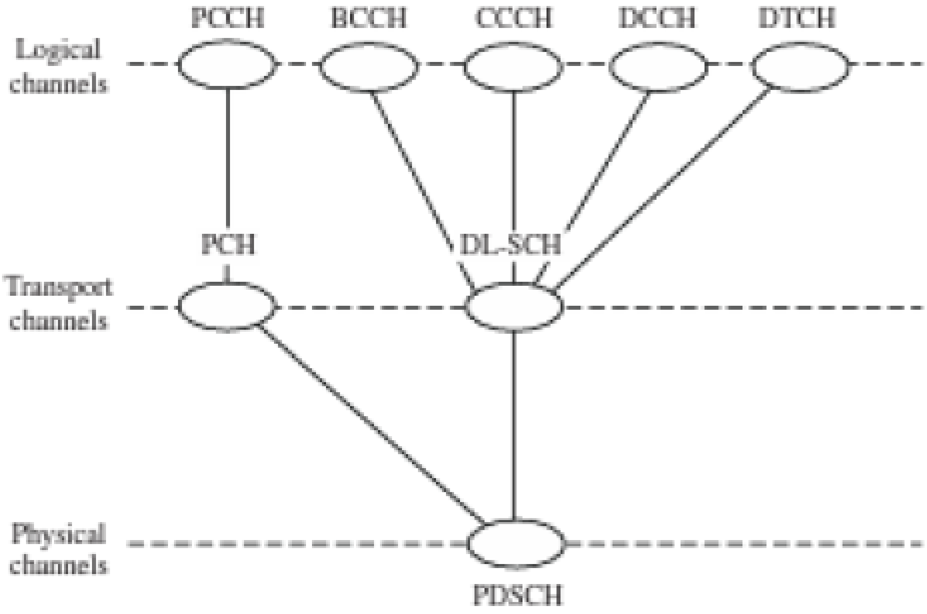


Figure 7.9 Channel mapping around the downlink shared channel.

7.2.1 Channel Coding and Modulation

- DL-SCH uses the rate 1/3 convolutional turbo encoder.
- Rate matching is used in order to achieve an effective channel coding rate that matches the payload capacity determined by number of resource block allocated to transport block of a given UE and the modulation scheme.
- The redundancy version used for repetition or puncturing depends upon H-ARQ transmission number and is indicated explicitly by e-NodeB.
- The modulation scheme allowed for DL-SCH includes QPSK, 16QAM, and 64QAM.
- Modulation scheme chosen based on the channel quality indicator (CQI) provided by the UE and various other parameters like size of transport block.
- The transport block size, redundancy version, and modulation order are indicated in the Downlink Control Information (DCI).

7.2 Downlink Shared Channel

7.2.1 Channel Coding and Modulation

- For MIMO spatial multiplexing with two code word, different modulation and coding can be used for each codeword, which requires individual signaling.

- The resource mapping of physical PDSCH is depends upon whether UE-specific reference signals are transmitted.

- In resource blocks without UE-specific reference signals, the PDSCH shall be transmitted on same set of antenna ports as PBCH, which is one of $\{0\}, \{0,1\}\ or\ \{0,1,2,3\}$.

- If UE-specific reference signals are transmitted, then PDSCH shall be transmitted on antenna port 5, i.e. beamforming is applied.

- Channel coding PCH transport channel is same as that for DL-SCH channel, both of which are mapped to the PDSCH physical channel.

7.2.2 Multiantenna Transmission

- As the main channel for downlink traffic data transmission, the PDSCH supports all MIMO modes specific in LTE.

- There are 7 different transmission modes defined for data transmission on 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 i.e. *port—0 and 1* if *two* physical antennas are used, port- *0,1, 2, 3* if *four* antenna physical antennas are used.

  3. **Open-loop (OL) spatial multiplexing:** one or two transport blocks are transmitted from two or four physical antennas. In this case, predefined precoder matrices are used based on the rank indicator (RI) feedback. The precoding matrix is fixed not adopted.

  4. **Closed loop (CL) spatial multiplexing:** one or two transport blocks are transmitted from two or four physical antennas. The precoding in this case is adapted based on precoding matrix indicator (PMI) feedback from UE.

7.2.2 Multiantenna Transmission

5. **Multiuser MIMO :** two UEs are multiplexed onto two or four physical antennas with one transport block to each UE. Rank-1 PMI feedback from each UE is used to create the overall PMI matrix.

6. **Closed loop Rank-1 precoding:** it is a special case for CL spatial multiplexing with single-layer transmission, i.e. a $P \times 1$ precoder is applied.

7. **Single antenna port (port-5):** a single transport block is transmitted from two or more physical antennas. The e-NodeB performs beamforming to a single UE using all physical antennas. Unlike other modes, in this case reference signals are also transmitted using same beamforming vector that is used for data symbols.

- Transmission mode-1 can be specified as Single-Input-Single-Output (SISO) mode, that doesn’t require any layer mapping or precoding.
- On the other hand transmission modes 2 to 6 can be specified as MIMO modes, which require explicit layer mapping and precoding.
- Downlink MIMO transmission, especially CL MIMO modes, requires explicit feedback from UEs, including RI and PMI contained in Uplink Control Information (UCI).

7.3 Downlink Control Channels

- Downlink control channels are carried over the Physical Downlink Control Channel (PDCCH) and they contained control information from MAC layer.

- Which includes Downlink Control Information (DCI), Control Format Indicator (CFI), and H-ARQ Indicator (HI).

- Channel mapping between control information and physical channel in downlink is shown in figure 7.11 below.

- On the physical layer the PDCCH and PDSCH are time multiplexed, such that the PDCCH is carried over the first few OFDM symbols of each subframe, and the PDSCH is carried oer 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.

- CFI is carried yet on another channel known as PCFICH.

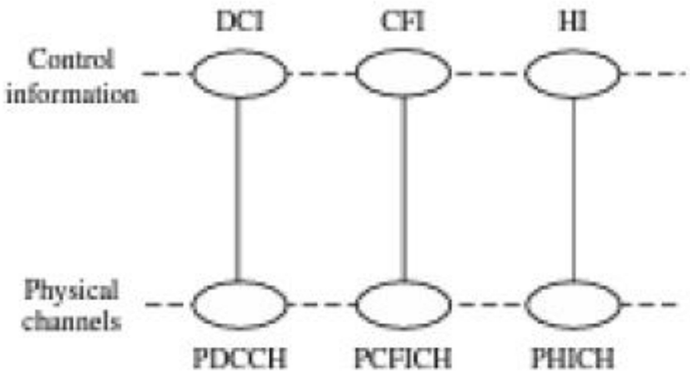


Figure 7.11 Channel mapping for control information in the downlink.

7.3 Downlink Control Channels

- PCFICH is always carried in a predetermined format over the OFDM symbol for each subframe.

- This predetermined format of PCFICH allows the UE to decode the CFI without ambiguity and thus determined the number of OFDM symbols in the beginning of each subframe.

7.3.1 Downlink Control Information (DCI) Format

- Among the control information in downlink, DCI is most important as it carries the detailed control information for downlink and uplink transmissions.

- DCI carries the downlink scheduling assignment, 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 the data symbols in the uplink.

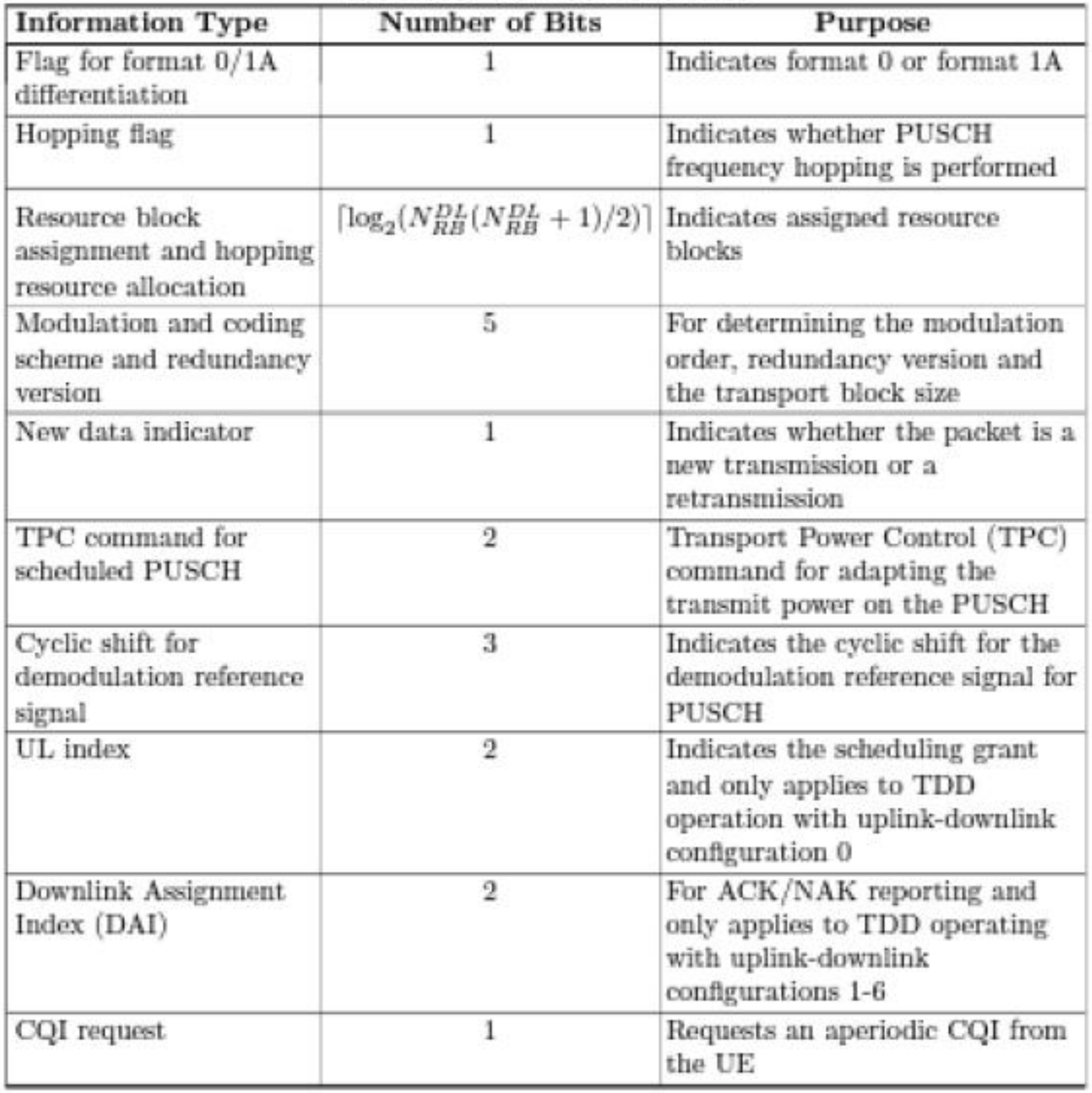
7.3.1 Downlink Control Information (DCI) Format

- LTE defines ten different DCI formats for different transmission scenarios.
  - **DCI format 0 :** carries uplink scheduling grants and necessary control information for uplink transmission.
  - **DCI format 1/ 1A/ 1B/ 1C/ 1D :** provides scheduling information for one codeword transmission without spatial multiplexing.
  - **DCI format 2 and 2A :** provides downlink scheduling information for CL and OL spatial multiplexing respectively. In this case DCI contains the information about the modulation and coding scheme, and redundancy version for each of two codes.
  - **DCI format 3 and 3A :** carry Transmit Power Control (TPC) command for the uplink.

7.3 Downlink Control Channels

7.3.1 Downlink Control Information (DCI) Format

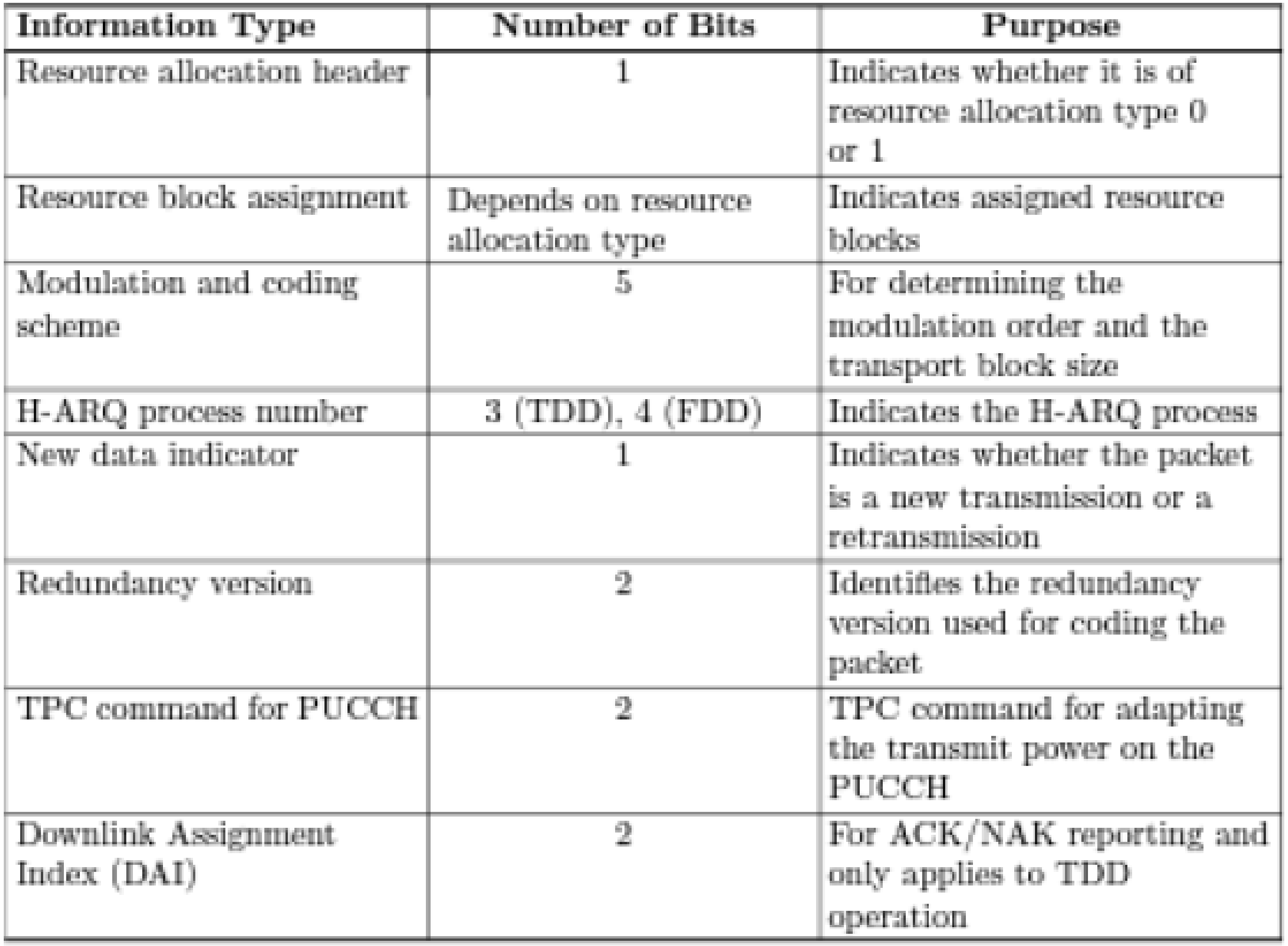
Table 7.10 Fields of DCI Format 0



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

7.3.1 Downlink Control Information (DCI) Format

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

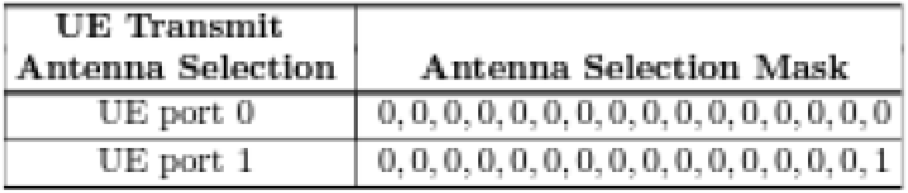
7.3.2 Channel Coding and Modulation

1. DCI

- DCI is mapped to PDCCH, and multiple PDCCH can be transmitted in a subframe.

- A 16-bit CRC is attached to the control information symbols. The CRC parity bits are then scrambled according to the following rules:
- If UE transmit antenna is not configured or applicable, the CRC parity bits are scrambled with one Radio Network Temporary Indicator (RNTI), which is the UE identity Then UE is able to detect its own DCI.
- If UE transmit antenna is configured or applicable, the CRC parity bits of PDCCH with DCI format 0 is scrambled with the corresponding RNTI and the antenna selection mask is indicated as in table below, which tells the UE about the selected antenna port.

Table 7.12 UE Transmit Antenna Selection Mask



UE Transmit Antenna Selection	Antenna Selection Mask
UE port 0	0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0
UE port 1	0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1

7.3.2 Channel Coding and Modulation

1. DCI

- The tail bitting convolutional code with 1/3 is used as the channel coding scheme, while QPSK is the modulation scheme.
- After channel coding cell-specific scrambling is applied.
- PDCCH shall be transmitted on the same set of antenna ports as the PBCH.

- PDCCH is located in the first n OFDM symbols of ach subframe, $1 \leq n \leq 4$.
- Such a special location can be used to support micro-sleep that saves UE battery life, and to reduce buffering and latency, i.e. UE can go to sleep if it sees no assignment.

- For frame structure type-2, PDCCH can be mapped onto the first OFDM symbols of DwPTS field, while the third OFDM symbol is for the primary synchronization signal.

7.3.2 Channel Coding and Modulation

1. DCI

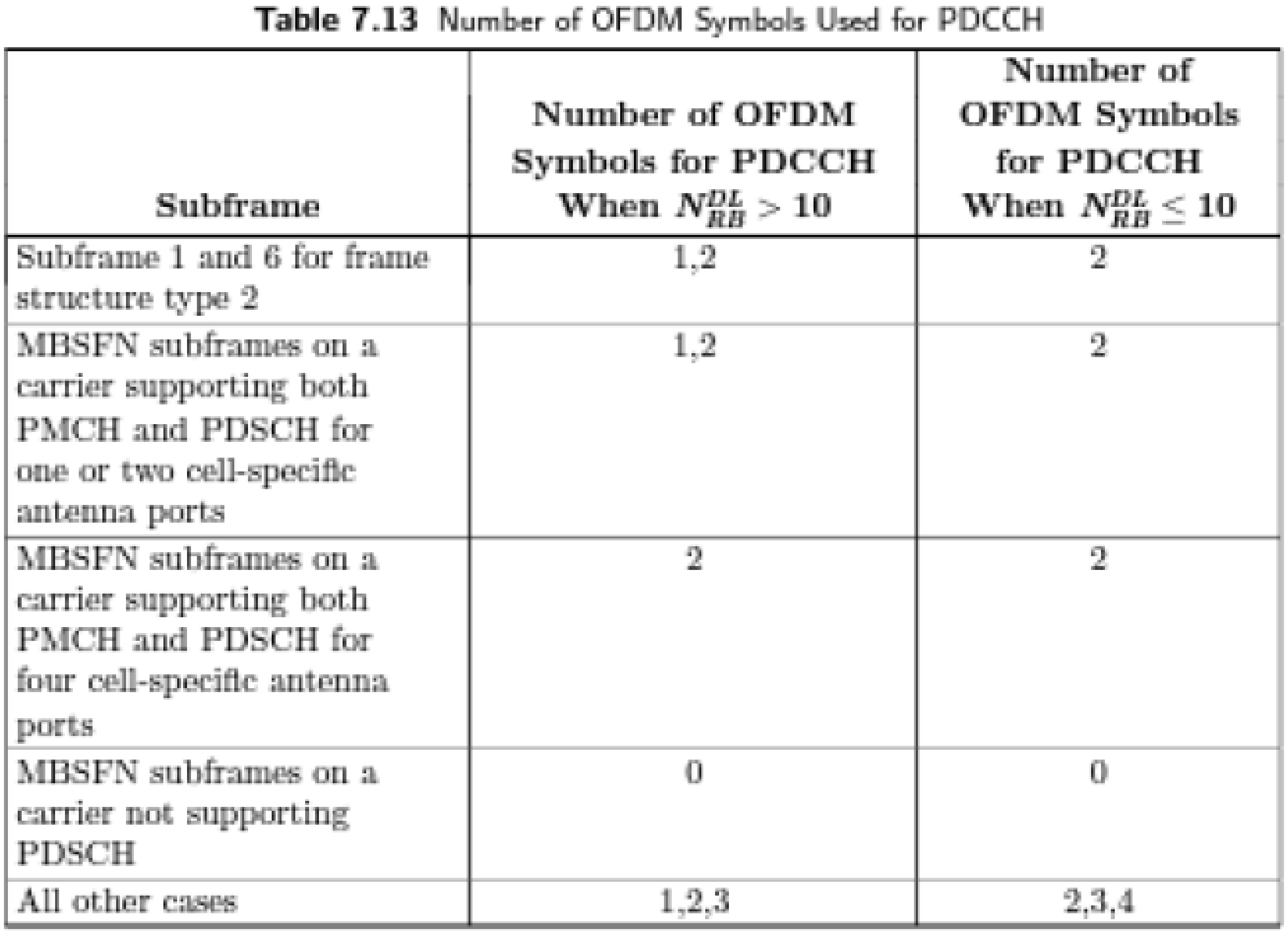


Table 7.13 Number of OFDM Symbols Used for PDCCH

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

7.3.2 Channel Coding and Modulation

1. DCI

- Each PDCCH is transmitted using one or more control cannel elements (CCEs), where each CCE is corresponds to nine sets of four physical resource elements known as resource element groups (REGs).

- Four QPSK symbols are mapped to REG.

- There are four different PDCCH formats defined in LTE with different numbers of CCEs.

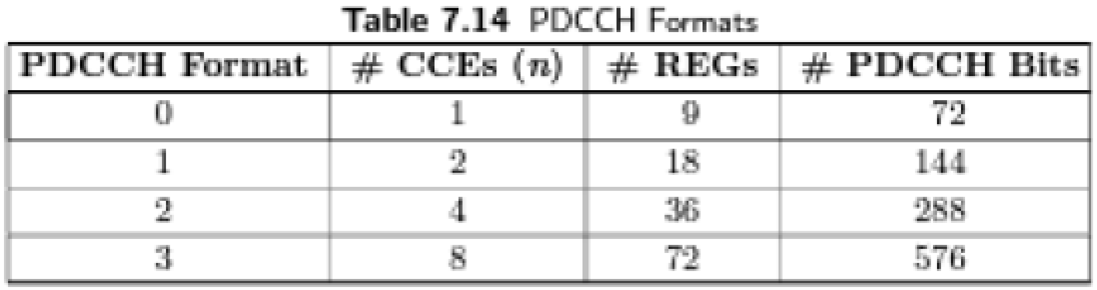


Table 7.14 PDCCH Formats

PDCCH Format	# CCEs (n)	# REGs	# PDCCH Bits
0	1	9	72
1	2	18	144
2	4	36	288
3	8	72	576

7.3.2 Channel Coding and Modulation

2. CFI

- CFI indicates how many OFDM symbols the DCI spans in a subframe.
- Such an indicator is needed because the load on PDCCH varies, depending upon number of resource blocks and the signaling conveyed on PDCCH.
- 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.

- PCFICH shall be transmitted on the same set of antenna ports as the BPCH.

7.3.2 Channel Coding and Modulation

3. H-ARQ indicator (HI)

- The control information HI is for H-ARQ acknowledgment in response to uplink transmission.

- It has two values HI = 1 for positive acknowledgment and HI= 0 for negative acknowledgment.

- HI is mapped onto PHICH.

7.3.3 Multiantenna Transmission

- OL transmit diversity is supported for downlink control information.

7.4 Broadcast Channels

- Broadcast channel carries information such as downlink system bandwidth, antenna configuration, and reference signal power.

- The UE can get necessary system information after cell search (or synchronization) procedure.

- Due to the large size of system information field, it is divided into two portions
  - Master Information Block (MIB) transmitted on PBCH
  - System Information Block (SIB) transmitted on PDSCH

- PBCH contains the basic system parameters necessary to demodulate the PDSCH (which contains the remaining SIB).

- Error detection is provided through a 16 bit CRC.

- Broadcast channel uses a fixed coding rate and tail-biting convolutional coding with rate 1/3 is used.

- Fixed modulation scheme (QPSK), and is transmitted using either one antenna or open loop transmit diversity.

7.4 Broadcast Channels

- The coded bits are rate matched to 1920 bits for normal CP and 1728 bits for extended CP.
- No H-ARQ is supported.
- For MIMO modes, PBCH supports single antenna transmission and OL transmit diversity.
- The PBCH occupies the most narrow bandwidth supported by the LTE (1.4 MHz) and it is located in the subframe guaranteed to be used in the downlink
- The mobile processes the PBCH blindly using all the possible ways in which the base station might have manipulated the information and only the correct choice allows the cyclic redundancy check to pass.
- By reading the master information block, the mobile can then discover the downlink bandwidth, the remaining bits of the system frame number and the PHICH configuration.
-

7.5 Multicast Channels

- Multimedia Broadcast and Multicast service (MBMS), supports multicast/broadcast services in a cellular system.

- It sends the same content information to all UEs (broadcast) or a given set of UEs (multicast), and is envisaged for delivering services such as mobile TV.

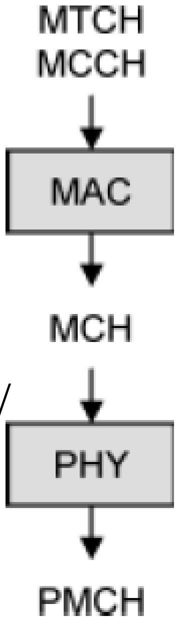
- In principle, MBMS transmission can originate from a single base station or multiple base stations.

- The LTE air interface delivers MBMS using the channels shown in figure →

- One major design requirement for LTE is to provide enhanced support for MBMS Transmission, E-MBMS, and it is achieved trough Single-Frequency Network (SFN).

- With OFDM based transmission in the downlink, over-the-air combining of multicast/ broadcast transmission is possible in LTE with an extended CP.

- Inn such Multicast/Broadcast Single Frequency Networks (MBSFNs), same information broadcast on the same radio resources from multiple synchronized neighboring base stations to multiple UEs.



7.5 Multicast Channels

- The multicast traffic and control channels are transported using the multicast channel (MCH) and the physical multicast channel (PMCH).

- Each MBSFN area contains multiple instances of the PMCH, each of which carries either the MCH, or one or more MTCH.

- The PMCH implements the MBSFN techniques and always uses the extended CP to handle the long delay spreads that result from the use of multiple base stations.

- It is transmitted on antenna port 4, to keep it separate from the base station's other transmissions, and does not use transmit diversity, spatial multiplexing or hybrid ARQ.

- Each instance of the channel uses a fixed modulation scheme and coding rate, which are configured by means of RRC signalling.

- MBSFN use point-to-multipoint mode, UE feedback such as ACK/NAK and CQI cannot be used.

- The PMCH uses a different set of reference signals from usual, known as *MBSFN reference signals*. These are tagged with the MBSFN area identity instead of the physical cell identity, to ensure that the mobile can successfully combine the reference signals that it receives from different cells.

7.5 Multicast Channels

- The PMCH and DL-SCH can be multiplexed with the following rules:

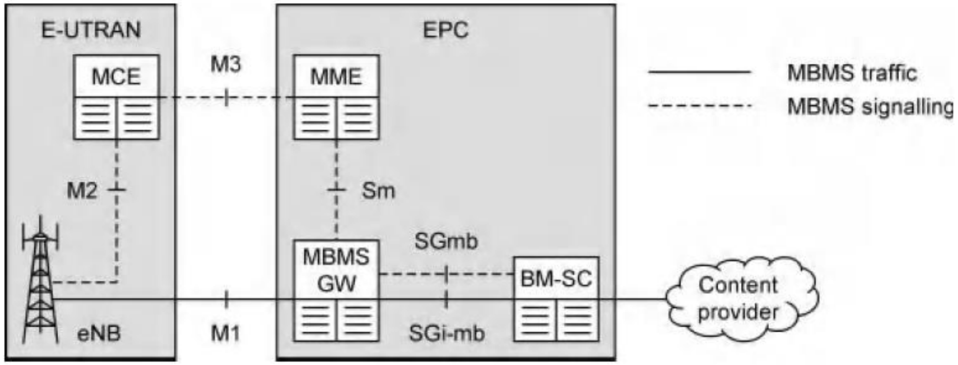
  1. The PMCH and DL-SCH can be multiplexed in a TDM manner on a subcarrier basis, but can not be transmitted within the same subframe.
  2. In the subframe where PMCH is transmitted on a carrier supporting a mix of PDSCH and PMCH transmission, upto 2 of first OFDM symbols of a subframe can be reserved for non-MBSFN transmission and shall not be used for PMCH transmission.
  3. In a cell with 4 cell-specific antenna ports, the first OFDM symbols of a subframe are reserved for non-MBSFN transmission in the subframe in which PMCH is transmitted.
  4. The non-MBSFN symbols shall used the same CP as used for subframe 0.
  5. PMCH shall not be transmitted in 0 and 5 on a carrier supporting mix of PDMCH and PMCH transmission.

7.5 Multicast Channels

Figure below shows the architecture that is used for the delivery of MBMS over LTE.

The *broadcast/multicast service centre* (BM-SC) receives MBMS content from a content provider.

The *MBMS gateway* (MBMS-GW) distributes the content to the appropriate base stations, while the *multicell/multicast coordination entity* (MCE) schedules the transmissions from all the base stations in a single MBSFN area.



7.6 Downlink Physical Signals

Includes downlink reference signals and synchronization signals.

7.6.1 Downlink References Signals

- Downlink reference symbols consists of known reference symbols that are intended for downlink channel estimation at the UE needed to perform coherent demodulation.

- These are used in two ways.

  - Their immediate role is to give the mobile an amplitude and phase reference for use in channel estimation.

  - Later on, the mobile will use them to measure the received signal power as a function of frequency and to calculate the channel quality indicators.

- There are three different types of reference signals
  - Cell-specific reference signals
  - MBSFN reference signals
  - UE-specific reference signals

7.6 Downlink Physical Signals

7.6.1 Downlink References Signals

1. Cell-specific reference signals

- Transmitted in all downlink subframes in a cell supporting non-MBSFN transmission.

- In the subframe used for transmission with MBSFN, only the first two OFDM symbols can be used for cell-specific reference symbols.

- Cell specific reference signals are defined only for normal subcarrier spacing of 15 kHz.

- In the time domain, for the antenna port $p \in \{0,1\}$, the reference symbols are inserted within the first and the third last OFDM symbols in each slot.

- for the antenna port $p \in \{2,3\}$, the reference symbols are inserted only in the second OFDM symbol.

- In frequency domain, the spacing between neighboring reference symbols in the same OFDM symbol is 5 subcarriers, i.e. reference symbols are transmitted every sixth subcarrier.

- While one antenna is transmitting a reference signal, all the others stay silent, in the manner required for spatial multiplexing.

1. Cell-specific reference signals

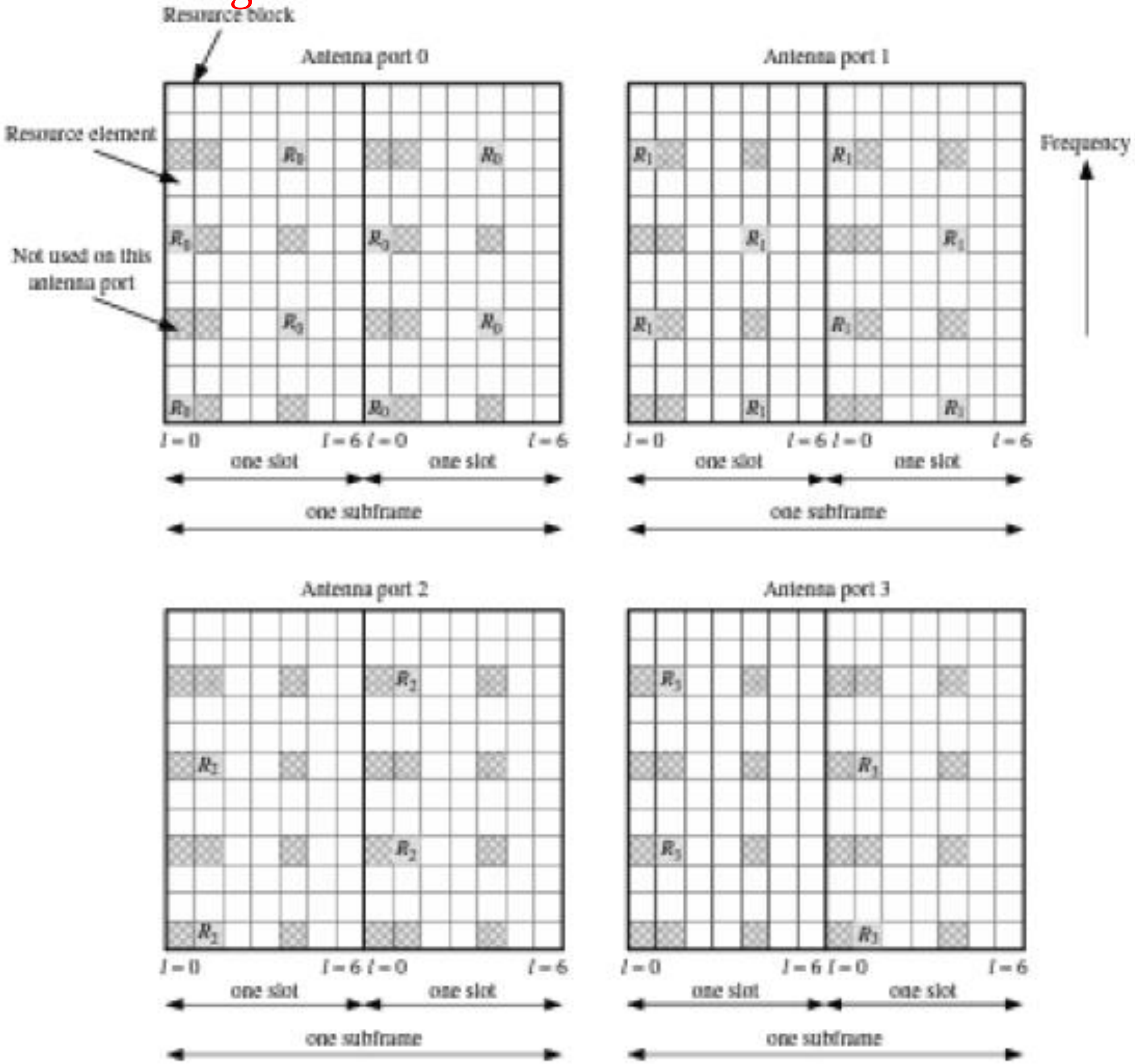


Figure 7.12 An example of mapping of downlink cell-specific reference signals, with four antenna ports and the normal CP. R_p denotes the resource element used for reference signal transmission on antenna port p.

7.6 Downlink Physical Signals

7.6.1 Downlink References Signals

2. MBSFN reference signals

- MBSFN reference signals are only transmitted in the subframe allocated for MBSFN transmission, which is only defined for extended CP and transmitted on antenna port-4.

- In the time domain,
  - For the even numbered slots, the reference symbols are inserted
    - in the 3rd OFDM symbol for $\Delta f = 15\ kHz$
    - In the 2nd OFDM symbol for $\Delta f = 7.5\ kHz$

  - For the odd numbered slots, the reference symbols are inserted
    - in the 1st and 5th OFDM symbol for $\Delta f = 15\ kHz$
    - In the 1st and 3rd OFDM symbol for $\Delta f = 7.5\ kHz$

- In frequency domain, the reference symbols are transmitted every two subcarriers for $\Delta f = 15\ kHz$ and every four subcarriers for $\Delta f = 7.5\ kHz$

- In frequency domain density of MBSFN signals are three times higher than that of cell-specific reference signals.

7.6 Downlink Physical Signals

7.6.1 Downlink References Signals

2. MBSFN reference signals

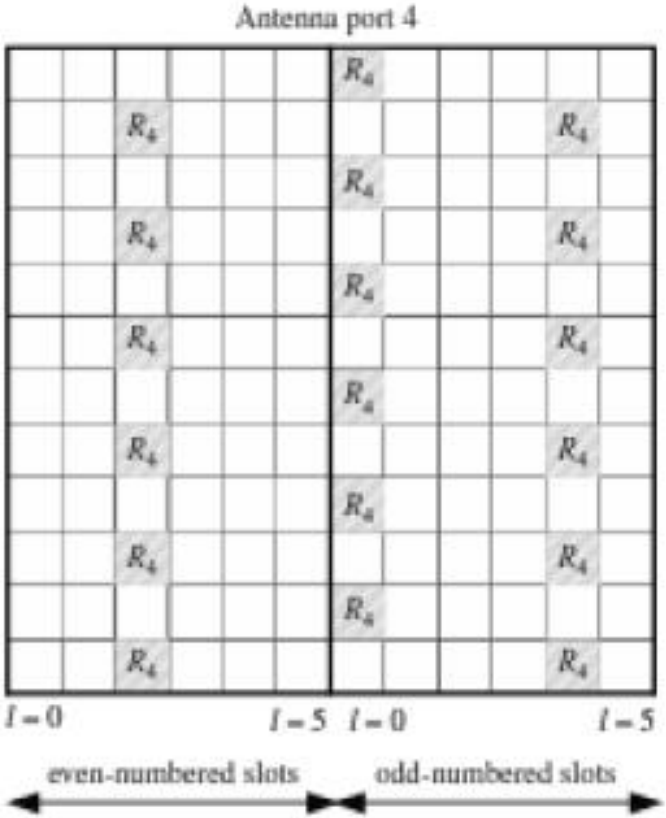


Figure 7.13 An example of mapping of MBSFN reference signals, with the extended CP and $\Delta f = 15\text{kHz}$.

7.6 Downlink Physical Signals

7.6.1 Downlink References Signals

3. UE-specific reference signals

- UE-specific reference signals supports single antenna port transmission with beamforming on PDSCH and are transmitted on antenna port 5.

- They are transmitted only on the resource block upon which the corresponding PDSCH is mapped.

- The UE-specific signals are not transmitted in resource elements in which one of the other physical signal or physical channel is transmitted.

- In the even-numbered slots, the reference symbols are inserted in the 4th and 7th OFDM symbols

- In the odd-numbered slots, the reference symbols are inserted in the 3rd and 6th OFDM symbols

7.6 Downlink Physical Signals

7.6.1 Downlink References Signals

3. UE-specific reference signals

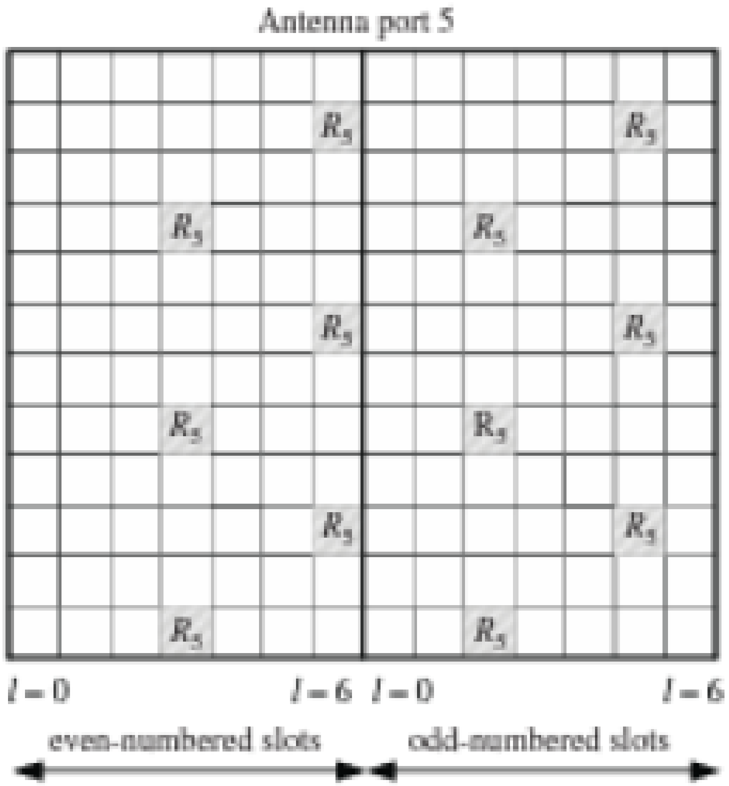


Figure 7.14 An example of mapping of UE-specific signals, with the normal CP.

7.6 Downlink Physical Signals

7.6.2 Synchronization Signals

1. Physical Cell Identity

- The physical cell identity is a number between 0 and 503, which is transmitted on the synchronization signals and used in three ways.

- Firstly, it determines the exact set of resource elements that are used for the cell specific reference signals and the PCFICH.

- Secondly, it influences a downlink transmission process known as scrambling, in a bid to minimize interference between nearby cells.

- Thirdly, it identifies individual cells during RRC procedures such as measurement reporting and handover.

- The physical cell identity is assigned during network planning or self configuration.

- Nearby cells should always receive different physical cell identities, to ensure that each of these roles is properly fulfilled.

7.6 Downlink Physical Signals

7.6.2 Synchronization Signals

1. Physical Cell Identity

- It would be hard for a mobile to find the physical cell identities in one step, so they are organized into *cell identity groups* as follows:

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

- In this equation, N_{ID}^{cell} is the physical cell identity.
- $N_{ID}^{(1)}$ is the cell identity group, which runs from 0 to 167.
- $N_{ID}^{(2)}$ is the cell identity within the group, which runs from 0 to 2.

- Using this arrangement, a network planner can give each nearby base station a different cell identity group, and can distinguish its sectors using the cell identity within the group.

7.6 Downlink Physical Signals

7.6.2 Synchronization Signals

2. Primary and Secondary Synchronization Signals

- Primary synchronization signals identify the symbol timing and cell ID-index $N_{ID}^{(2)}$
- Secondary synchronization signals used for detecting the cell ID-index $N_{ID}^{(1)}$ and the frame timing.
- The signals are both transmitted twice per frame.
- Both signals are transmitted on the 62 subcarriers centered around DC subcarrier, with 5 reserved subcarrier on either side in the frequency domain, so there are total 72 subcarriers occupied by synchronization signals.
- In time domain both signals are transmitted twice per 10 ms in predefined slots.
- For frame structure type-1, both signals are mapped to the last and the 2nd to the last OFDM symbol in slot 0 and 10.
- For frame structure type-2, the primary synchronization signal is mapped to the 3rd OFDM symbol in slot 2 and 12.

7.6 Downlink Physical Signals

7.6.2 Synchronization Signals

2. Primary and Secondary Synchronization Signals

- For frame structure type-2, the secondary synchronization signal is mapped to the last OFDM symbol in slot 1 and 11.

- Difference in the location of synchronization signals enables the UE to detect the duplex mode of the cell.

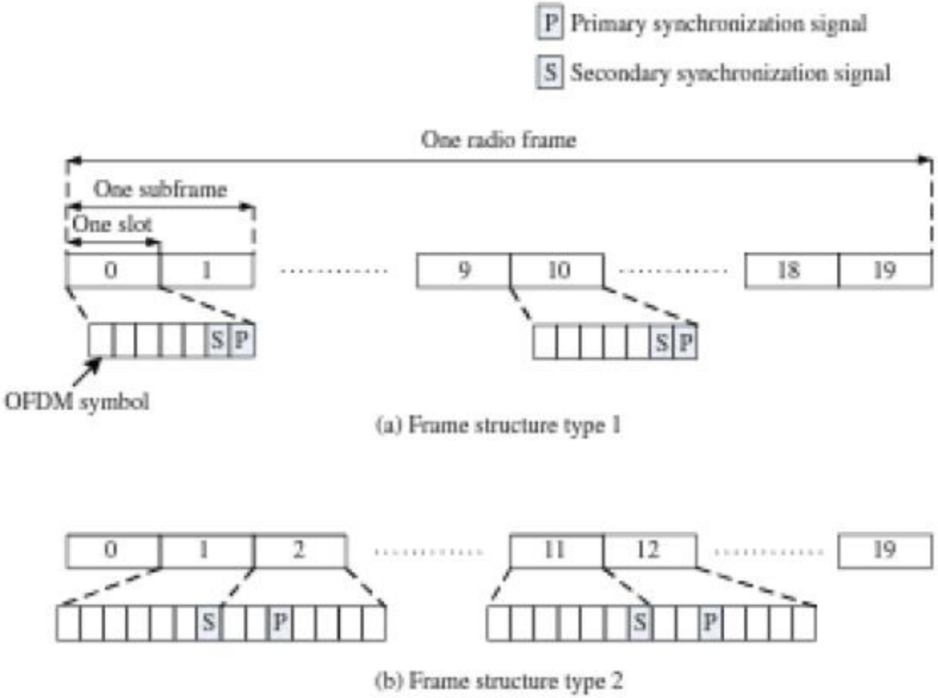


Figure 7.15 The mapping of primary and secondary synchronization signals to OFDM symbols for frame structure type 1 and type 2, with the normal CP. 'P' and 'S' denote primary and secondary synchronization signals, respectively.

7.7 H-ARQ in downlink

- Home work.

15EC81

Wireless Cellular and LTE 4G Broadband
Module - 4

Robin Singla
Assistant Prof.
Dept. of ECE
BMSIT

Syllabus:-
Module – 4

Uplink Channel Transport Processing: Overview, Uplink shared channels, Uplink Control Information, Uplink Reference signals, Random Access Channels, H-ARQ on uplink (Sec 8.1 – 8.6 of Text).

Physical Layer Procedures: Hybrid – ARQ procedures, Channel Quality Indicator CQI feedback, Precoder 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(Sec 9.1- 9.6, 9.8, 9.9, 9.10 of Text).

8.1 Uplink Transport Channel Processing Overview

- Transport channel processing is divides into two distinct steps, channel coding and modulation.

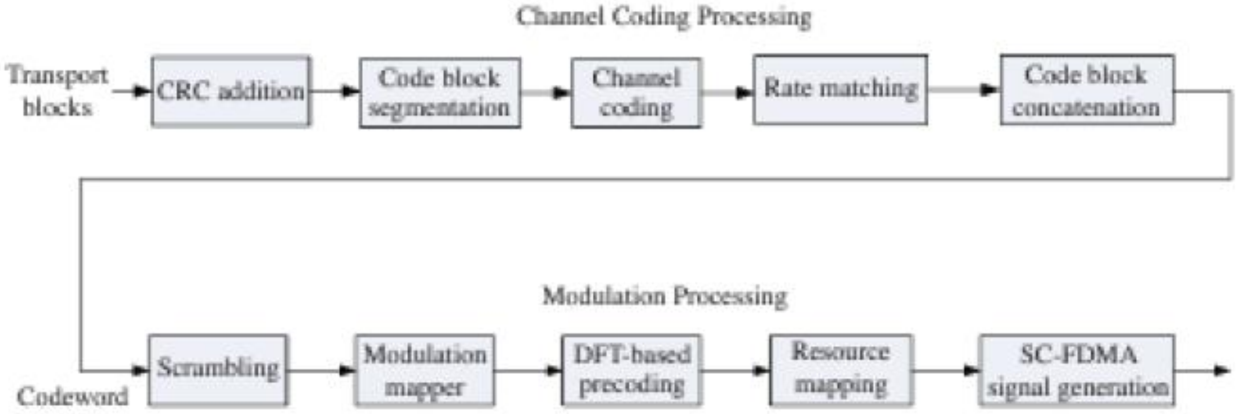


Figure 8.1 Overview of uplink transport channel processing.

uplink

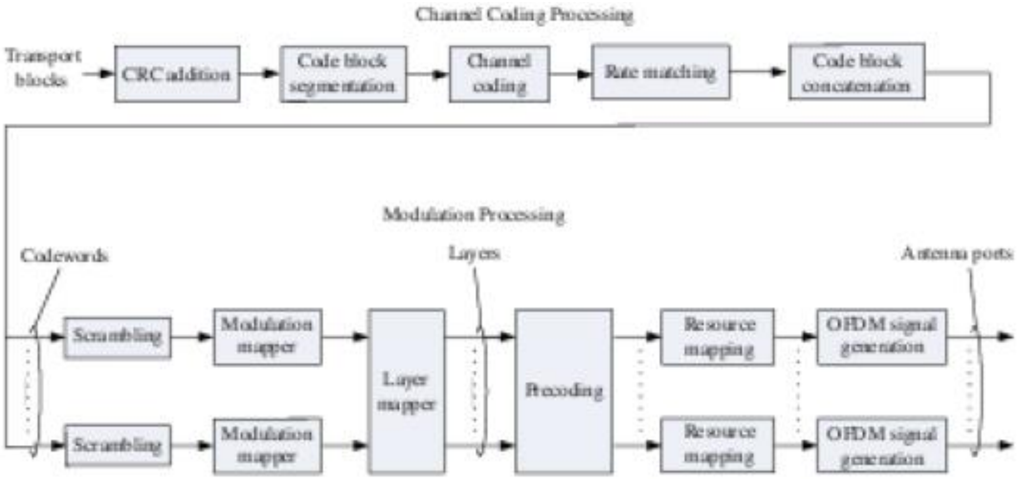


Figure 7.1 Overview of downlink transport channel processing.

downlink

8.1 Uplink Transport Channel Processing Overview

8.1.1 Channel Coding Processing

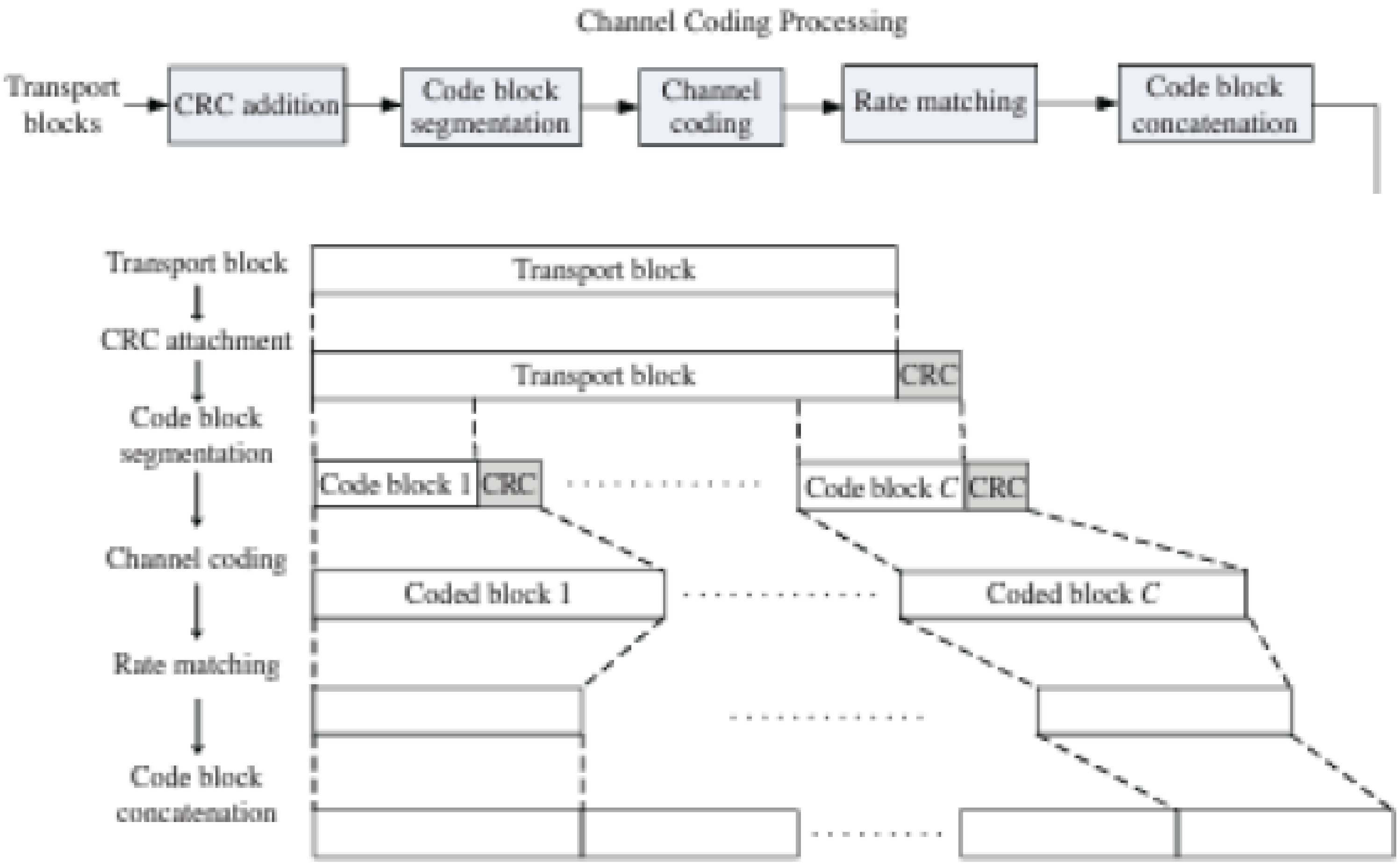


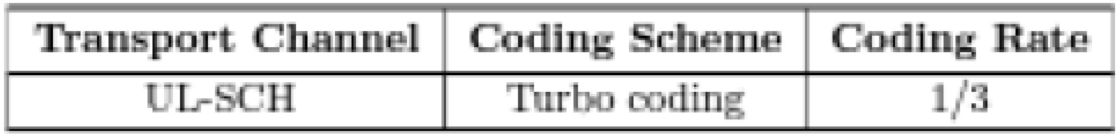
Figure 7.2 Channel coding processing.

8.1 Uplink Transport Channel Processing Overview

8.1.1 Channel Coding Processing

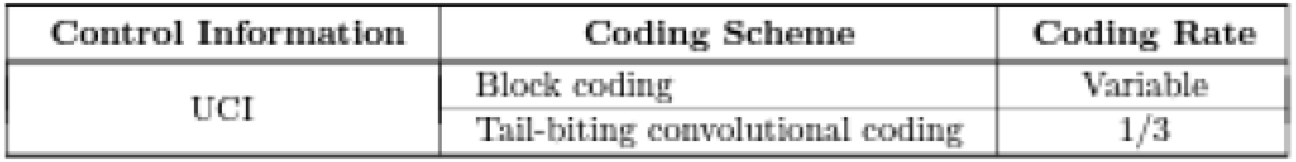

Channel Coding Processing

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

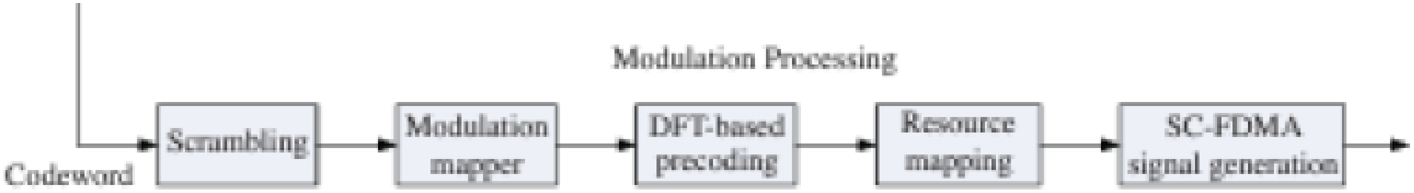
Table 8.2 Usage of Channel Coding Scheme and Coding Rate for Uplink Control Information



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

8.1 Uplink Transport Channel Processing Overview

8.1.2 Modulation Processing



- In uplink UE specific scrambling is applied is applied in order to randomize the interface.
- spatial multiplexing is not supported in the uplink there is no layer mapping or MIMO precoding.

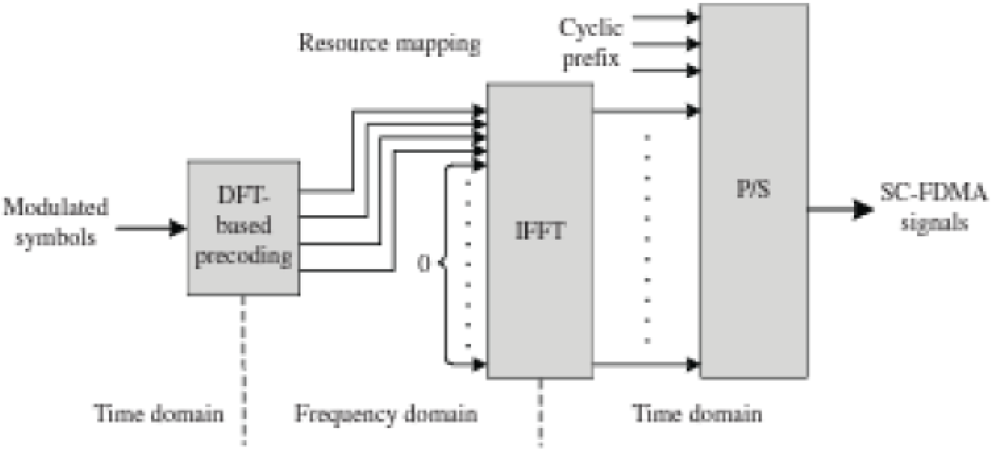


Figure 8.2 Generation of SC-FDMA baseband signals, where P/S denotes the parallel-to-serial converter.

8.2 Uplink Shared Channels

- In uplink UL-SCH is the only transport channel that carries traffic data.
- It can also be used to transfer control signals for higher layers.

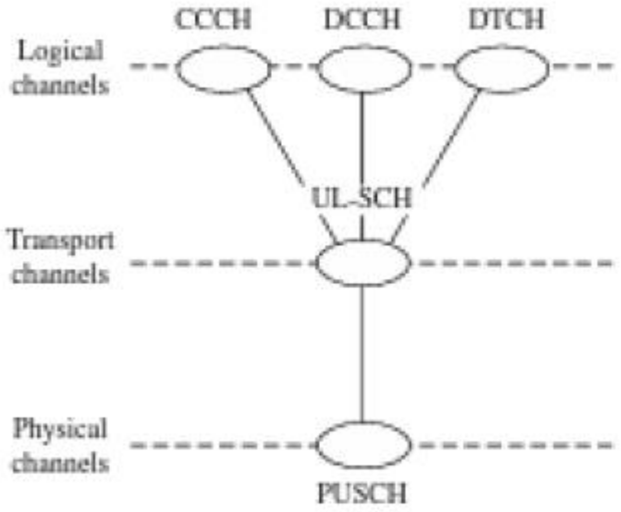


Figure 8.3 Channel mapping around the uplink shared channel.

8.2 Uplink Shared Channels

8.2.2 Channel Coding and Modulation Processing

- Rate 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 size block, the modulation scheme and the assigned radio resource.
- Encoded symbols are scrambled prior to modulation, which is done to randomize the interference.
- Instead of using cell-specific scrambling as in downlink, a UE-specific scrambling is applied.
- UL-SCH is mapped to PUSCH , which supports QPSK, 16QAM and 64QAM modulation scheme.
- The QPSK and 16QAM modulation scheme are mandatory and support for 64QAM is optional and depends upon UE capability.

8.2 Uplink Shared Channels

8.2.2 Channel Coding and Modulation Processing

- The modulation order and the redundancy version for the channel coding of H-ARQ protocol are contained in the 5-bit “modulation and coding scheme and redundancy version” field (I_{MCS}) in the downlink control information (DCI) carried on PDCCH with format 0.

8.2 Uplink Shared Channels

8.2.3 Frequency Hopping

- LTE supports frequency hopping on PUSCH, which provides additional frequency diversity gain in the uplink.

- Frequency hopping can also provide the interference averaging when system is not 100% loaded.

- In LTE both intra-subframe and inter-subframe frequency hopping is supported

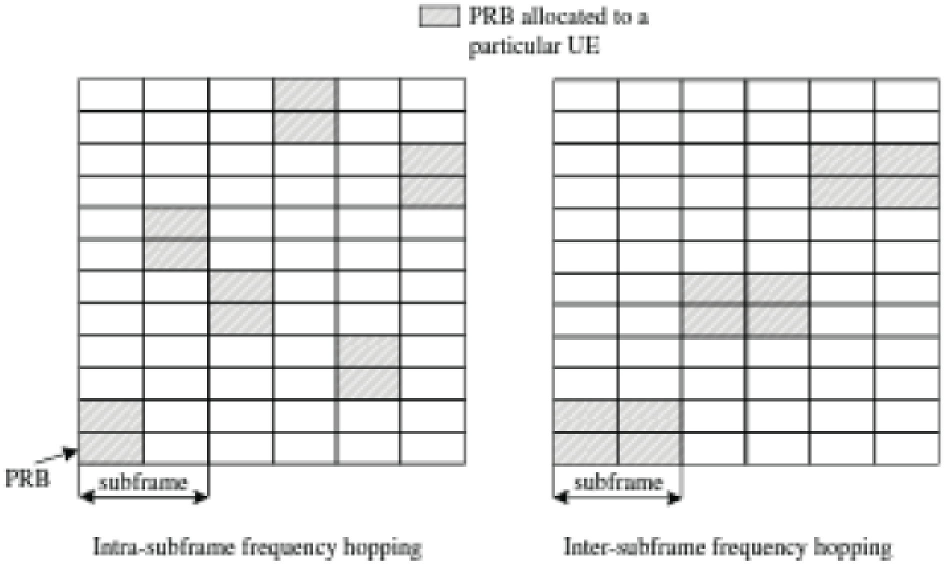


Figure 8.4 Illustrations of frequency hopping on PUSCH.

8.2 Uplink Shared Channels

8.2.3 Frequency Hopping

- If the 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 , otherwise no frequency hopping is performed.

  - **No frequency hopping –** if uplink frequency hopping is disabled (FH=0), the set of physical resource block is to be used for transmission is given by $n_{prb} = nvrb$ where n_{vrb} is the virtual resource block index obtained from the uplink scheduling grant.

  - **Frequency hopping-** if uplink frequency hopping is enabled (FH=1), there are two frequency hopping types. *Type-1 hopping* uses and explicit offset in the second slot, determined by parameters in the DCI format 0. In *type-2 hopping* the set of physical resource blocks to be used for transmission is given by the scheduling grant together with a predefined hopping pattern.

- The UE first determined the allocated resource blocks after applying all the frequency hopping rules, and then data is mapped onto these resources.

8.2 Uplink Shared Channels

8.2.4 Multiantenna Transmission

- Considering cost and complexity of UE, LTE only supports a limited number of multiantenna transmission scheme in uplink:
  a) Transmit antenna selection
  b) Multiuser MIMO (MU-MIMO)

- **Transmit antenna selection** – with two or more antenna at the UE, transmit antenna selection can be applied, which is able to provide spatial diversity gain. Multiantenna transmission at the UE depends upon the signaling from the higher layers.
  - **No antenna selection** – if transmit antenna selection is disabled or not supported by UE, the UE shall transmit from transmission port 0.
  - **Closed loop (CL) antenna transmission**
  - **Open loop (OL) antenna transmission**

- **MU-MIMO in uplink** – also referred to as virtual MIMO transmission.
  - Two UEs transmit simultaneously on the same radio resource, forming a virtual MIMO channel and e-NodeB separate the data for each UE, e.g. using multiuser detection.
  - This technique provides a spatial multiplexing gain to increase the uplink spectrum efficiency, even with single antenna UEs.

8.3 Uplink Control Information (*UCI)*

- UCI is to assist physical layer procedures by providing the following types of physical layer control information:
  - Downlink CQI, which is used to assist the adaptive modulation and coding and the channel dependent scheduling of the downlink transmission. The CQI indicates the highest modulation and coding rate that can be supported in the downlink with a 10% block error rate on the first H-ARQ transmission.
  - H-ARQ acknowledgement (H-ARQ-ACK) associated with downlink H-ARQ process.
  - Scheduling request (SR) to request radio resource for uplink transmission.
  - Precoding Matrix Indicator (PMI) and Rank Indictor (RI) for downlink MIMO transmission. RI indicates the maximum number of layer that can be used for spatial multiplexing in downlink, while PMI indicates the preferred precoding matrix.

8.3 Uplink Control Information (*UCI*)

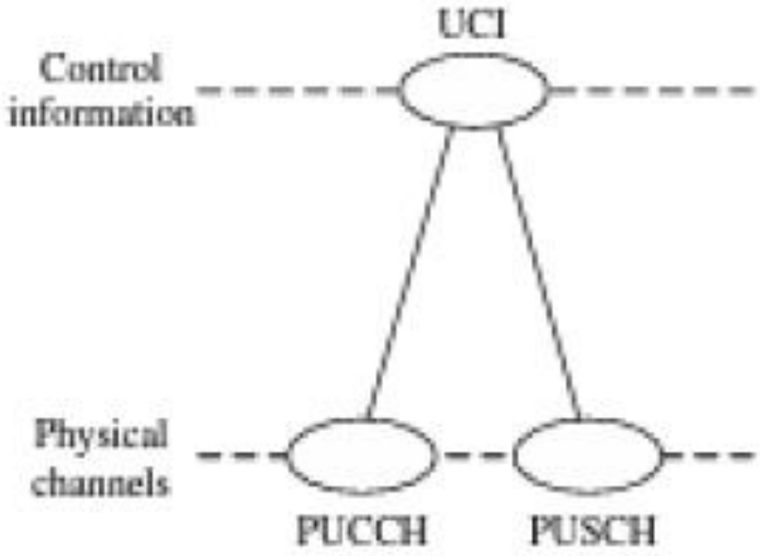


Figure 8.5 Channel mapping for control information in the uplink.

8.3 Uplink Control Information (*UCI)*

8.3.1 Channel Coding for Uplink Control Information

UCI on PUCCH

When the UCI is transmitted on PUCCH, three channel coding scenarios are considered:

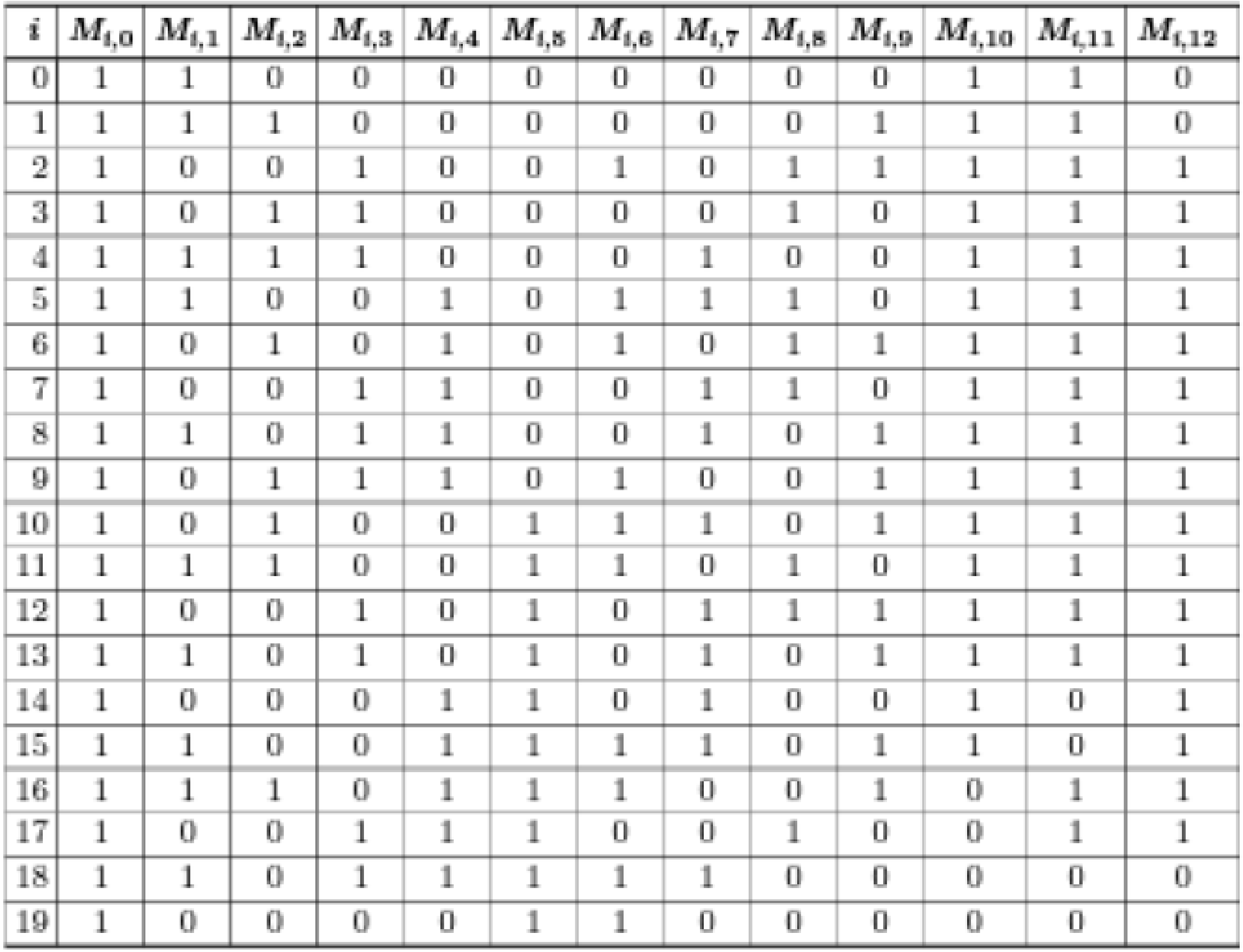
1. The UCI contains CQI/PMI but not H-ARQ-ACK
2. The UCI contains H-ARQ-ACK and/or RI but not CQI/PMI
3. The UCI contains both CQI/PMI and H-ARQ-ACK

- The channel coding processing for each of these scenarios is explained in the following:

  - **Encoding CQI/PMI** – the CQI/PMI is encoded using a (20, N_{CQI}) code, with codewords being a linear combination of 13 basis sequence that are defined in table (next slide). N_{CQI} is the number of CQI and PMI bits.

8.3.1 Channel Coding for Uplink Control Information

Table 8.3 Basis Sequences for (20, N) Code



i	$M_{i,0}$	$M_{i,1}$	$M_{i,2}$	$M_{i,3}$	$M_{i,4}$	$M_{i,5}$	$M_{i,6}$	$M_{i,7}$	$M_{i,8}$	$M_{i,9}$	$M_{i,10}$	$M_{i,11}$	$M_{i,12}$
0	1	1	0	0	0	0	0	0	0	0	1	1	0
1	1	1	1	0	0	0	0	0	0	1	1	1	0
2	1	0	0	1	0	0	1	0	1	1	1	1	1
3	1	0	1	1	0	0	0	0	1	0	1	1	1
4	1	1	1	1	0	0	0	1	0	0	1	1	1
5	1	1	0	0	1	0	1	1	1	0	1	1	1
6	1	0	1	0	1	0	1	0	1	1	1	1	1
7	1	0	0	1	1	0	0	1	1	0	1	1	1
8	1	1	0	1	1	0	0	1	0	1	1	1	1
9	1	0	1	1	1	0	1	0	0	1	1	1	1
10	1	0	1	0	0	1	1	1	0	1	1	1	1
11	1	1	1	0	0	1	1	0	1	0	1	1	1
12	1	0	0	1	0	1	0	1	1	1	1	1	1
13	1	1	0	1	0	1	0	1	0	1	1	1	1
14	1	0	0	0	1	1	0	1	0	0	1	0	1
15	1	1	0	0	1	1	1	1	0	1	1	0	1
16	1	1	1	0	1	1	1	0	0	1	0	1	1
17	1	0	0	1	1	1	0	0	1	0	0	1	1
18	1	1	0	1	1	1	1	1	0	0	0	0	0
19	1	0	0	0	0	1	1	0	0	0	0	0	0

8.3 Uplink Control Information (*UCI)*

8.3.1 Channel Coding for Uplink Control Information

UCI on PUCCH

- **Encoding H-ARQ-ACK and SR** –
  - the H-ARQ-ACK bits and SR indication are received from higher layers.
  - For positive acknowledgment (ACK) it is encoded as a binary '1' while each negative acknowledgment (NAK) is encoded as a binary '0'.
  - There is one H-ARQ-ACK bit for single-codeword transmission and two H-ARQ-ACK bit for two-codeword transmission (spatial multiplexing).

- **Encoding CQI/PMI + H-ARQ-ACK –**
  - with the normal CP, the CQI/PMI is encoded using the (20, N_{CQI}) code and then the H-ARQ-ACK bits are added at the end of the resulting codeword.
  - with the extended CP, the CQI/PMI + H-ARQ-ACK are jointly encoded using the same (20,N) code as that of encoding CQI/PMI alone, N as the sum of CQI/PMI bits and H-ARQ-ACK bits.

8.3 Uplink Control Information (*UCI)*

8.3.1 Channel Coding for Uplink Control Information

UCI on PUCCH

Based on the different types of control information carried on PUUCH there are 6 six different PUCCH formats defined in LTE, as shown in table below.

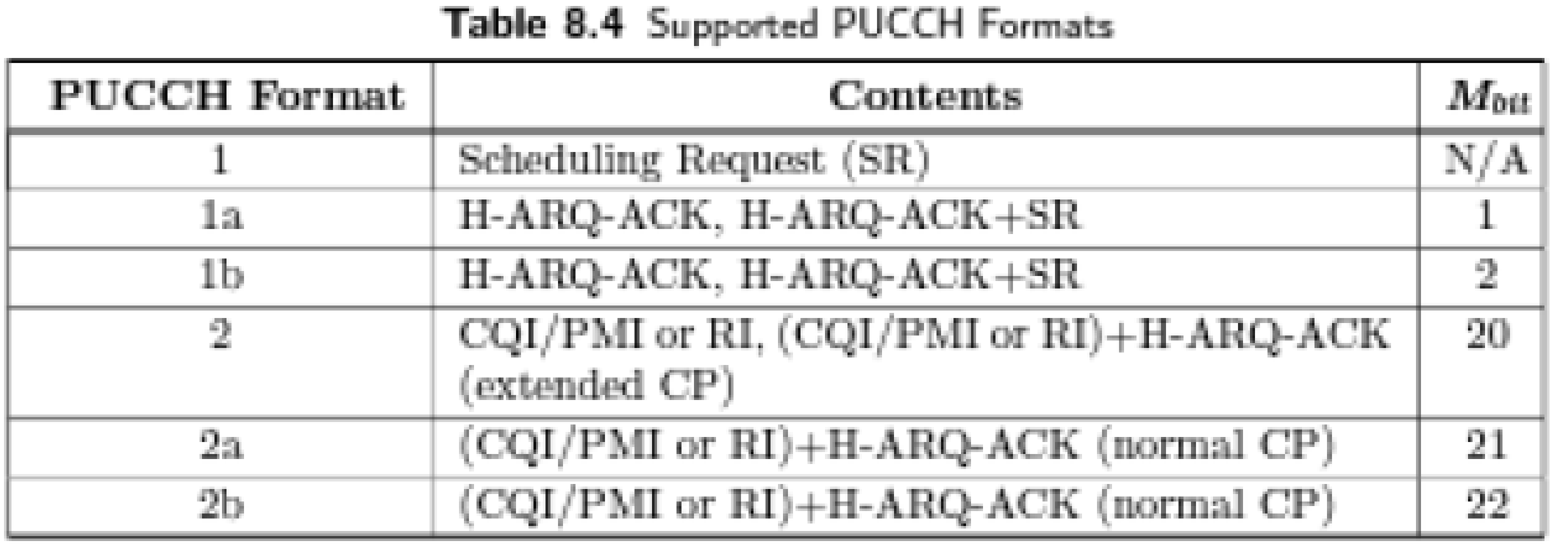


Table 8.4 Supported PUCCH Formats

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

8.3 Uplink Control Information (*UCI)*

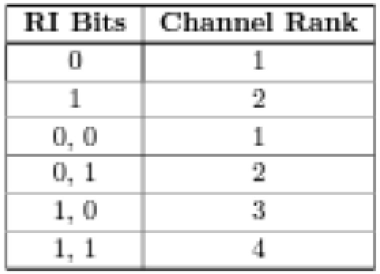
8.3.1 Channel Coding for Uplink Control Information

UCI on PUSCH with UL-SCH Data

If there is uplink radio resource assigned to UE, the UCI can be multiplexed with the UL-SCH data on the PUSCH channel and there is no need to send SR.

- **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, wit different information bits:
    - ACK/NAK bundling, which consists of one or two bits information.
    - ACK/NAK multiplexing, which consists of between one or four bits of information.
- **Coding of RI** – the mapping between the RI bits and the channel rank is shown in table below. Denoted by N_{RI} as the number of RI bits.

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

8.3 Uplink Control Information (*UCI)*

8.3.1 Channel Coding for Uplink Control Information

UCI on PUSCH with UL-SCH Data

- **Coding for CQI/PMI** – the coding scheme for CQI/PMI depends upon the total number of CQI and PMI bits
    - If the payload size N_{CQI} is less than or equal to 11 bits, the CQI/PMI bits are first encoded using a $(32,N_{CQI})$ block code, with the codeword as a linear combination of 11 length-32 basis sequences.
    - If $N_{CQI} > 11$, first a CRC is added, and then the tail-bitting convolutional code with 1/3 is used as the coding scheme.

8.3 Uplink Control Information (*UCI)*

8.3.1 Channel Coding for Uplink Control Information

UCI on PUSCH with UL-SCH Data

After channel encoding, the CQI encoded scheme is multiplexed with the UL-SCH data, the output of which is interleaved with the RI and H-ARQ-ACK encoded sequence as shown in figure below.

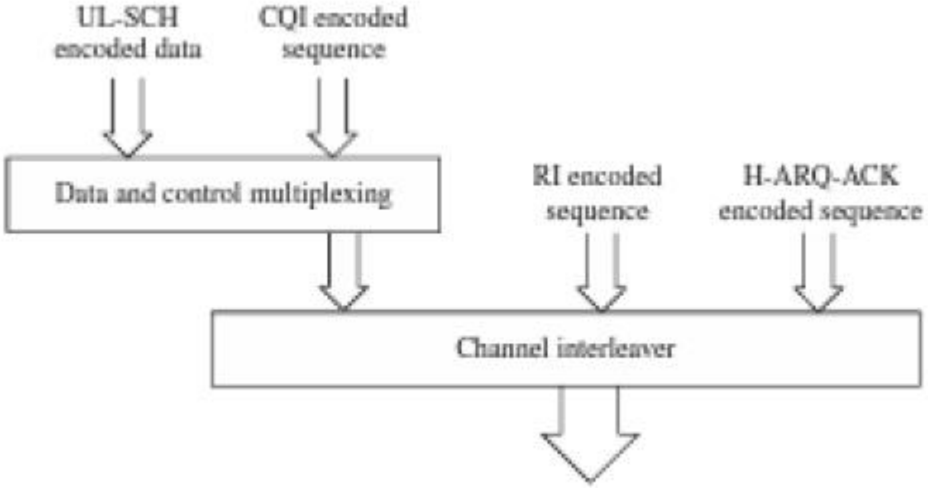


Figure 8.6 Multiplexing of data and control information on the PUSCH channel.

8.3 Uplink Control Information (*UCI)*

8.3.1 Channel Coding for Uplink Control Information

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 sequence is interleaved.

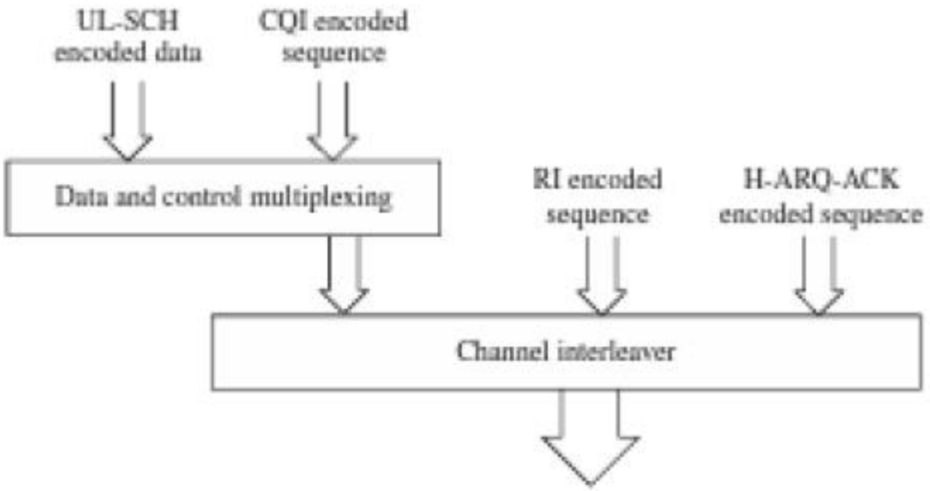


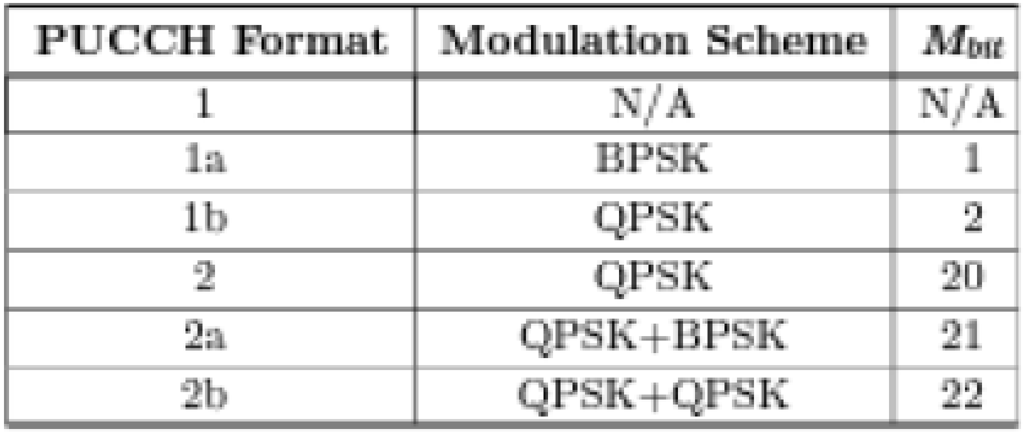
Figure 8.6 Multiplexing of data and control information on the PUSCH channel.

8.3 Uplink Control Information (*UCI)*

8.3.2 Modulation of PUCCH

- When UCI is transmitted on PUSCH, the modulation scheme is determined by the scheduler in the MAC layer.
- When UCI is transmitted on PUCCH, then no uplink resource is assigned to the UE.
- The modulation scheme and different numbers of bits per subframe for different PUCCH formats are specified in this table.

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

8.3 Uplink Control Information (*UCI)*

8.3.2 Modulation of PUCCH

- All PUCCH formats use 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 CDM.

8.3 Uplink Control Information (*UCI)*

8.3.3 Resource Mapping

- The PUCCH is never transmitted with the PUSCH from the same UE, i.e. PUCCH is time division multiplexed with the PUSCH from the same UE. This is done in order to retain single carrier frequency of SC-FDMA

- However, PUCCH can be frequency division multiplexed with PUSCH from other UEs in the same subframe.

- The PUCCH used one resource block in each of two slots in a subframe.

8.3 Uplink Control Information (*UCI)*

8.3.3 Resource Mapping

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

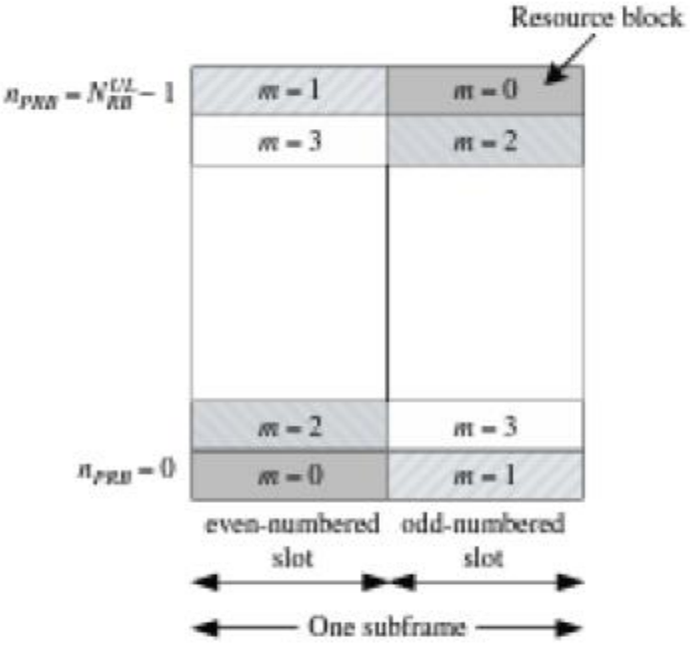


Figure 8.7 Mapping to physical resource blocks for PUCCH.

8.4 Uplink Reference Signals

In LTE there are two types of reference signals defined in the UPLINK:

1. Demodulation reference signals:
   - transmitted on the uplink resource assigned to UE, are for coherent demodulation of data and control information at the e-NodeB.
   - As PUCCH can not be transmitted simultaneously with PUSCH, there are demodulation reference signals defined for them.
2. Sounding Reference Signals:
   - These are the wideband reference signals for the e-NodeB to measure uplink channel quality information for uplink resource allocation.
   - They are not associated with transmission of PUCCH and PUSCH.

The reason for having two types of reference signals in uplink is because, unlike the downlink, the demodulation reference signals can be transmitted only on subcarriers assigned to UE and therefore can not provide the wideband channel quality information for resource allocation, particularly over the resource blocks that are not allocated to UE.

8.4 Uplink Reference Signals

- Unlike downlink , the reference signals in uplink can not be transmitted at the same time as user data.

- Instead the uplink reference signals are time division multiplexed with the uplink data on the same subcarrier.

- In this way the power level of the reference signals can be different from that of data symbols as they are transmitted over different SC-FDMA symbols so the PAPR is minimized over each SC-FDMA symbol.

8.4 Uplink Reference Signals

8.4.1 Reference Signals Sequence

- Both the demodulation and sounding reference signals are defined by the cyclic shift of the same sequence.

- The generation of the base sequence depends upon the reference signal sequence length, which is

$$M_{sc}^{RS} = mN_{sc}^{RB} \text{ with } 1 \le m \le N_{RB}^{max,UL}$$

where m is the size of the resource blocks assigned to the UE.

I. If $m \ge 3$ (the UE is assigned three resource blocks or more), the base sequence is based on prime-length Zadoff-Chu sequence that are cyclically extended to the desired length.

II. For $m = 1 \; or \; m = 2$, the base station is of form $e^{j\varphi(n)\pi/4}$, where $0 \le n \le M_{sc}^{RS} - 1$.

8.4 Uplink Reference Signals

8.4.1 Reference Signals Sequence

- Multiple reference signals can then be created by different shift of same base sequence.

- As the Zadoff-Chu sequence has the property that cyclic shifted versions of the same sequence are orthogonal to each other, generating reference signals in such a manner can reduce inter-cell interference for the reference signal transmission.

- The orthogonality of reference signals with in the same cell is obtained via FDM.

- Reference signals in UE are always UE specific.

8.4 Uplink Reference Signals

8.4.2 Resource Mapping of the Demodulation Reference Signals

For PUSCH, the demodulation reference signals sequence is mapped to resource element (k, l), with $l = 3$ for normal CP and $l = 2$ for extended CP, with increasing order first in k and then in slot number.

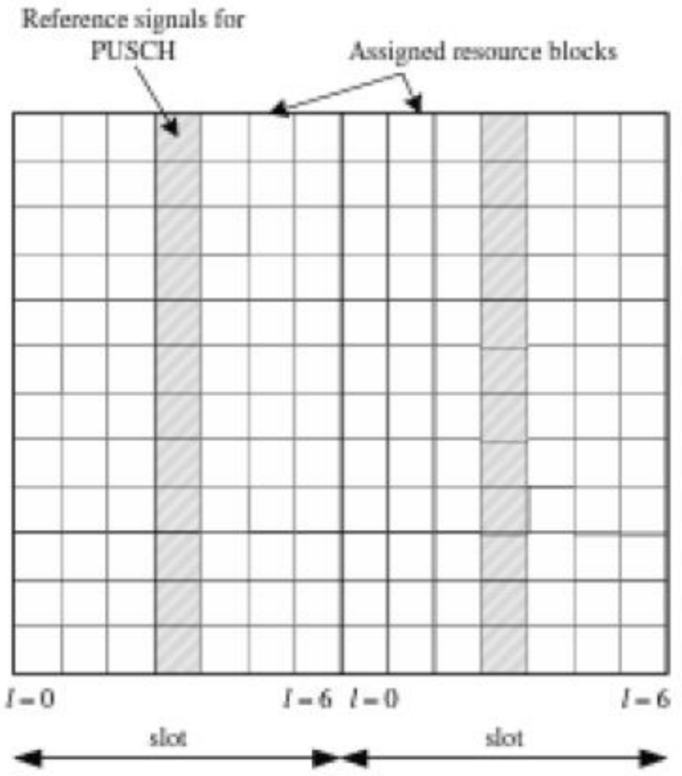


Figure 8.8 Resource mapping of demodulation reference signals for PUSCH with the normal CP.

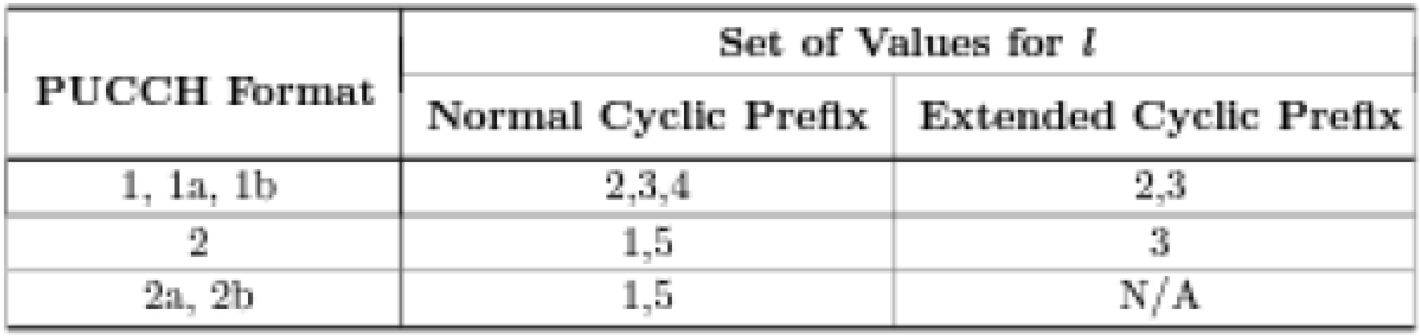
8.4 Uplink Reference Signals

8.4.2 Resource Mapping of the Demodulation Reference Signals

PUCCH supports six different formats and the resource mapping for SC-FDMA symbols are for different format is listed in the table below.

The number of PUCCH demodulation reference symbols are different for different formats, which is related to the number of control symbols in each format.

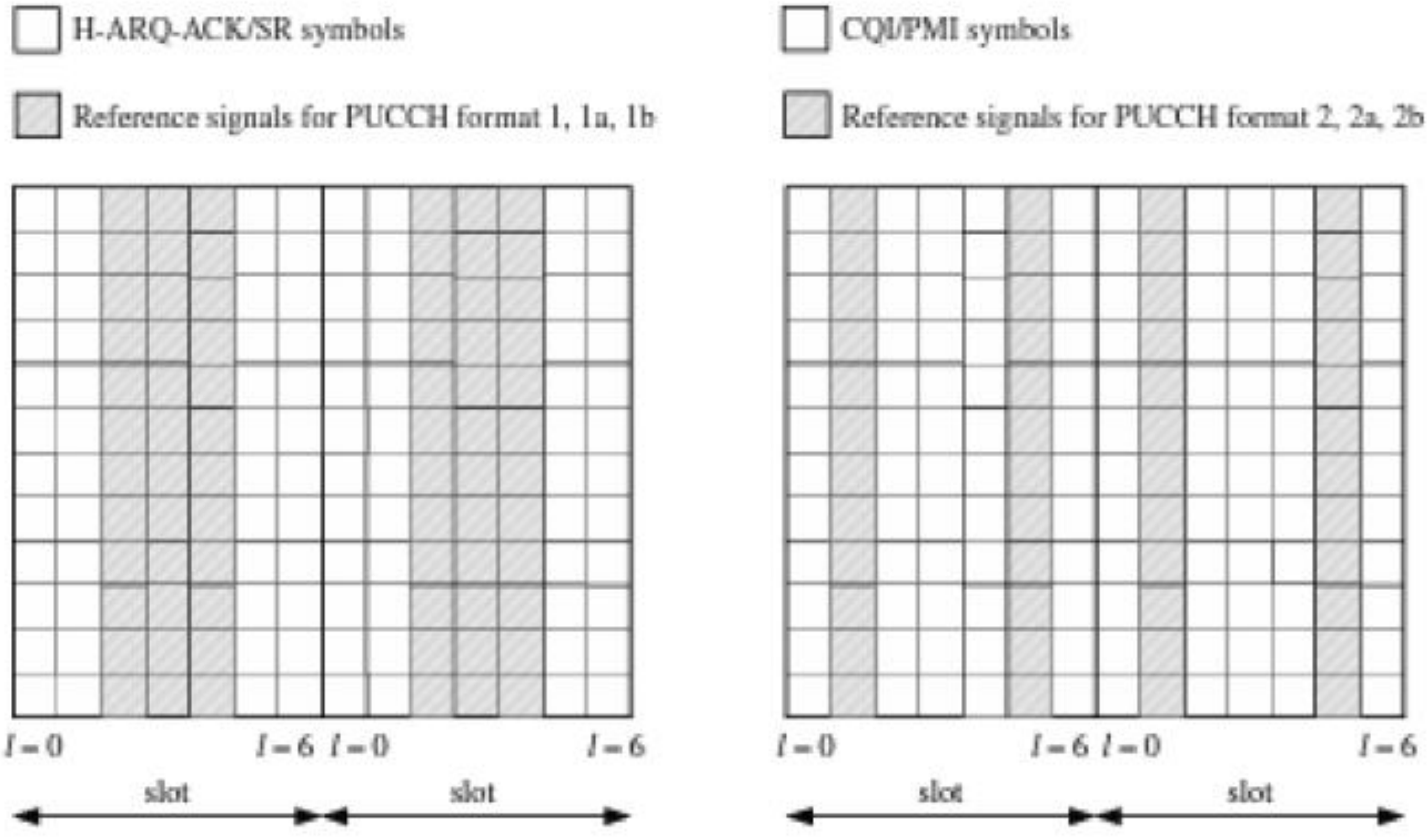
Table 8.9 Demodulation Reference Signal Location for Different PUCCH Formats



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

8.4 Uplink Reference Signals

8.4.2 Resource Mapping of the Demodulation Reference Signals



(a) PUCCH format 1, 1a, 1b

(b) PUCCH format 2, 2a, 2b

Figure 8.9 Resource mapping of demodulation reference signals for PUCCH with the normal CP.

8.4 Uplink Reference Signals

8.4.3 Resource Mapping of the Sounding Reference Signals

- For FDD mode the sounding reference signal is transmitted in the last SC-FDMA symbol in the specific subframe.

- For TDD mode the sounding reference signal is transmitted only in the configured uplink subframe or the UpPTS field in the special subframe.

- The subframes in which sounding reference signals are transmitted are indicated by broadcast signaling and there are 15 different signaling.

8.4 Uplink Reference Signals

8.4.3 Resource Mapping of the Sounding Reference Signals

- In the frequency domain, the mapping starts from the position k_0, which is determined by system parameters and filled every other subcarrier.

- By allocating every other subcarrier to a UE for sounding reference signal, the system allows two UEs to use the same resource for sounding reference signals.

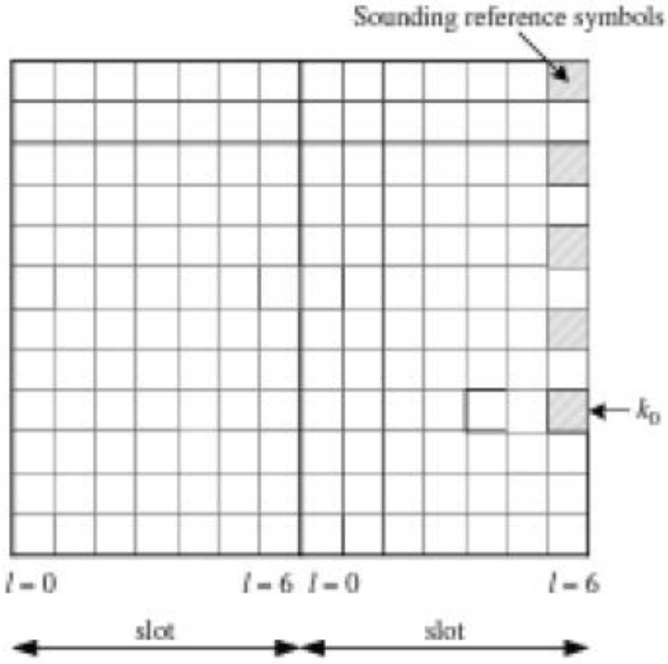


Figure 8.10 An example of resource mapping of sounding reference signals, with the normal CP.

8.5 Random Access Channels

- The uplink random access procedure is used during initial access or to re-establish the uplink synchronization.

- Random access preamble consists of a CP of length T_{CP} and a sequence part of length T_{SEQ}.

- A Guard Time (GT) is also needed to account for round trip propagation delay between the UE and the e-NodeB.

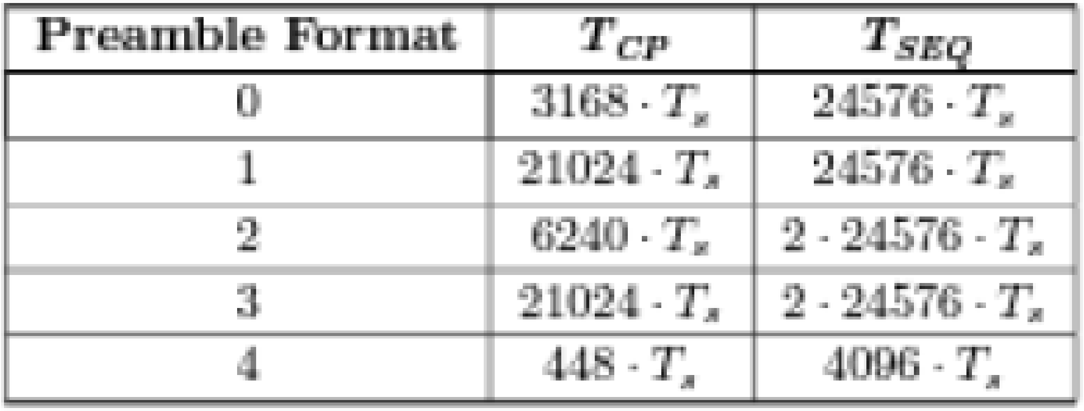
- The values of T_{CP} and T_{SEQ} depends upon cell size and base station implementation.

Figure 8.11 The random access preamble format.

8.5 Random Access Channels

- There are five different preamble formats defined in LTE, shown in table below. Where $Ts = 1/(15000 \times 2048)$ sec.
  - Format 0 is for normal cells
  - Format 1, also known as extended format, is used for large cells
  - Format 2 and 3 use repeated preamble sequences to compensate for increased path loss and are used for small cells and large cells respectively.
  - Format 4 is defined only for frame structure type-2.

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	$448 \cdot T_s$	$4096 \cdot T_s$

8.5 Random Access Channels

- Random access preamble also generated from Zadoff-Chu sequence, which is similar to the reference signals.

- The network configures the set of preamble sequence that a UE is allowed to use.

- In each cell, there are 64 available preamble, which are generated from one or several root Zadoff-Chu sequences.

- Due to zero cross-correlation between different cyclic shift of same Zadoff-Chu sequence, there is no intra-cell interference from multiple random access attempts using different preamble in the same cell.

- The transmission of random access preamble is restricted to certain time and frequency resources.

- The PRACH resources within a radio frame are indicated by a PRACH configuration index, which is given by higher layers.

8.5 Random Access Channels

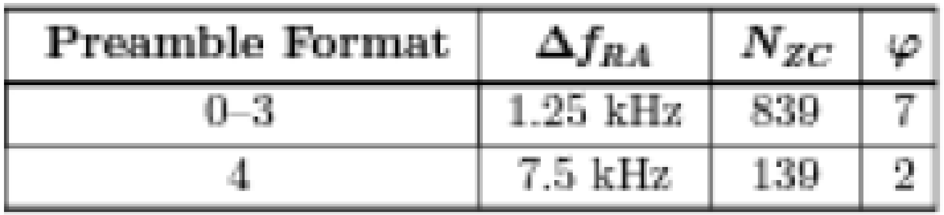
- For frame structure type-1 with preamble format 0-3, there is at most one random access resource per subframe.

- For frame structure type-2 with preamble format 0-4, there might be multiple random access resource in an uplink subframe depending upon the uplink/downlink configuration.

- In 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 use a different subcarrier spacing (Δf_{RA}) than other physical channels.

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

8.5 Random Access Channels

- The data symbol subcarrier spacing, $\Delta f = 15\,kHz$, is an integer multiple of PRACH subcarrier spacing ΔfRA.

- This is to minimize the orthogonality loss in the frequency domain and can also reuse the IFFT/FFT component.

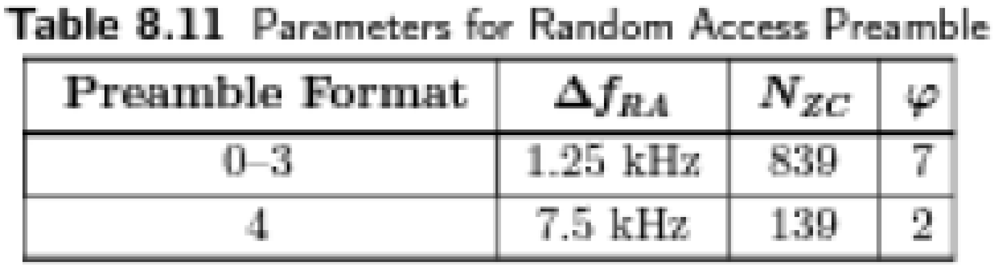


Table 8.11 Parameters for Random Access Preamble

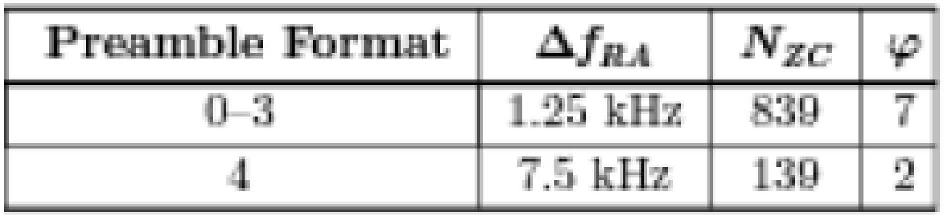
Preamble Format	Δf_{RA}	N_{ZC}	φ
0–3	1.25 kHz	839	7
4	7.5 kHz	139	2

8.5 Random Access Channels

- The data symbol subcarrier spacing, $\Delta f = 15\,kHz$, is an integer multiple of PRACH subcarrier spacing $\Delta f RA$.

- This is to minimize the orthogonality loss in the frequency domain and can also reuse the IFFT/FFT component.

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

8.6 H-ARQ in UPLINK

- As in downlink the H-ARQ retransmission protocol is also used in LTE uplink, so the eNode-B has the capability to request retransmission of incorrectly received data packets.

- For uplink H-ARQ process, the corresponding ACK/NAK information is carried on PHICH.

- There are two types of H-ARQ operation in uplink: the non-subframe bundling operation (normal H-ARQ) operation and the subframe bundling operation (also called TTI bundling), in which four redundancy version are transmitted over four consecutive uplink subframes.

8.6 H-ARQ in UPLINK

8.6.1 FDD mode

- For FDD mode
  - there are 8 parallel H-ARQ processes in the uplink for the non-subframe bundling operation,
  - and 4 H-ARQ process for the subframe bundling operation

.

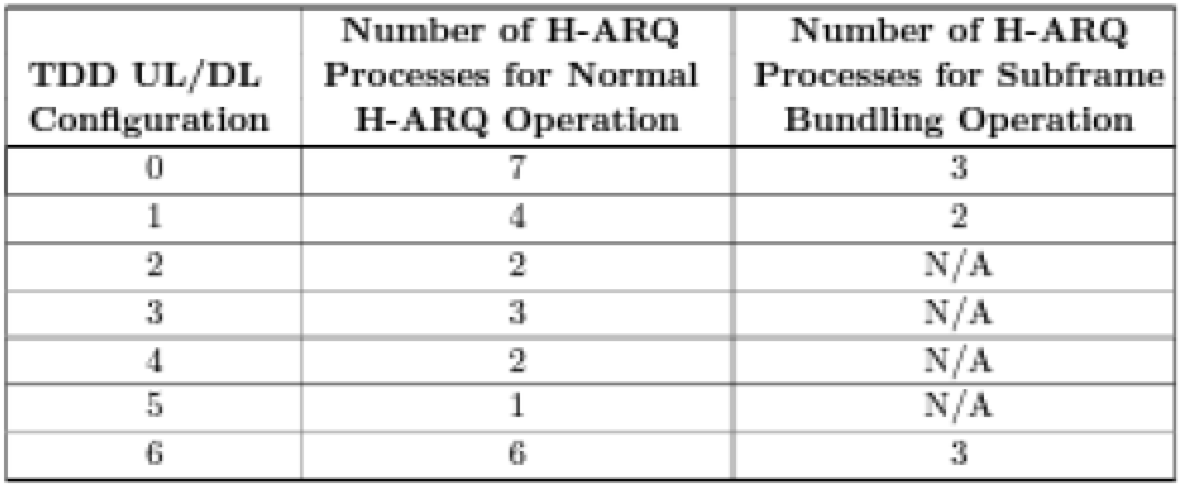
- With normal H-ARQ operation, upon detection of a NAK in subframe n, the UE retransmit the corresponding PUSCH in subframe n+4.

- With subframe bundling operation, upon detection of a NAK in subframe n-5, the UE retransmit the corresponding first PUSCH transmission in the bundle in subframe n+4.

8.6 H-ARQ in UPLINK

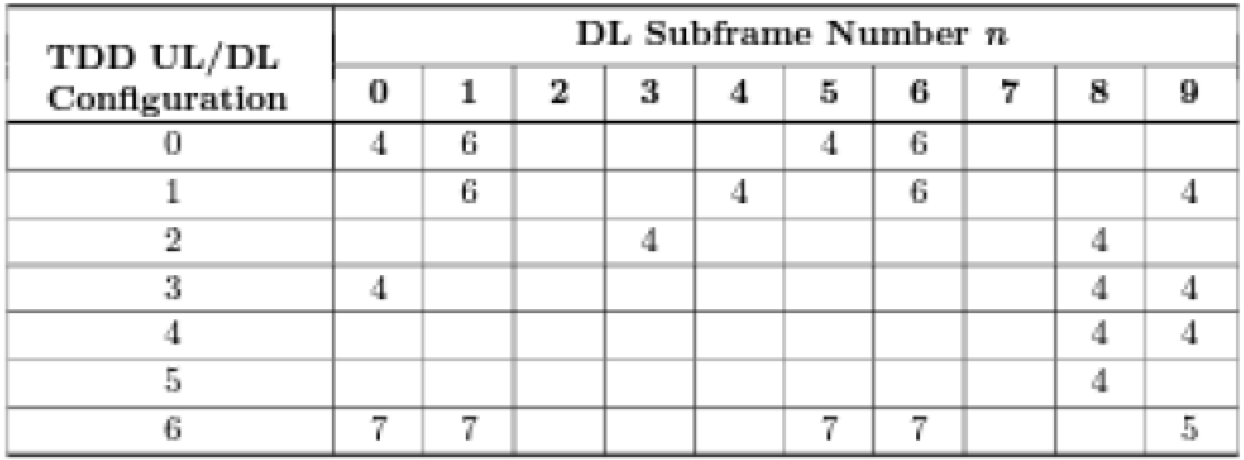
8.6.2 TDD mode

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

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

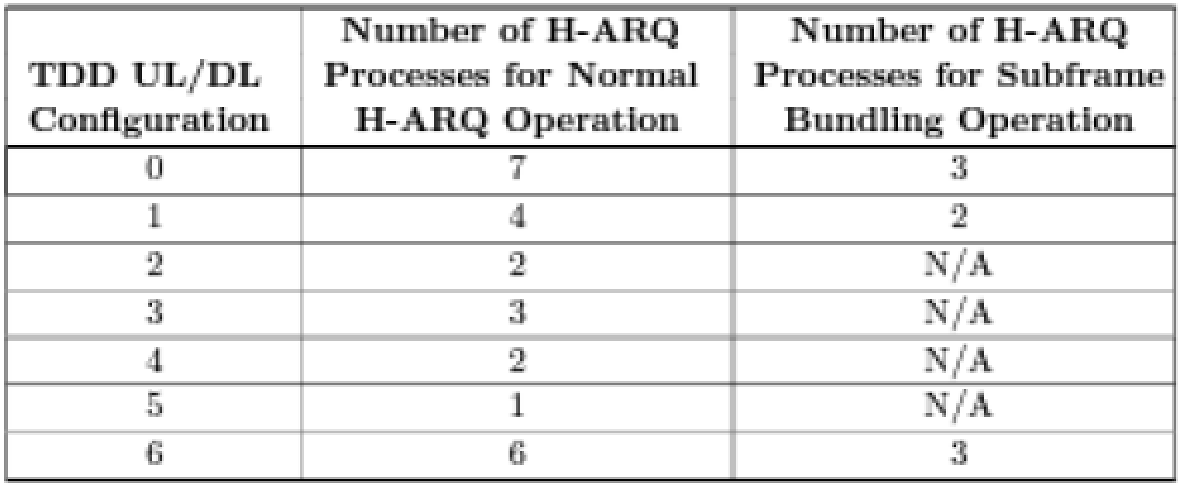


TDD UL/DL Configuration	DL Subframe Number n									
	0	1	2	3	4	5	6	7	8	9
0	4	6				4	6			
1		6			4		6			4
2				4					4	
3	4								4	4
4									4	4
5									4	
6	7	7				7	7			5

8.6 H-ARQ in UPLINK

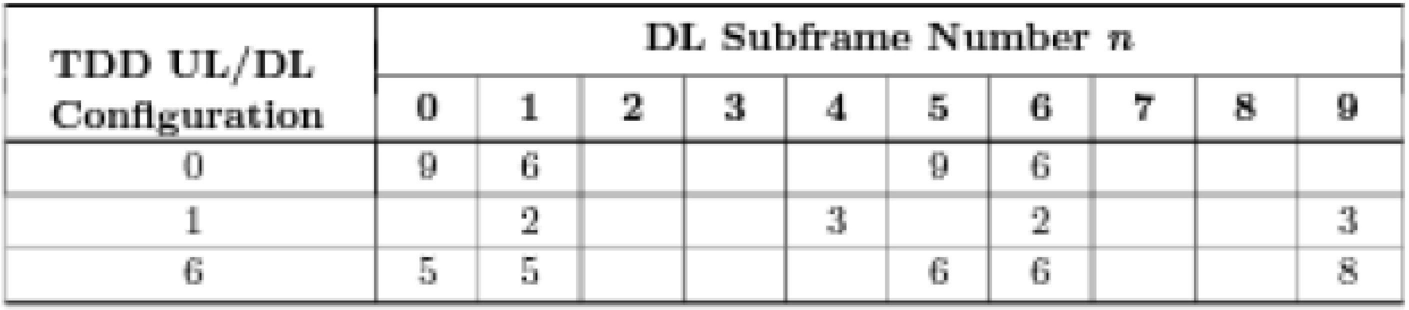
8.6.2 TDD mode

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

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

Syllabus:-
Module – 4

Uplink Channel Transport Processing: Overview, Uplink shared channels, Uplink Control Information, Uplink Reference signals, Random Access Channels, H-ARQ on uplink (Sec 8.1 – 8.6 of Text).

Physical Layer Procedures: Hybrid – ARQ procedures, Channel Quality Indicator CQI feedback, Precoder 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(Sec 9.1- 9.6, 9.8, 9.9, 9.10 of Text).