TUTORIAL ON FUNCTIONALITY AND PERFORMANCE

OF U_U LINK (AIR INTERFACE)

OF LTE SYSTEM

by

PRASHANT SRIVASTAVA

Presented to the Faculty of the Graduate School of

The University of Texas at Arlington in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

THE UNIVERSITY OF TEXAS AT ARLINGTON

December 2010

ACKNOWLEDGEMENTS

I am deeply indebted to Dr.R.Stephen Gibbs, who has been my instructor for this work. I am grateful for his guidance, encouragement and invaluable cooperation.

I am deeply and forever obliged to my family for their love, support and encouragement throughout my entire life.

At the end, I would like to thank all the member of Radio Study Group for their cooperation and team work in making this work a success.

November 19, 2010

ABSTRACT

TUTORIAL ON FUNCTIONALITY AND PERFORMANCE OF

U_U LINK (AIR INTERFACE) OF

LTE SYSTEM

Prashant Srivastava, M.S

The University of Texas at Arlington, 2010

Supervising Professor: Stephen Gibbs

In this thesis we have discussed about the air interface for LTE. We have shown the extensive details of the two different types of access that is downlink access- Orthogonal frequency multiple access (OFDMA) and uplink access- Single carrier frequency division multiple access (SC-FDMA).We started with basic concepts about these techniques and proceeded ahead by discussing the operation and design of both types of methods. Also we have shown the transmission chain for downlink and uplink showing step by step that how the data and control information are transmitted over air in LTE. We have presented a brief overview of the link budget for DL and UL in LTE.

Furthermore we have discussed about the physical layer procedure like cell search, timing advance, and HARQ and power control in detail to build a solid understanding. We have analyzed various smart antenna technologies in detail and discussed when and where each of these methods may be useful depending on many factors like channel condition, traffic load, cell center users or cell edge users. Also, we observed that dynamic switching between some MIMO techniques can be useful depending upon the various conditions.

Finally we presented some of the real world implementation or simulations based on real world scenario and discussed the results.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

Figure Page

LIST OF TABLES

Table Page

CHAPTER 1

INTRODUCTION

We have seen a tremendous amount of growth in past few decades in wireless communication industry. It started with first generation (1G) system which was basically deployed for voice communications and very limited mobility. After this it was the second generation (2G) which provided better capacity and better voice quality compared to 1G system. 2G system mainly consisted of GSM (global system for mobile communications) and CDMA (code division multiple access) which were designed with voice service in the mind. Data traffics were supported in 2G system but the user throughput was very less and later both the technology felt a need to upgrade their system to support higher data throughput along with support for voice. This gave result to a new revolution, which we sometime refer to third generation or 3G systems. 3GPP's 3G standard was called UMTS (wideband CDMA using 5 MHz bandwidth) and 3GPP2's standard was named cdma2000-3X.

However, with the first release of 3G, the requirement for high speed data was not completely fulfilled. Today is the world where we need a telecommunication system which has to fulfill the requirements for voice, video, telephony, interactive media, streaming media, and some services with lossless requirements such as file transfer and email. UMTS networks have already been upgraded with High Speed Packet Access (HSDPA) and currently it is getting evolved to HSPA+ which will have multiple antennas deployment, new modulation scheme and some improvements in system protocols.

We can expect 10 more years for further improvements with HSPA + and to ensure competitiveness of UMTS new concepts are being investigated in LTE to fulfill these demands.

With LTE, we will have new access schemes like OFDMA in downlink SC-FDMA in uplink. Also, LTE will have new concept called multiple input and multiple output (MIMO) with 2 receive antenna and 1 transmit antenna at UE which will support 100 Mbps DL data rate and 50 Mbps UL data throughput. In DL spectral efficiency is about 3 times and sometimes 4 times better and in UL it's 2 to 3 times better. The evolution of wireless communication system in 3GPP is shown in Figure 1.1:

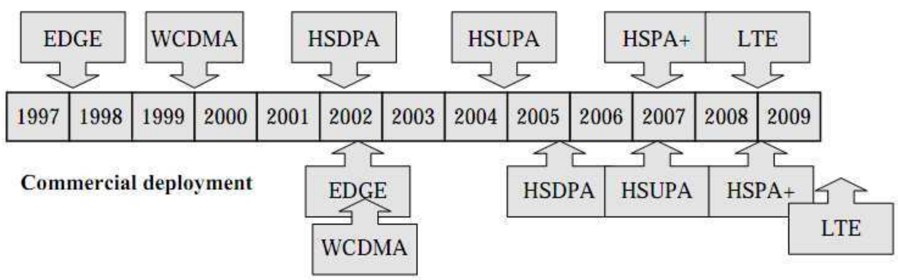


Figure 1.1 Schedule of 3GPP standard and their commercial deployments [1]

We have new term in LTE called E-UTRAN which is nothing but evolved UTRAN from UMTS. Here Base stations are renamed as enodeB. These enodeB's may be interconnected to each other and also to gateways (SAEs) and Mobile management entities (MMEs), which are located in EPC.

The main targets of LTE can be explicitly pointed as follows:

• To have an enhanced system capacity with reduced cost per bit, with ability to utilize existing 2G and 3G spectrum along with the new spectrum.

•To have reduced delays in connection establishment and transmission latency. To achieve remarkably higher data rates compared to existing 3G systems, with theoretical maximum of

100Mbps in downlink and over 50Mbps in uplink.

•To have reduced delays in connection establishment and transmission latency.

• To have a simplified network architecture.

• To have seamless mobility, this includes call handling between different radio-access technologies.

• To have improved cell edge performance.

• It should be optimized for low mobile speed but should be able to support high speed too.

• To have as simplified and minimum number of interface as possible.

• Last but not the least- to have reasonable power consumption for the user equipment.

1.1 LTE Network Architecture

In LTE flat architecture more intelligence is added to the Base Station. If we compare to HSDPA and HSUPA various new functionalities have been added to BS such as the radio-related functionalities are all located in the BS, compared to HSDPA/HSUPA the new functionalities are Radio Link Control (RLC) Layer, Radio Resource Control (RRC) and Packet Data Convergence Protocol (PDCP).

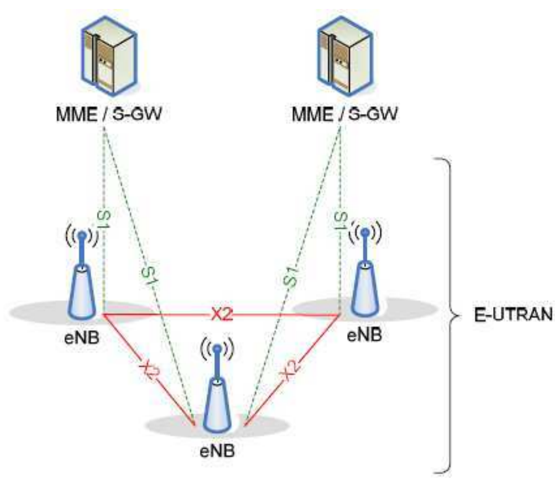


Figure 1.2 Overall E-UTRAN architecture [11]

The only single element in the Evolved-UTRAN (E-UTRAN) is the evolved Node B (eNB) which has to perform all the functions for Radio resource management (RRM), such as radio admission control radio bearer control, connection mobility control and dynamic resource allocation (scheduling). The interface by which eNBs are interconnected is called *X2* interface. For handover purposes it can be assumed that there is always an *X2* interface between the eNBs which will be needed to communicate with each. Connected to the eNBs, by means of *S1* interfaces, is the Evolved Packet Core (EPC).

The EPC is composed by three basic entities -the Mobility Management Entity (MME) and the Serving Gateway (S-GW) and the Packet Data Network (PDN) Gateway (P-GW). The interface between core and radio access network is defined in such a way that implementation in the core network side would be possible with control (*S1_MME*) and user-plane (*S1_UE*) traffic processing in separate physical elements. The S1 interface supports a many-to-many relation between MMEs / S-GWs and eNBs.

The S-GW and P-GW are used for tasks like- processing the user-plane data, to handle tasks related to the mobility management inside the LTE, they are also defined for IP header compression and encryption of user data streams and to terminate user-plane packets for paging reason. MME function includes the control plane signaling, it also handles the mobility management and idle-mode scenarios by the distributing different paging messages to the eNodeBs.

Functional spilt for E-UTRAN and EPC is shown in the Figure 1.3. The UMTS RNC's functions of UMTS RNC were divided between BS and S-GW, which also performs the task of that of SGSN. The P-GW is comparable to GGSN and the MME to the HLR and VLR in UMTS.

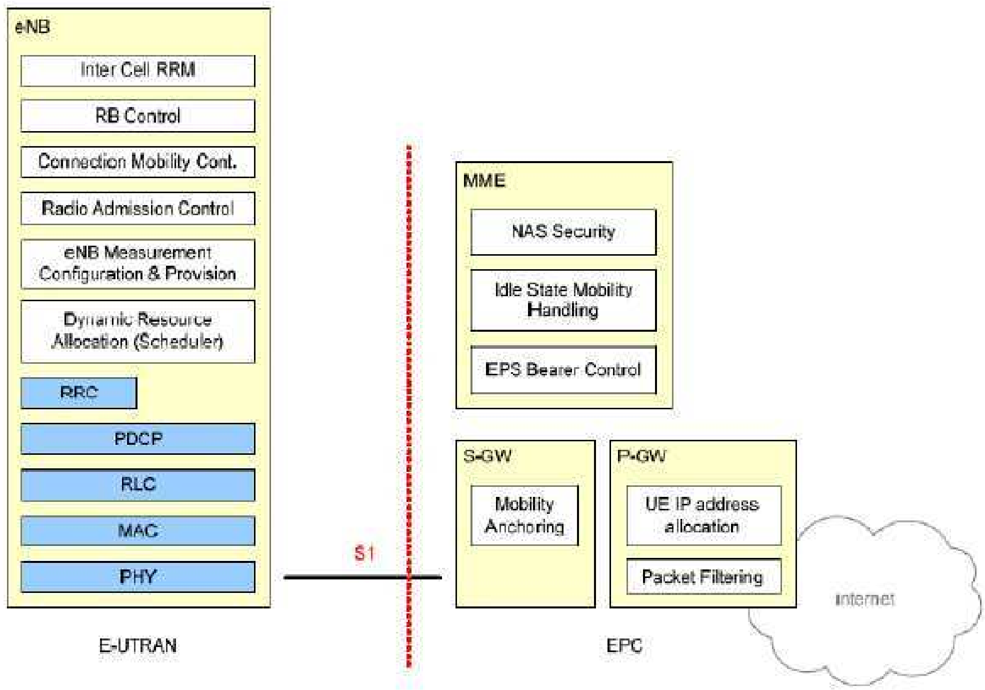


Figure 1.3 Functional split between E-UTRAN and EPC (extracted from [3GPP08])

1.2 Scope and organization of thesis

This thesis is organized into 3 main sections. Chapter 2, "LTE Air interface" introduces the concept of new downlink access technology called OFDMA (orthogonal frequency division multiple access) and uplink technology called SC-FDMA (single carrier-frequency division multiple access). It also gives insight into downlink and uplink data transmission procedure with an introduction to link budget calculation for uplink and downlink in LTE. Chapter 3, "Physical layer procedures" gives and overview of the physical layer procedures performed by L1 in LTE like Timing advance, random access, power control and cell search. Chapter 4, "Smart Antenna technology in LTE" discusses the multi antenna transmission schemes used in LTE. It starts with the fundamental of MIMO (multi-input multi-output) and describes most of the methods in detail. It also highlights the challenges in implementing UE MIMO and finally puts some light on practical world tests and results which are being carried in the real world.

CHAPTER 2

AIR INTERFACE FOR LTE

Before discussing the actual air interface access in detail, we will first have an overview of channels specified in LTE as they will be frequently referred while discussing the air interface. We describe different channel types like logical, transport and physical channels and specific use of each of them.

2.1 Overview of Channels

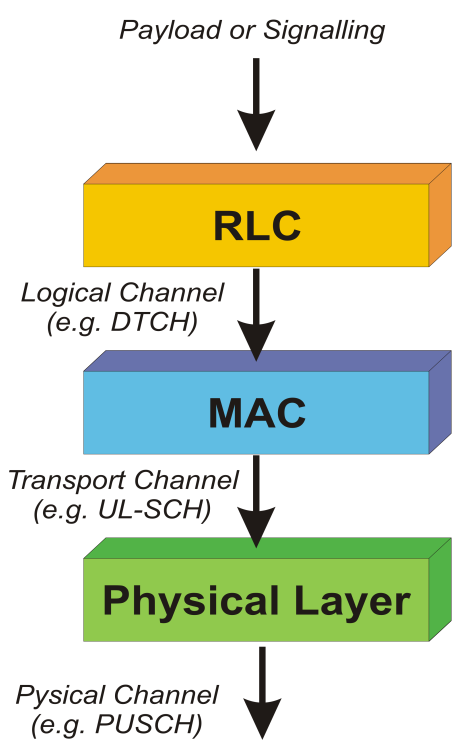


Figure 2.1 Channel Types [9]

There are basically three types of channels defined for LTE system:

- Logical Channels: These channels are used at the interface of RLC and MAC. They basically define the type of data to be transferred, which can either be control data or user specific data.
- Transport channels: These channels define the interface between MAC and physical layer. To put it more specifically, they are used to define the services offered by L1 to higher layers. They indicate how and with which characteristics data has to be transferred.
- Physical channels: These are the channels which finally carry the user and control messages. Physical characteristics such as frequency and sub carrier are defined by these channels.

2.1.1 Logical channels

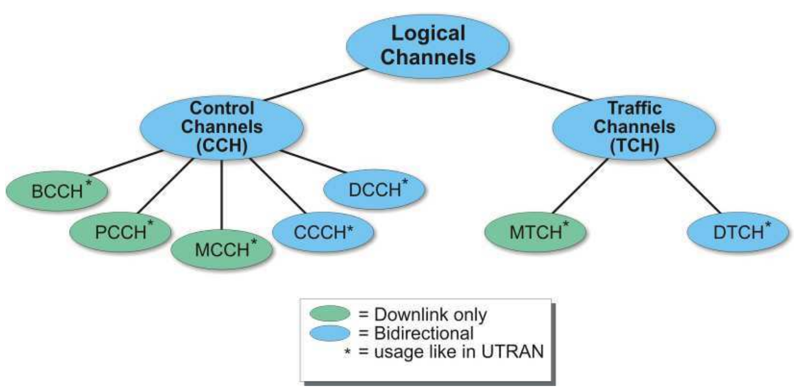


Figure 2.2 Logical Channel Structure [9]

2.1.1.1 Control channels

- Paging control channel (PCCH): It is a downlink channel whose main purpose is to transfer system information change notifications in addition to transfer paging information. Actually this channel is used for paging when the network does not know the location cell of the UE. So we can say it is used for searching a UE in the LTE network.
- Broadcast control channel (BCCH): This control channel provides system information to all mobile terminals connected to the eNodeB.
- Common control channel (CCCH): This channel provides random access information, e.g. to set up a connection. It is used for UE which do not have any RRC connection.
- Dedicated control channel (DCCH): This control channel is used only if UEs have RRC connection to carry user-specific control information, e.g. for controlling actions including handoff and signaling involved with power control.
- Multicast control channel (MCCH): Basically it is a point-to-multipoint channel used to transmit MBMS control information from the network to the UE, it may be for one or more than one MTCHs. UEs capable of receiving MBMS make use of this channel (Multimedia Broadcast single frequency).

2.1.1.2 Traffic channels

- Dedicated Traffic channel (DTCH): This traffic channel is used for the transmission of user information. It should be noted that DTCH can exist, both in uplink and downlink.
- Multicast traffic channel: This is like MCCH but here it contains user data from network to UE. Again it is only for the UEs who receive MBMS.

2.1.2 Transport channels

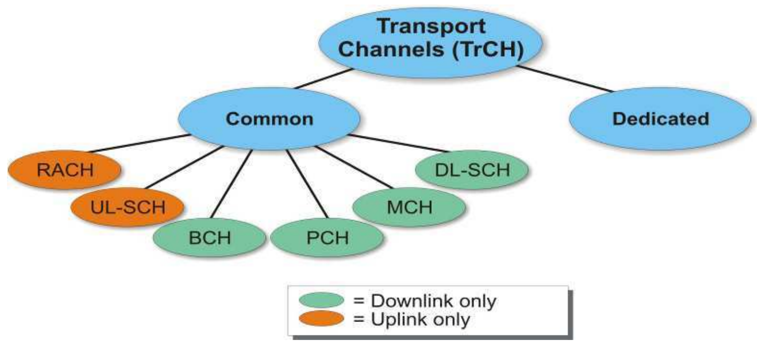


Figure 2.3 Transport Channel Structure [9]

- Paging channel (PCH): This channel supports UE discontinuous reception (DRX) and thus helps in saving UE power. It is broadcasted in the entire cell coverage.
- Broadcast channel (BCH): The LTE transport channel maps to Broadcast Control Channel (BCCH).

  It has generally fixed, pre-defined transport format. It is also broadcasted in the entire coverage area of the cell.
- Multicast channel (MCH): This transport channel is used to transmit MCCH information to set up multicast transmissions. Again it is broadcasted in the entire coverage area of the cell.
- Downlink shared channel (DL_SCH): Now this is the most important transport channel for downlink data transfer. It is used by many logical channels. Some of its functions are [10]:

  •It Supports Hybrid ARQ

  •It Supports dynamic link adaptation by varying the modulation, coding and transmit power

• Sometime broadcast in the entire cell is also supported;

• Also used to support beam forming

• Dynamic and static both resource allocation are supported

• Supports UE discontinuous reception (DRX) to enable UE power saving

• Supports MBMS transmission.

2.1.3 Physical channels

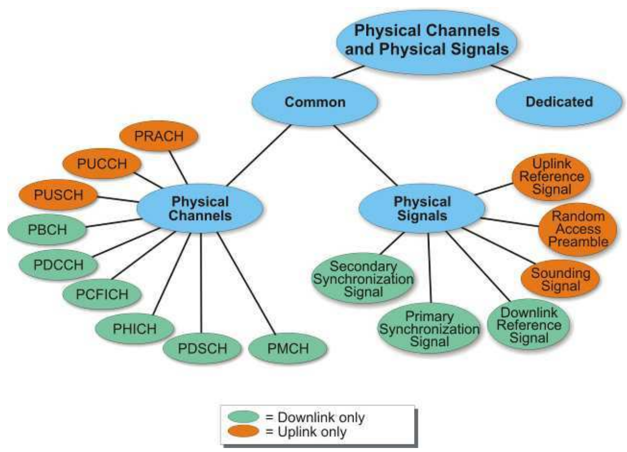


Figure 2.4 Physical channel structure [9]

- Physical Downlink Shared Channel (PDSCH): This channel contains the DL payload. It can use QPSK, 16-QAM or 64 QAM. Smart antenna technologies like MIMO make use of it.
- Physical Downlink Control Channel (PDCCH): The main function defined for it is to carry scheduling information. That is it carries Uplink scheduling grant. It Informs the UE about the Hybrid ARQ information related to DL-SCH and also the resource allocation of PCH and DL-SCH. It is modulated by QPSK modulation as its control information.

- Physical Hybrid ARQ Indicator Channel (PHICH): This channel is used to report the Hybrid ARQ status. That is it carries Hybrid ARQ ACK/NAKs in response to uplink transmissions.
- Physical Broadcast Channel (PBCH): This physical channel carries system information for UEs requiring access to the network.
- Physical Multicast Channel (PMCH): This physical channel carries system information for multicast purposes

Table 2.1 A glance on all channels [9]

TrCH / Physical Channel	Resource Blocks	OFDM/SC-FDMA Symbol	Modulation	Channel Coding	Rate	Number of Bits	CRC
- / Primary sync. Signal	6 RB's around DC carrier	Slot 0 and 10 last OFDMA symb.	Zadoff-Chu Sequence	NA	NA	NA	NA
- / Secondary sync. Signal	6 RB's around DC carrier	Slot 0 and 10 last but one OFDMA symb.	2 linked binary sequences	NA	NA	NA	NA
BCH / PBCH	6 RB's around DC carrier	first 4 OFDMA symbols in slot 1	QPSK	tail biting conv. coding	1/3	19	16=f(# ant port)
- / PHICH	as configured	1st up to 3rd (4th) symbol in DL subframe	[FFS + spreading]	repetition coding	1/3	1	none
- / PCFICH	f(LTE carrier bandwidth,cell ID)	first OFDMA symbol in every DL subframe	QPSK	32 bit codewords	1/16	2	none
- / PDCCH	all	1st up to 3rd(4th) symb. in every DL subframe	QPSK	tail biting conv. coding	1/3	19 - 59	16 XOR RNTI
PCH + DL-SCH / PDSCH MCH / PMCH	as scheduled	other symbols in DL subframe not occupied by (PBCH), L1 control channels, (sync. signals)	QPSK 16-QAM 64-QAM	Turbo coding	1/3	16 - 73712	24
RACH / PRACH	6 RB on config. position: perf. edge of carrier	1 or 2 subframes	Zadoff-Chu Sequence	NA	NA	6	NA
- / Sounding Ref. Signal	as scheduled	if exists last symbol of subframe	Zadoff-Chu Sequence	NA	NA	NA	NA
- / PUCCH Format 1 SR only 1a A/N 1b A/N 2 CQI 2a CQI / A/N 2b CQI / A/N	1 RB on configured position: perf. edge of carrier	complete UL subframe	N/A BPSK QPSK QPSK QPSK/BPSK QPSK/QPSK	"Zadoff-Chu + spreading + repetition" "Zadoff-Chu" + (20,13) (+repetition) (+repetition)	N/A 1/2 1/2 13/20 ... + 1/2 ... + 1/2	N/A 1 2 13 13/1 13/2	none
UL-SCH / PUSCH	as scheduled	complete UL subframe	QPSK 16-QAM 64-QAM	Data: Turbo Coding CQI: Tail biting CC Other L1 info: repetition	1/3	16 - 73712	24 for data 8 for CQI

In DL, OFDMA (orthogonal frequency division multiple access) is chosen as the transmission scheme, the main reason being the simplicity of the receiver which we will discuss in further sections and SC-FDMA (single carrier frequency multiple access) for uplink.

2.2 Downlink Access

Having known the basics of GSM, UMTS etc., a natural question that comes to our mind when we talk about the downlink access technology is why OFDMA is used in LTE , why not WCDMA as in the case of UMTS. There are some solid reasons for switching over to different downlink method, let us see some of them.

In a WCDMA downlink (Node-B to UE link), the transmissions on different Walsh codes are orthogonal when they are received at the UE, the reason being that the signal is transmitted from a fixed location (base station) on the downlink and all the Walsh codes are received synchronized. So we can say when there is no multipath transmissions on different codes do not interfere with each other. Is this the actual case in real world? The answer is NO, we have many things in the space which will result in multi-path propagation, and this is very much typical in cellular environments. So the Walsh codes are no longer orthogonal and interfere with each other resulting in inter-user and/or inter-symbol interference (ISI). However, we can remove the ISI by using an advanced receiver such as linear minimum mean square error (LMMSE) receiver. But this implementation is somewhat costly and over that it will increase in receiver complexity.

Another reason for not employing WCDMA for LTE was lack of flexible bandwidth support because bandwidths supported in WCDMA can only be multiples of 5MHz and also bandwidths smaller than 5MHz cannot be supported. So people thought of employing some downlink method which can solve these problem without increasing the receiver cost and yet delivering better performances.

2.2.1 OFDMA Operation

The main goal by using OFDM is to simplify channel equalization process and that is done by letting each channel experience almost flat-fading. Actually the name OFDM comes from the fact that we take frequency responses of the sub channels, they are overlapping and orthogonal. It can be seen in Figure 2.5 that when the subcarrier with sub frequency fq is sampled, the output produced by other subcarriers is zero.

Similarly when f q+1 is sampled, fq and all other subcarriers produce no output and hence don't interfere with each other.

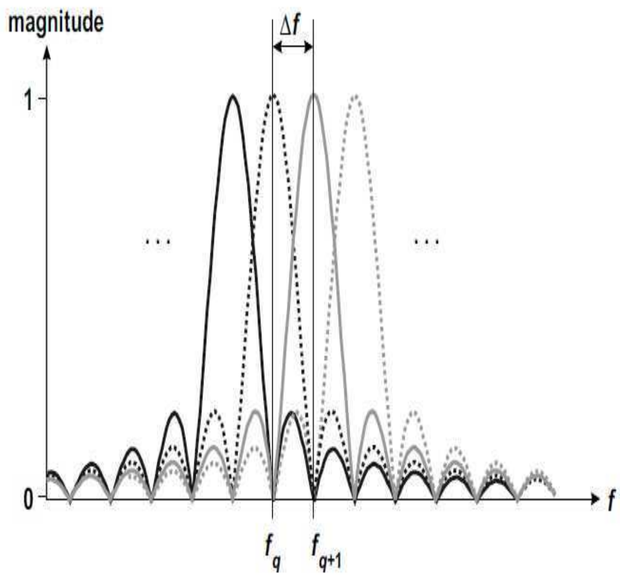


Figure 2.5 Orthogonal sub carriers [1]

It should be noted that almost 50% of the bandwidth is saved due to the orthogonally of the code compared to a non-overlapping techniques. This BW saving is show in Figure 2.6.

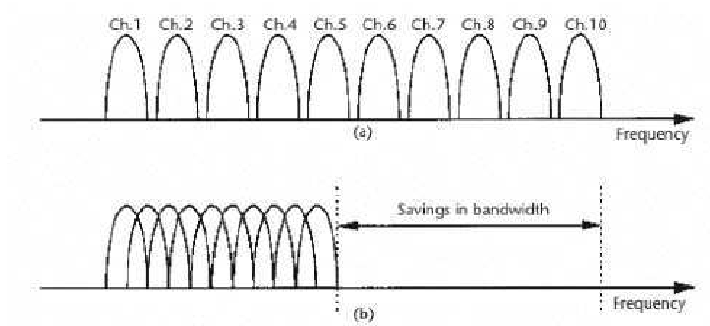


Figure 2.6 OFDM Modulation saves BW [5]

Processing steps: In the Figure 2.7 given below, it illustrates how an OFDM Symbol is formed. Here each subcarrier is modulated by a data symbol and the final OFDM symbol is made by merely adding the modulated sub carriers. In real situation there will many such carries getting modulated by various symbols.

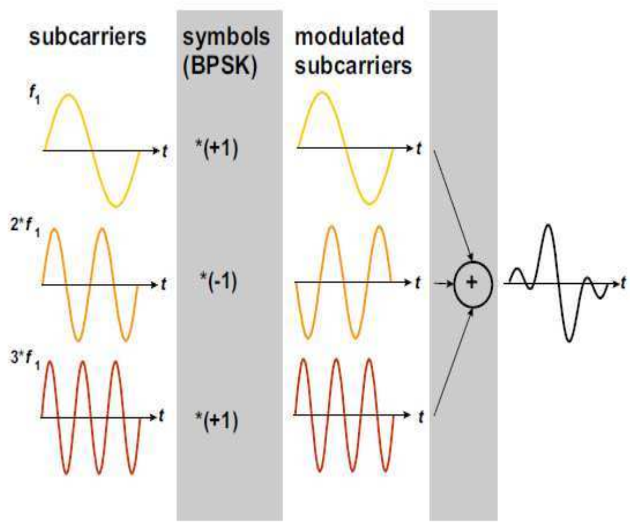


Figure 2.7 OFDMA processing [2]

Let's us see the same case with 5 symbols where it is modulated by 1 unlike +1 and -1 in previous case.

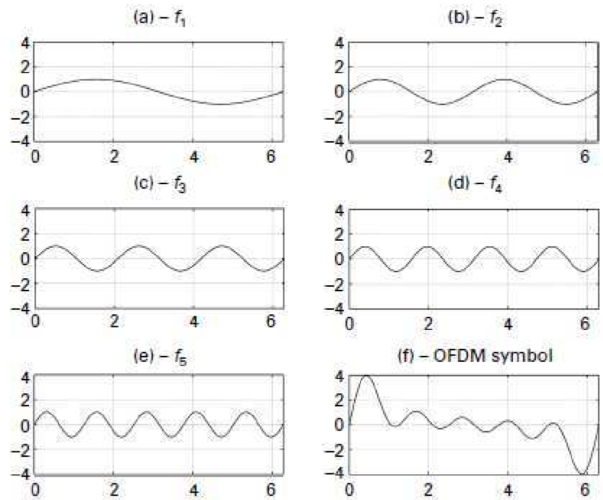


Figure 2.8 An illustration of subcarriers and OFDM symbol [3]

In the Figure 2.8 we see and an interesting observation that is the OFDM symbol signal has much larger signal amplitude variations than the individual subcarriers. This characteristic of OFDM signal leads to larger signal peakiness .This peakiness problem in OFDM symbols make it difficult to be used in uplink as is discussed in some details in further pages.

2.2.2 Cyclic Prefix

A small part of the OFDM Symbol is cut from the ending and attached to the beginning of the symbol before transmitting. Thus we need not have break in the transmission to act as guard time. We transmit continuously. We add the cyclic prefix which is larger than the channel impulse response so that the effect of the previous symbol can be avoided by removing the CP at the receiver side. The cyclic prefix length is generally chosen to accommodate the maximum delay spread of the wireless channel. There are different designs of CP.

At the receiver the delay spread due to multipath is absorbed much more efficiently and it also helps in maintaining frequency orthogonality. It is a temporal redundancy which should be taken into account for computation of data rates. The ratio μ/N_s must be chosen carefully for example-a high value of this ratio is needed if the multipath effect is important, which however decreases the useful data rate, similarly a relatively smaller value of this ratio can be used if the multipath effect is lighter. This is illustrated in Figure 2.9.

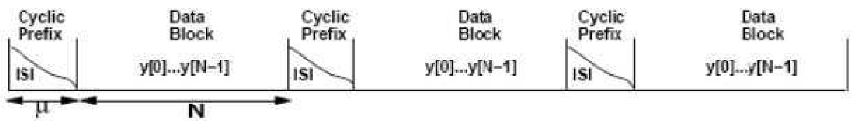
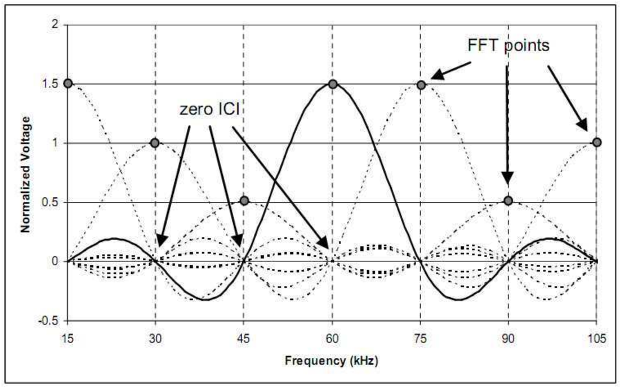


Figure 2.9 Cyclic prefix demonstration [4]

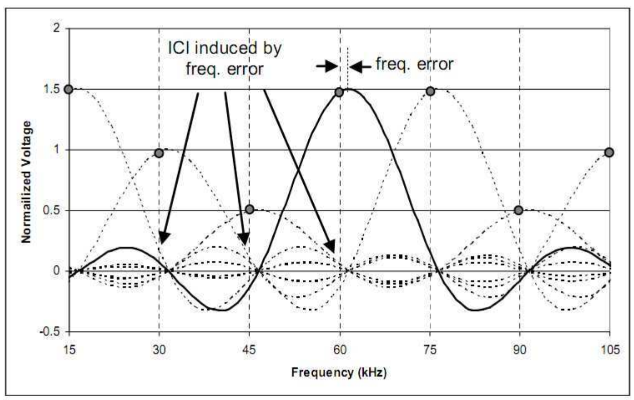
2.2.3 Disadvantage of OFDM

We see some of the advantages of OFDM, but indeed there are some disadvantages also if the implementation is not perfect. Two basic and commonly seen problems with OFDM are-susceptibility to frequency errors and a large peak to average power ratio (PAPR). Zero ICI can only be achieved if each subcarrier gets sampled exactly at its own center frequency. However, if it is not the case IC may happen. Sometimes the local oscillators (LO) at transmitter and receiver may drift and eNodeB should send synchronization signals to rectify it at UE side.

Some other sources of frequency errors may be Doppler shift and oscillator phase noise. Any offset in frequency of signal at the receiver must be corrected at the baseband processor to avoid ICI which if in excess will result in drop of that corrupted packet. Following diagram depicts the scenario of ICI in LTE.



Demodulated Signal without Frequency Offset (Zero ICI)



Demodulated Signal with Frequency Offset Causing ICI

Figure 2.10 Frequency offset results in ICI [18]

Another problem with OFDM is high PAPR (Peak to Average power ratio) where the instantaneous transmitted RF power within an OFDM symbol may vary dramatically as it is the combination of various subcarriers and some subcarrier voltage may add in phase at some point in symbol. This result in a peak which is comparatively higher than average power and that is why we say it end up having high PAPR (Peak to Average power ratio).

It puts very stringent requirements on A/D and D/A converter and also decreases the RF power amplifier (RFPA) efficiency. In case of single carrier systems where constant envelope modulation is used like GMSK and PSK and they do not have requirement of high linearity for RF amplifier and efficiency of RFPA is around 70%.

But for OFDM, within duration of OFDM there may be larger peaks and which should not get clipped off anyway and this requires larger amplifier with a larger back-off to remain in linear region so that no clipping takes place which means the efficiency of the RFPA is very less around 20 percent. The back-off requirement is depicted in Figure 2.11.

If x[n] is the sequence of symbols, then PAPR is defined as square of the peak amplitude divided by the mean power i.e.

$$PAPR = \frac{max_n\{|x[n]|^2\}}{E\{|x[n]|^2\}}$$

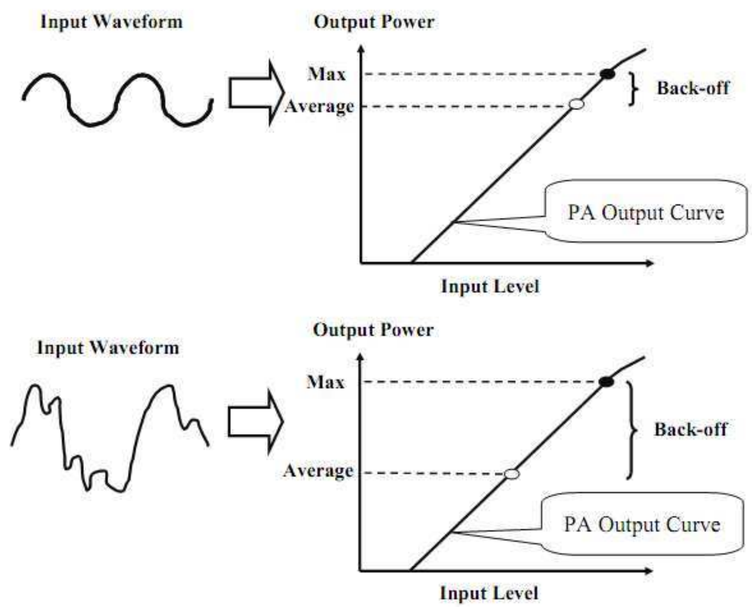


Figure 2.11 Power amplifier back-off requirements for different input waveforms [1]

2.3 Downlink data transmission

2.3.1 Frame structure

There are two types of frame structure defined for the LTE –Type1 and Type 2. Type 1 uses both TDD duplexing and type 2 which uses TDD duplexing. Type 1 is used with 3.84 UTRA systems and type 2 is basically optimized to be used with TD-SCFDMA. We will discuss about type 1 frame structure.

In type 1, the radio frame (as shown in Figure 2.1 2) in case of LTE is 10 ms long which comprises of 10 subframe (1 ms each). One subframe contains 2 slots which are 0.5ms each. Basically 1 frame has 20 time slots. We have a grid structure as show in the Figure 2.13 where grid may contains a repetitive pattern called Resource block or physical resource block (PRB).In order to have multiple access , bandwidth is allocated to UEs in terms of resource blocks. A PRB consists of 12 subcarriers in frequency domain and in time domain it consists of 6 or 7 OFDM symbols depending upon what type of CP is used.

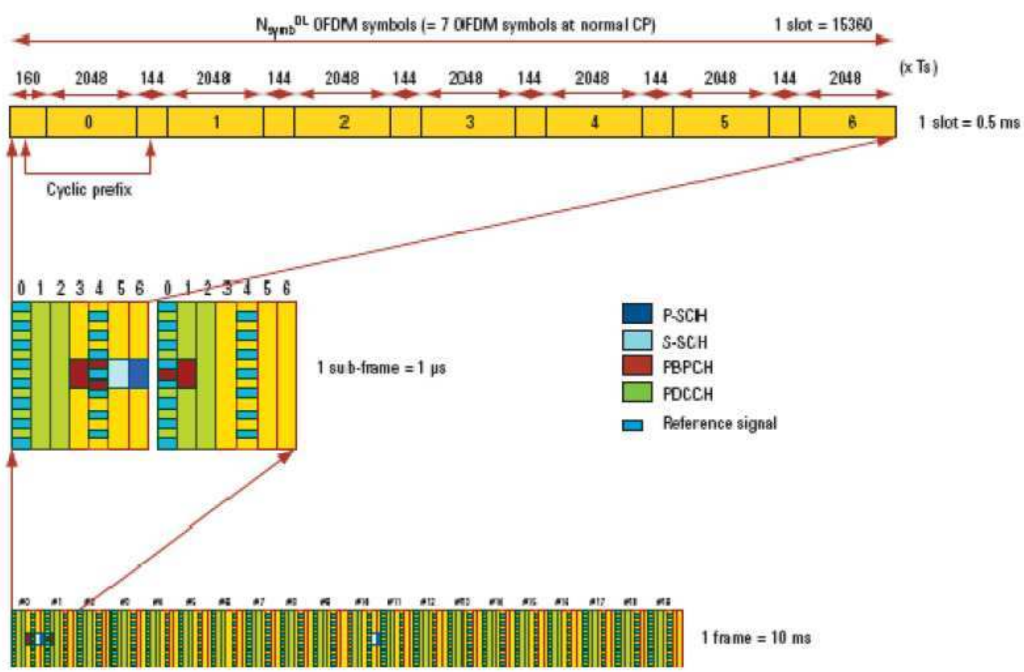


Figure 2.12 DL frame structure type [4]

2.3.2 Resource grid

In OFDM data is divided over a number of sub-carriers. The spacing between two sub-carriers is fixed at 15 kHz. The smallest unit in time and frequency in OFDM is called a resource block and it consists of 12 sub-carriers and 7 consecutive OFDMA symbols over one slot duration. In case of extended CP we have6 OFDMA symbols per slot Therefore it can be concluded that a RB has 84 resource elements (12 sub-carriers x 7 symbols).This sub-frame is also the minimum transmission time interval (TTI) and having such a small (TTI) helps to achieve the requirements of low latency. OFDM however exhibits a higher peak-to-average-power-ratio; this is not considered to be a major problem on the network side.

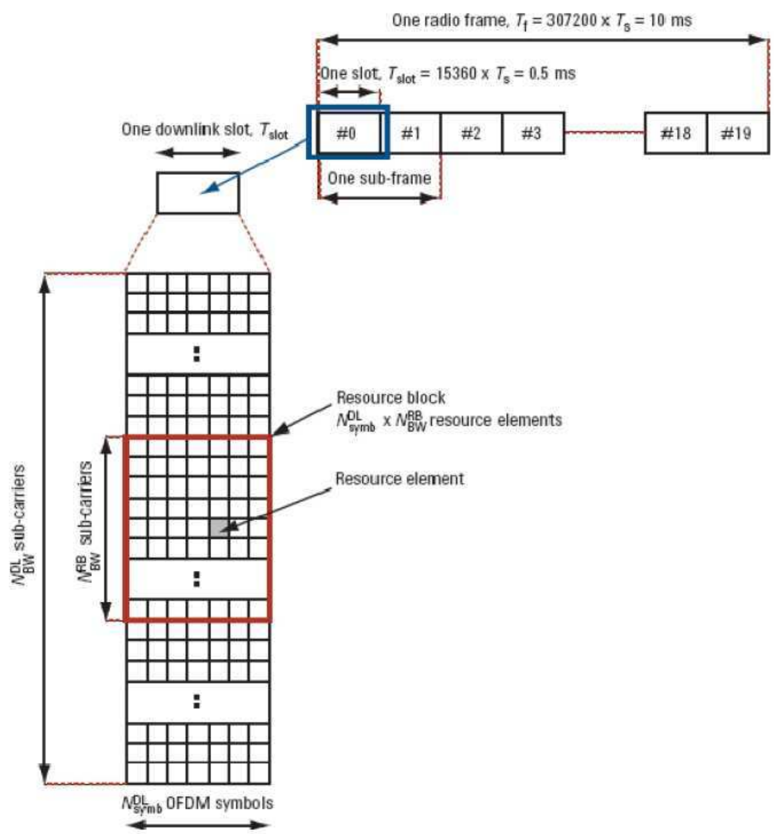


Figure 2.13 DL Resource Grid [4]

For all the possible bandwidth, the size of RB remains the same therefore the count of resource blocks depends on the transmission bandwidth. Figure 2.14 depicts the number of RBs for different transmission BWs.

Bandwidth (MHz)	1.25	2.5	5.0	10.0	15.0	20.0
Subcarrier bandwidth (kHz)	15					
Physical resource block (PRB) bandwidth (kHz)	180					
Number of available PRBs	6	12	25	50	75	100

Figure 2.14 Available bandwidth is divided into PRB [1]

2.4 Some sequences in LTE

There will be instances where the term “sequences” will be used in this text and therefore let’s see different kind of sequences generally used in LTE system.

2.4.1 PN Sequence

Pseudo–noise (PN) sequences have found various uses in LTE at different implementation level like to scramble DL and UL data transmission, to scramble the reference signals and to generate other hopping sequences.

LFSR (Linear feedback shift registers) can be used to generate PN sequence and if we have sequences with maximum possible period with an *l*-stage register then it is called maximum length sequence or m-sequences. Following is the autocorrelation function (periodic) for an m-sequence x(n) :

$$R(k) \triangleq 1\frac{1}{M}\sum_{n=0}^{M-1} x(n)x(n+k)$$

The periodic autocorrelation function R(k) is :

$$R(k) = \begin{cases} -1.0, & k = pM \\ -1/M, & k \neq pM \end{cases}$$

It can be seen that the autocorrelation fuction for the m-sequence is 1 for zero lag and nearly zero for other lags which indicates that autocorrelation of such sequence approches unit impluse respose as length of the sequence increases.

2.4.2 Gold Sequence

Exoring 2 same length m-sequence will give us a gold sequence, which means that to create a Gold sequence of length n=2l -1 , we need to have 2 LFSR sequences each of length n=2l -1 as shown in Figure 2.15. For some m-sequences , the cross correlation only takes 3 possible values {-1,-t,(t-2)},where t is dependent on the length og LFSR used. So for an LFSR with l memory elements :

$$t = \begin{cases} 2^{\frac{(l+1)}{2}} + 1, & l, odd \\ 2^{(l+2)/2} + 1, & l, even \end{cases}$$

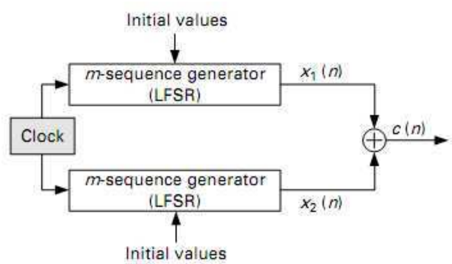


Figure 2.15 A Gold sequence generator [3]

2.4.3 PN-Sequence generation in LTE

Using Gold sequences of length 31, PN sequence for LTE can be generated. The output sequence c(n), where n=0,1,......,(MPN -1) is given as :

$$c(n) = \left(x_1(n+N_c) + x_2(n+N_c)\right) mod\, 2$$

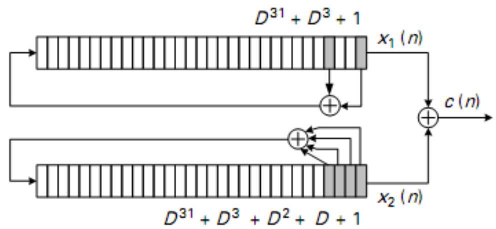


Figure 2.16 PN scrambling code generation in the LTE system [3]

Here two m-sequences x1(n) and x2(n) are generated by using the feedback polynomial D^{31} $+D^3$ +1 and D^{31} $+D^3$ $+D^2$ + D + 1 as below:

$$x_1(n+31) = \left(x_1(n+3) + x_1(n)\right) mod\, 2$$

$$x_2(n+31) = \left(x_2(n+3) + x_2(n+2) + x_2(n+1) + x_2(n)\right) mod\, 2$$

Where x1(n) and x2(n) are the m-sequences and initialsed as :

$$x_1 = \begin{cases} 1, & n = 0 \\ 0, & 0 < n < 31 \end{cases}$$

$$c_{init} = \sum_{i=0}^{30} x_2(i).2^i$$

If c_{init} is based on cell ID that is c_{init} = $N_{cell\ ID}$ =255 , the second m-sequence is initialized as

$$x_2 = \begin{cases} 1, & n \le 8 \\ 0, & 8 < n < 31 \end{cases}$$

2.4.4 Zadoff-Chu(ZC) sequences

This sequence is used in LTE for primary and secondary synchronization signals. It is and random access channel. It can be defined as:

$$x_u(m) = \begin{cases} e^{-j\frac{\pi u m^2}{N_{ZC}}}, & \text{when } N_{ZC} \text{ is even} \\ e^{-j\frac{\pi u m(m+1)}{N_{ZC}}}, & \text{when } N_{ZC} \text{ is odd} \end{cases} \qquad m = 0,1,\ldots,(N_{ZC}-1),$$

2.5 Downlink Reference Signals

The reference signals may be basically used for various type of measurements like for scheduling, link adaptation, handoff and some time for data demodulations. There are basically two types of approaches for downlink reference signal multiplexing- TDM and FDM as shown in Figure 2.17.

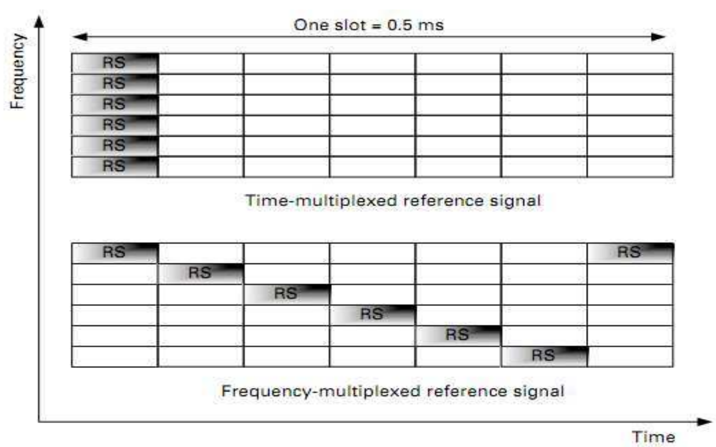


Figure 2.17 An illustration of time and frequency-multiplexed reference signal [3]

- Time division multiplexing option: The main idea behind TDM approach was to enable micro sleep mode at UE. This is done by time multiplexing the scheduling control information with TDM pilot, for e.g. by putting them just after the TDM pilot. This enables UE to decode the control information just after estimating the channel with TDM pilot. Once it decodes the scheduling control information, UE will determine whether it is scheduled in current sub frame or not-If UE is scheduled, then UE will buffer the rest of transmission and if it is not scheduled, UE will turn off the receiver and thus save some power.

The disadvantage with TDM is that power between the reference signal and data Cannot be shared. It is sometimes required to enable the better channel estimate by boosting the reference signal power, which is not possible in the TDM approach.

- Frequency division multiplexing option: In this the reference signals are fully scattered. The advantage with this approach is that, reference signal power spectral density can be boosted by lowering the data PSD. But the disadvantage is that UE has to continuously monitor the whole sub frame to estimate the channel and decode the control information which will tell whether UE is scheduled or not. This leads to more battery consumption as receiver has to be on for a longer duration and thus the micro sleep is not achievable at UE terminal.

Solution to the above problem was to implement Hybrid TDM/FDM approach for reference signal multiplexing. In this approach we frequency multiplex the reference signal with data transmission in few OFDM symbols. And the control information can be derived from the reference signals in first two OFDM symbols. Thus micro sleep at UE terminal can also be achieved.

Further three types of downlink reference signals have been defined-Cell specific and UE specific for MBSFN and MBSFN specific reference signal for MBSFN transmission.
The number of cell specific reference signal depends on the number of antenna ports supported by the eNodeB whereas MBSFN specific and UE specific reference signal are defined with single antenna port.

In LTE, the cell specific reference signals can be used for two purposes-downlink measurements (like MIMO rank calculation ,MIMO precoding vector/matrix ,channel quality measurements and measurements for hand-offs) and demodulation of non-MBSFN transmissions whereas UE reference signal is used only for demodulation purposes.

2.6 Transmission on Downlink

2.6.1 Downlink User data transmission

In the downlink side, user data is carried over Physical downlink shared channel (PDSCH). We have 1ms resource allocation with 12 subcarrier and 180 KHz unit. In case of PDSH, as OFDMA is used as multiple access so each carrier has to be transmitted as a parallel 15 KHz carrier and hence the user data rate will eventually be dependent on the number of subcarrier allocated to the UE. This resource allocation is carried out based on Channel Quality indicator from the UE as shown below in the Figure 2.18.

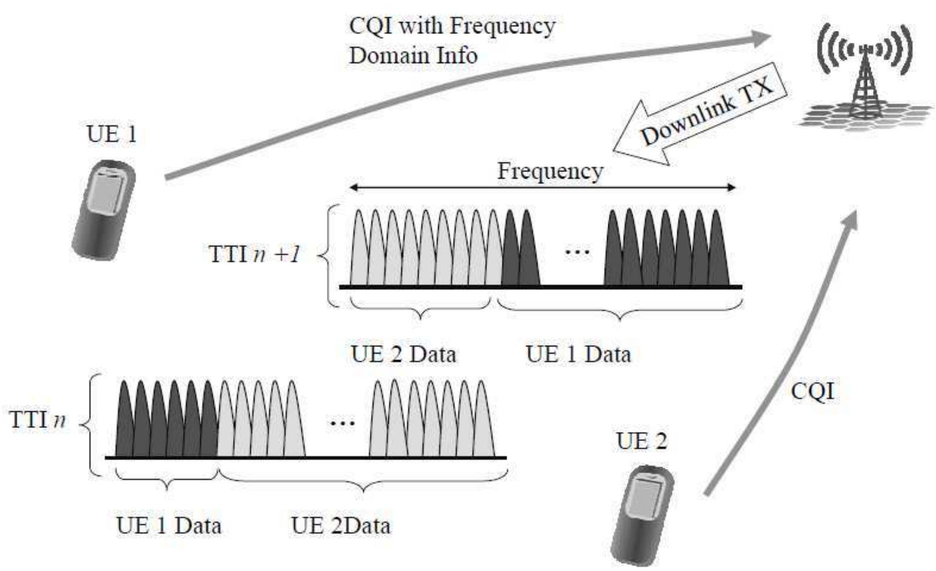


Figure 2.18 Downlink resource allocations at eNodeB [1]

The control signals are carried on PDCCH and user data on PDSCH. In a 0.5m slot of a sub frame, PDCCH can occupy 3 to 6 symbols .Also it should be noted that in a 1ms TTI , only 1st 0.5ms is used for PDCCH, the second PDCCH is purely for data i.e. for PDSCH as shown in Figure 2.19.

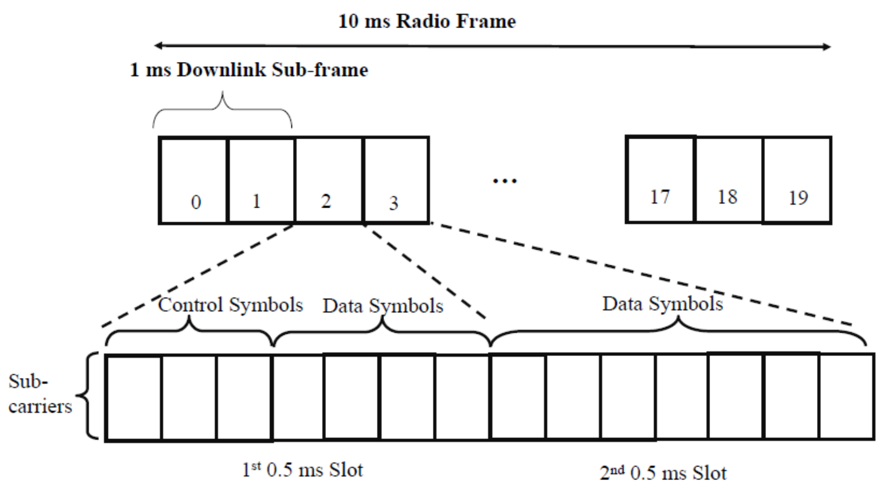


Figure 2.19 Downlink slot structure for bandwidths above 1.4 MHz [1]

The channel coding of 1/3 turbo coding is used in DL direction which is same for uplink case. The maximum block size for turbo coding is limited to 6144 bits to reduce the processing gain. The coding chain for DL is shown in the Figure 2.20.

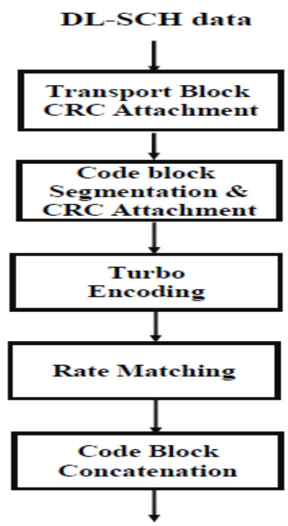


Figure 2.20 DL-SCH channel encoding chain [1]

As shown in Figure 2.21, once the channel coding is done , these code words go ahead for scrambling so that wrong device should not be able to decode the data in case the resource allocation in two cells happen to be exactly identical. After this it is modulated using QPSK, 16QAM or 64 QAM, as desired and later on fed for layer mapping and precoding. In case of single antenna transmission, this layer mapping and precoding is not the part of signal generation. It’s only the part, if Multi-antenna transmission is being used. In case of multi antenna transmission (2 or 4), the data can be further divided into many streams before the generation of OFDM symbol.

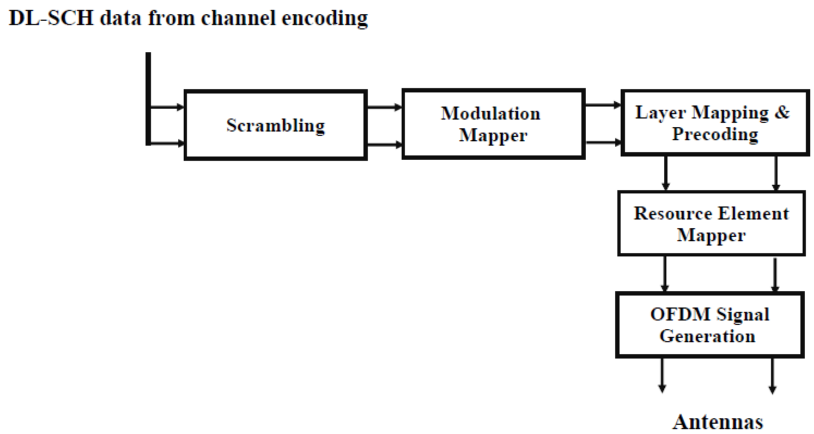


Figure 2.21 Downlink signal generation [1]

The instantaneous user throughput depends on the factors like modulation, allocated amount of subcarriers, channel coding rate and also on number of transmits antennas being used. It ranges from 0.7Mbps to 170 Mbps. With 4X4 MIMO, even 300 Mbps is achievable.

2.6.2 Downlink Physical Layer signaling transmission

We have three different types of control messages to carry the DL control information:

- Control Format Indicator: It defines the amount of resource allocated to control channel use, it is mapped to Physical Control Format Indicator Channel (PCFICH).
- HARQ Indication (HI): It has been defined to take into account the success of uplink packets received .It is mapped to Physical HARQ Indicator channel (PHICH).
- Downlink Control Information- It controls the different physical layer resource allocation in both uplink and downlink. Its physical layer mapping is called as Physical downlink control channel (PDCCH).

2.6.2.1 Physical Control Format Indicator Channel (PCFICH)

It tells the UE that how many OFDMA symbols in a TTI are reserved for control information. It can be 1 to 3 symbols in a 1ms sub frame. So, UE knows from PCFICH, which symbols to treat as control information. In Figure 2.22 we can see that ,PDCCH allocation changes from 1 symbol to 3 symbol in next 0.5ms.However, it should be noted that PDCCH can occupy only first 0.5ms in a 1ms TTI sub frame, rest id for user data. Talking of overhead, it changes from 1/14 to 3/14 for the following case.

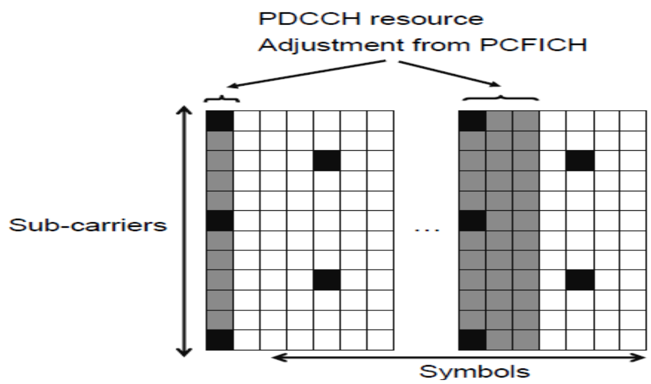


Figure 2.22 PDCCH resource allocations from PCFICH for bandwidths above 1.4 MHz [1]

2.6.2.2 Physical Downlink Control Channel (PDCCH)

The DCI mapped on PDCCH may have different formats and it is transmitted with one or more Control channel elements (CCEs). 9 resource element groups form one CCE and each group has 4 resource elements. PDCCH is control information and therefore modulated with QPSK, so a single RE contains 2 bits and thus a resource element group has 8 bits. The DCI mapping on PDCCH has four different formats carrying following control information, as shown in the table:

-PUSCH allocation information (DCI Format 0)

-PDSCH information with one codeword (DCI Format)

-PDSCH information with two codewords (DCI Format 2)

-Uplink power control information (DCI Format 3)

Table 2.2 PDCCH format and their size [1]

PDCCH format	Number of CCEs	Number of resource-element groups	Number of PDCCH bits
0	1	9	72
1	2	18	144
2	4	36	288
3	8	72	576

Downlink Assignment is the name which is given to the PDCCH which contains PDSCH related information. In this DL assignment message following information are transmitted for UE's knowledge:

-Resource block information- a bitmap of given PRBs can be indicated or there may be an index of the first PRB along with contiguously allocated PRBs.

-The modulation and coding scheme that is used for user data.

-The HARQ process number for retransmission purposes.

-A new data indicator which tells whether it is transmission or retransmission.

-MIMO specific signaling are also transmitted in DL assignment.

2.6.2.3 Physical Broadcast Channel (PBCH)

It carries the system information needed to access the system like RACH parameters etc. Always for this channel 1.08 MHz bandwidth is allocated and as the data rate is not too high convolutional encoding is done for this channel. Broadcast information is an extensive set of messages containing MIB and SIBs. Out of which MIB (master information block) is carried on PBCH and rest of SIBs may be carried over PDSCH.

The PBCH should be detected by UE without prior knowledge of the system bandwidth. It is done by placing PBCH in the central 72 subcarriers of the OFDM signal. As said, PBCH only carries MIB and it is just 14 bits and is repeated every 40 ms which corresponds to data rate of PBCH to be 350bps. PBCH structure is shown in Figure 2.23.

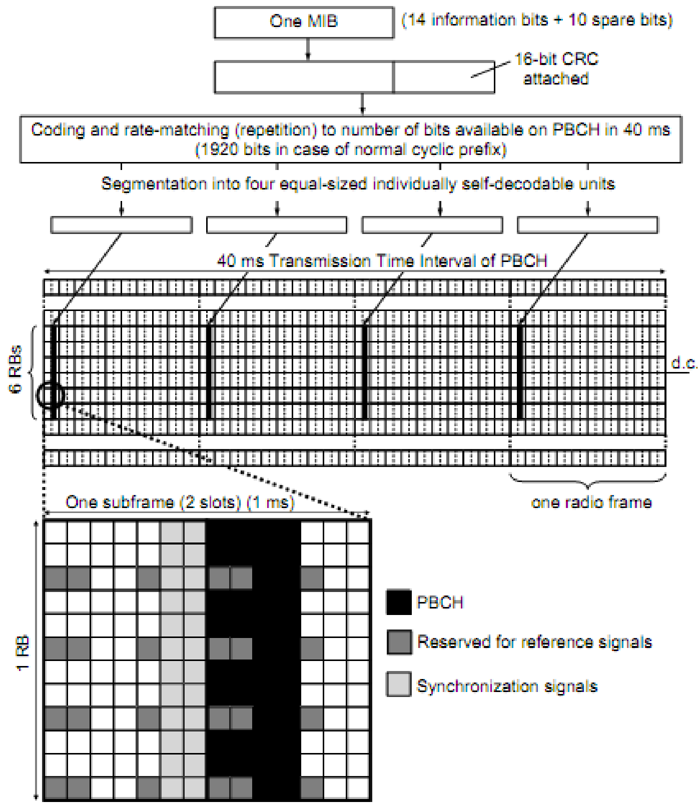


Figure 2.23 PBCH structures [16]

2.6.2.4 Physical HARQ Indicator Channel (PHICH)

The only job of this channel is to indicate if the uplink packet was correctly received or not at eNodeBs.

2.7 Downlink Transmission modes

UE should know beforehand, which of the transmission to expect from eNodeB, because if the transmission mode is dynamically changed, UE has to keep an eye for all possible DCI formats which will increase the number of blind decoding. The UE is notified about the transmission mode via RRC signaling. In release 8 of LTE seven transmission modes were defined. [1]

1. Single-antenna port; port 0

This is the simplest mode of operation with no pre-coding.

2. Transmit Diversity

Transmit diversity with two or four antenna ports using SFBC.

3. Open-loop spatial multiplexing

This is an open loop mode with the possibility to do rank adaptation based on the RI feedback. In the case of rank = 1 transmit diversity is applied similarly to transmission mode 2. With higher rank spatial multiplexing with up to four layers with large delay, CDD is used.

4. Closed-loop spatial multiplexing

This is a spatial multiplexing mode with pre-coding feedback supporting dynamic rank adaptation.

5. Multi-user MIMO

Transmission mode for downlink MU-MIMO operation.

6. Closed-loop Rank = 1 pre-coding

Closed loop pre-coding similar to transmission mode 5 without the possibility of spatial multiplexing, i.e. the rank is fixed to one.

7. Single-antenna port; port 5

This mode can be used in a beam forming operation when UE specific reference signals are in use.

2.8 Uplink Access -SCFDMA

There is a possibility of using OFDMA in uplink also as we would have a commonality in downlink and uplink. The only and big issue with use of OFDMA in uplink is high PAPR/CM. So a new technique was researched with all desirable aspects from OFDMA and a low PAPR/CM too. This was called SC-FDMA.

In SC-FDMA also we use the same principle like OFDM, that is dividing the transmission bandwidth into multiple parallel subcarriers, and orthogonality is maintained by using a Cyclic Prefix (CP) or guard period. With the use of CP Inter-Symbol Interference (ISI) between SC-FDMA information blocks can be avoided. In OFDM, data symbols have to independently modulate each subcarrier directly ,however with SC-FDMA, at any time instant, the signal modulated onto a given subcarrier is a linear combination of all the data symbols .This is how in each symbol period, all the transmitted subcarriers of an SC-FDMA signal carry a component of each modulated data symbol.

2.8.1 Frequency domain generation of SC-FDMA signal

For generation of SC-FDMA signal in frequency domain Discrete Fourier Transform – Spread OFDM (DFT-S-OFDM) is used as shown in Figure 2.24.

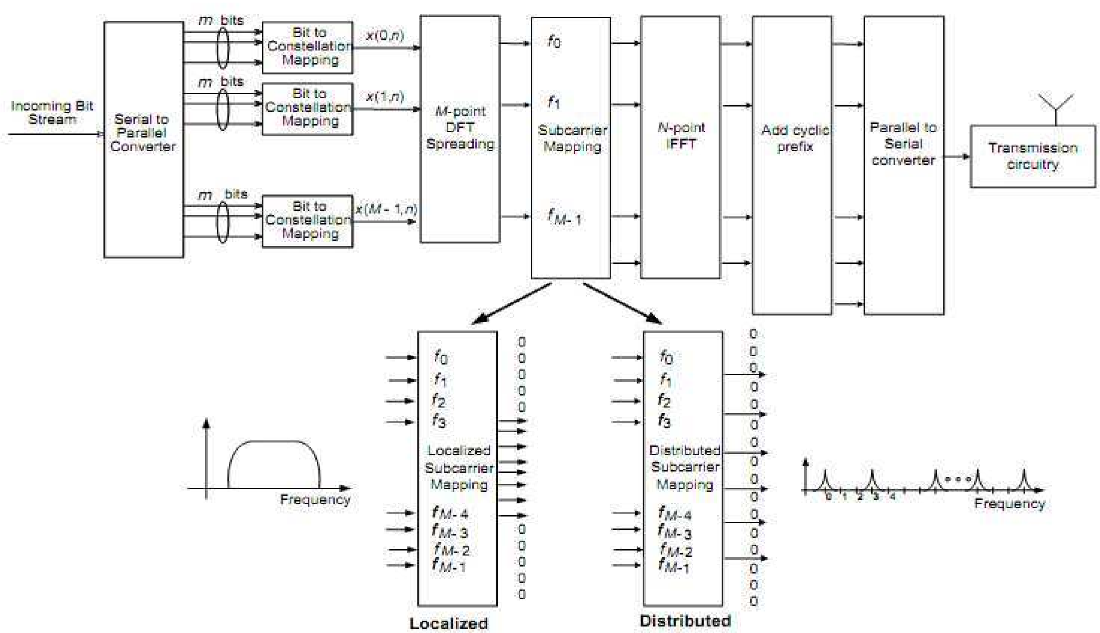


Figure 2.24 Processing (DFT-S-OFDM) showing localized and distributed subcarrier mappings [16]

As a first step, an M-point DFT operation is performed on each block of M QAM symbol. To match size to N-carrier OFDM modulator some zeros may be needed to add on the output of

DFT. Output of zero padded DFT is then mapped to N-subcarriers where position of zeros will determine that DFT –precoded data is mapped to which subcarrier.

Just to mention a M-point DFT is calculated as:

$$X(k) = \sqrt{\frac{1}{M}} \sum_{m=0}^{M-1} x(m)\, e^{-j2\pi k}\frac{m}{M}$$

N is chosen to be larger than the maximum number of occupied subcarriers, which hence provides for efficient oversampling and 'sinc' (sin(x)/x) pulse-shaping. There are two types of transmission which are possible from DFT-S-OFDM: localized and distributed transmission.

2.8.1.1 Localized Transmission:

A user is allocated a group of M adjacent subcarriers through subcarrier mapping. With M less than N, output of DFT is zero padded which results in un-sampled/interpolated version of original M QAM data symbols at the IFFT output of OFDM modulator. [16] The signal which is created for transmission now resembles a narrow band single carrier with a CP.

2.8.1.2 Distributed Transmission:

Here L-1 zeros are inserted between the M DFT outputs .Also, prior to IFFT, some zeros are inserted on either side of DFT output. Zeros that are inserted in between the DFT outputs result in waveform repetition in time domain while zeros appended on the sides provide up-sampling or sinc interpolation.

2.9 Design of SC-FDMA for LTE

2.9.1 Transmit processing for LTE

Frequency domain generation of SC-FDMA is almost same in function as Time domain SC-FDMA generation but there may be some requirement for slightly different parameterization for generating efficient signal to transmit. Frequency domain method has more bandwidth efficiency compared to time domain processing as it has zero excess bandwidth resulting from zero padding and IFFT.

As an example, consider an operating BW of 5MHz. With time domain implementation with 256 subcarriers and 16KHz spacing results in a sampling rate of 4.096 Mps which gives 82% bandwidth efficiency. On the other hand with almost equivalent parameters (300 subcarrier and 16KHz spacing), we get 90 % BW utilization giving 10% increase in spectral efficiency compared to time domain implementation and this results for higher data rate.

Also, in time domain generation use of pulse shaping filter requires ramp up and ramp down times of 3-4 samples duration and also results in reduction of CM by 0.25 to 0.5 dB compared to DFT-S-OFDM ,where is no explicit pulse shaping filter .This is shown in Figure 2.25.

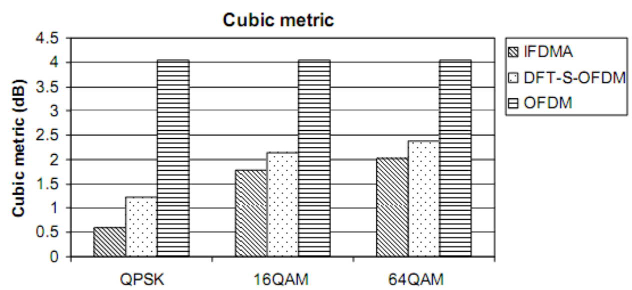


Figure 2.25 CM Metric comparison [16]

So, In conclusion we can say that there is tradeoff between the CM reductions and spectral efficiency while choosing time or frequency domain SC –FDMA signal generation. In LTE uplink , mostly DFT-S-OFDM method is used to generate SC-FDMA signal because it provides commonality with downlink OFDM technique as it has same parameters like same 15KHz spacing, CP length and number of subcarriers in a given bandwidth.

2.9.2 SC-FDMA Parameters for LTE:

Many of the parameters in uplink are same as Downlink like: We have a 10ms frame in uplink with 20 slots (10 sub frames) with slot duration being 0.5ms and the subcarrier spacing being 15 KHz. CP durations are also same as that of downlink- 4.69 microsecond for normal CP and 16.67 microseconds for extended CP (used for cells with larger delay spread characteristics). Parameters are listed in following table:

Table 2.3 LTE uplink SC-FDMA parameterization [16]

Parameter	Value	Description
Subframe duration	1 ms	
Slot duration	0.5 ms	
Subcarrier spacing	15 kHz	
SC-FDMA symbol duration	66.67 μs	
CP duration	Normal CP:	5.2 μs first symbol in each slot, 4.69 μs all other symbols
	Extended CP:	16.67 μs all symbols
Number of symbols per slot	7 (Normal CP) 6 (Extended CP)	
Number of subcarriers per RB	12	

One difference compared to DL is that the uplink coverage is limited in because of the maximum UE transmit power capability, especially at the cell edge. A new concept was introduced for handling this –TTI bundling- the main purpose of which is to improve the cell edge coverage and in house reception for voice. So, as soon as the eNodeB finds that UE is unable to boost up the transmission power and reception is getting worse-it can instruct UE to activate TTI bundling in which the same packet can be sent in consecutive TTIs with different error detection and correction bits thus it saves a lot more signaling overhead. Holma and Toskala have anticipated 4dB cell edge gain for VOIP if TTI bundling is used.

2.10 Uplink Reference signal

Uplink reference signals are always UE specific and it cannot be frequency multiplexed with data transmission as if it is done so it will look like multicarrier transmission and would violate the single carrier property and would result in increased PAPR/CM.

There are two types of uplink reference signals supported -1.Demodulation reference signal (DMRS) which is used to estimate the channel for PUSCH or PUCCH demodulation and 2. Sounding reference signal (SRS) used to measure uplink channel quality.

The uplink demodulation reference signals for normal CP and extended CP is shown in Figure 2.26 and Figure 2.27.

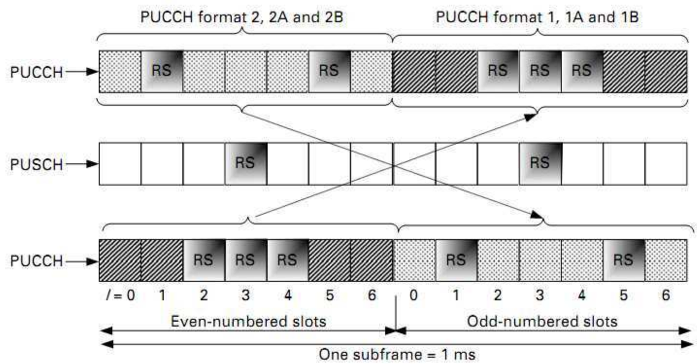


Figure 2.26 Uplink demodulation reference signals for the normal cyclic prefix [3]

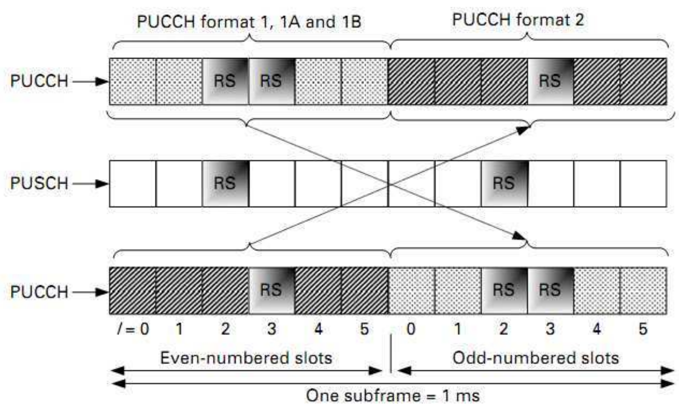


Figure 2.27 Uplink demodulation reference signals for the extended cyclic prefix [3]

For PUSCH, the demodulated reference signal is sent in OFDM symbol l=2 for extended CP case and in symbol l=3 for Normal CP.

In case of PUCCH, for format 1,1A and 1B the demodulation signal is sent in OFDM symbol number l=2, 3,4 for normal CP case and in two symbols l=2,3 for extended case. For PUCCH format 2,2A and 2B the demodulation reference signal for normal CP case is sent in symbols l=1, 5 and for Format 2, the ref signal is sent in single symbol (l=3) for extended cyclic case.

2.11 Uplink user data transmission

In uplink the user data is carried over the channel called Physical uplink shared channel, which is 10ms in length. It is based on the allocation of resource in time and frequency domain with 1ms and 180 KHz resolution. eNodeB schedules the resource allocation as shown in Figure 2.28.

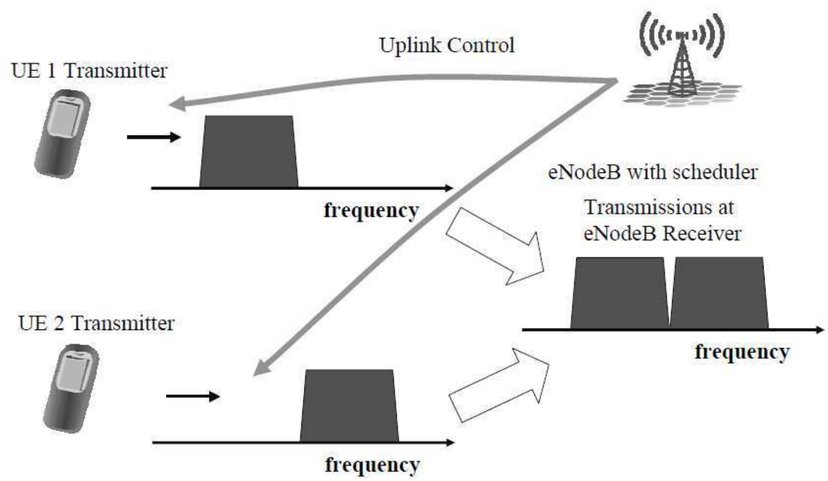


Figure 2.28 Uplink resource allocation controlled by eNodeB scheduler [1]

If there is no prior signaling, UE cannot transmit anything, it can only attempt to begin random access procedure by using random access resources.

By now we know that we have a sub frame of 1ms with 2 slots in it each of 0.5ms. Both user data and reference symbols have to be carried in this 0.5ms slot along with control signaling. We have two possibilities of using cyclic prefix in uplink- short or extended. Thus depending on which type of CP has to be used, we can have either 6 or 7 symbols in a 0.5ms slot.

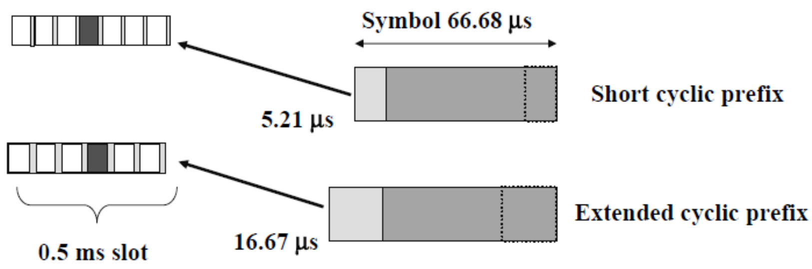


Figure 2.29 Uplink slot structure with short and extended cyclic prefix [1]

The instantaneous user data rate is uplink is function of many things like:

- Modulation scheme used- To have varied user data rate 2, 4 or 6 bits symbol per modulation symbol can be used depending upon the modulation order like QPSK, 16QAM or 64QAM.
- Bandwidth applied-For example with 1.4 MHz, the overhead is maximum and we have 12 subcarrier per PRB as against 1200 subcarrier in 20 MHZ band width.
- Channel coding applied.

As a rough estimate, the user data in uplink varies from 700 Kbps to 86 Mbps.

Figure 2.30 shows the channel coding chain for uplink. We can see that the data and control symbols are coded separately and later on for true transmission –mapped to separate symbols. In LTE, it was decided that control information will have specific location around the reference symbols and thus they are placed in predefined set of modulation symbol. However, the modulation used is same for data and control signal within 1ms TTI.

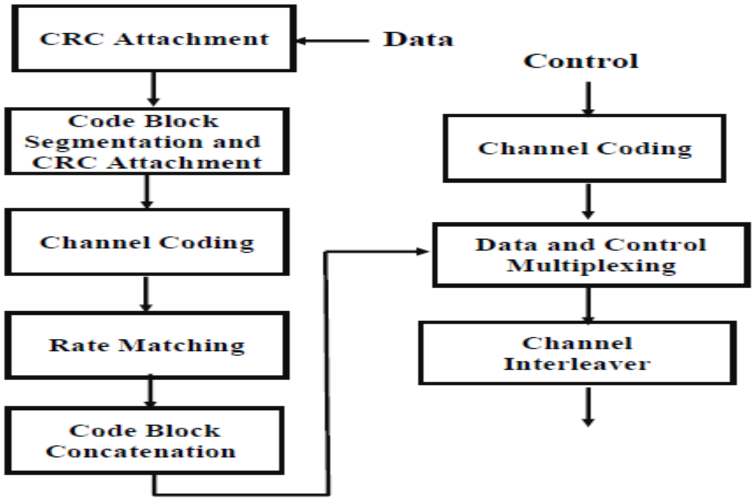


Figure 2.30 PUSCH channel coding chain [1]

2.12 Peak data rates

2.12.1 L1 Peak Bit Rates for Downlink

The peak data rate provided by L1 depends on many parameters like bandwidth, order of modulation and whether multi stream transmission is being used or not. QPSK carries 2 bits per symbol and 64QAM carries 6 bits per symbol –so if no coding is used then QPSK carries 2bps and 64 QAM carries 12bps and if ½ coding is implemented then it will be 1bps and 6bps for QPSK and 64 QAM respectively.

In general following formula is used to calculate the raw L1 throughput rates:

$$Peak\ bit\ rate\ [Mb/s] = \frac{Number\ of\ symbols\ per\ Subframe}{1ms} * \left(\frac{bits}{Hz}\right) * Numbers\ of\ Subcarriers$$

Depending on this different rates on DL can be listed below depending up the BW with theoretical maximum up to 325 Mbps with 4x4 MIMO.

Table 2.4 Downlink Peak bit rates (Mbps) [1]

Resource blocks								
Modulation and coding	Bits/ symbol	MIMO usage	1.4 MHz 6	3.0 MHz 15	5.0 MHz 25	10 MHz 50	15 MHz 75	20 MHz 100
QPSK 1/2	1.0	Single stream	0.8	2.2	3.7	7.4	11.2	14.9
16QAM 1/2	2.0	Single stream	1.5	4.4	7.4	14.9	22.4	29.9
16QAM 3/4	3.0	Single stream	2.3	6.6	11.1	22.3	33.6	44.8
64QAM 3/4	4.5	Single stream	3.5	9.9	16.6	33.5	50.4	67.2
64QAM 1/1	6.0	Single stream	4.6	13.2	22.2	44.7	67.2	89.7
64QAM 3/4	9.0	2×2 MIMO	6.6	18.9	31.9	64.3	96.7	129.1
64QAM 1/1	12.0	2×2 MIMO	8.8	25.3	42.5	85.7	128.9	172.1
64QAM 1/1	24.0	4×4 MIMO	16.6	47.7	80.3	161.9	243.5	325.1

2.12.2 L1 Peak Bit Rates for Uplink

Table 2.5 Uplink Peak data rates [1]

Resource blocks								
Modulation and coding	Bits/ symbol	MIMO usage	1.4 MHz 6	3.0 MHz 15	5.0 MHz 25	10 MHz 50	15 MHz 75	20 MHz 100
QPSK 1/2	1.0	Single stream	0.9	2.2	3.6	7.2	10.8	14.4
16QAM 1/2	2.0	Single stream	1.7	4.3	7.2	14.4	21.6	28.8
16QAM 3/4	3.0	Single stream	2.6	6.5	10.8	21.6	32.4	43.2
16QAM 1/1	4.0	Single stream	3.5	8.6	14.4	28.8	43.2	57.6
64QAM 3/4	4.5	Single stream	3.9	9.7	16.2	32.4	48.6	64.8
64QAM 1/1	6.0	Single stream	5.2	13.0	21.6	43.2	64.8	86.4

Up to 86 Mbps is achieved with 64 QAM and 57 Mbps with 16 QAM –if 20 MHz is the operating Bandwidth. The peak data rate is much lesser than DL and the reason being that in release 8 , use of multi antennas a UE side is not specified as it will need two power amplifiers and increased the volume and cost of the UE.

2.13 Link Budgets

The main purpose of preparing link budget in any type of wireless communication system is to estimate the path loss between the base station and mobile station. It gives an idea of maximum signal attenuation and this information if calculated with proper propagation model gives the cell range –i.e. the number of base station to cover the whole coverage area.

The parameters for LTE uplink and downlink link budget calculations are given in following table. It is calculated for 1Mbps DL with 2 antennas UE receive diversity and 64Kbps UL with 2 antenna receiver diversity.

Table 2.6 Uplink Link budget [1]

	Uplink	GSM voice	HSPA	LTE
	Data rate (kbps)	12.2	64	64
	Transmitter – UE			
a	Max tx power (dBm)	33.0	23.0	23.0
b	Tx antenna gain (dBi)	0.0	0.0	0.0
c	Body loss (dB)	3.0	0.0	0.0
d	EIRP (dBm)	30.0	23.0	23.0
	Receiver – Node B			
e	Node B noise figure (dB)	–	2.0	2.0
f	Thermal noise (dB)	−119.7	−108.2	−118.4
g	Receiver noise (dBm)	–	−106.2	−116.4
h	SINR (dB)	–	−17.3	−7.0
i	Receiver sensitivity	−114.0	−123.4	−123.4
j	Interference margin (dB)	0.0	3.0	1.0
k	Cable loss (dB)	0.0	0.0	0.0
l	Rx antenna gain (dBi)	18.0	18.0	18.0
m	Fast fade margin (dB)	0.0	1.8	0.0
n	Soft handover gain (dB)	0.0	2.0	0.0
	Maximum path loss	162.0	161.6	163.4

Where d=Calculated as a + b – c; g= e + f; i= as g + h;

Table 2.7 Downlink Link budget [1]

	Downlink	GSM voice	HSPA	LTE
	Data rate (kbps)	12.2	1024	1024
	Transmitter – Node B			
a	Tx power (dBm)	44.5	46.0	46.0
b	Tx antenna gain (dBi)	18.0	18.0	18.0
c	Cable loss (dB)	2.0	2.0	2.0
d	EIRP (dBm)	60.5	62.0	62.0
	Receiver – UE			
e	UE noise figure (dB)	–	7.0	7.0
f	Thermal noise (dB)	−119.7	−108.2	−104.5
g	Receiver noise floor (dBm)	–	−101.2	−97.5
h	SINR (dB)	–	−5.2	−9.0
i	Receiver sensitivity (dBm)	−104.0	−106.4	−106.5
j	Interference margin (dB)	0.0	4.0	4.0
k	Control channel overhead (%)	0.0	20.0	20.0
l	Rx antenna gain (dBi)	0.0	0.0	0.0
m	Body loss (dB)	3.0	0.0	0.0
	Maximum path loss	161.5	163.4	163.5

Where d = a + b – c; g = e+ f; i = g + h

From the link budget shown it can be concluded that the path loss for LTE is comparable with existing system like HSPA and thus deployment of LTE is possible with GSM and HSPA sites with the assumption that same frequency will be used for LTE as is being used for HSPA and GSM. This is summarized in Figure 2.31. As the transmission power level, noise figures etc. are almost the same for LTE as for GSM and HSPA, LTE as such does not provide any coverage boost.

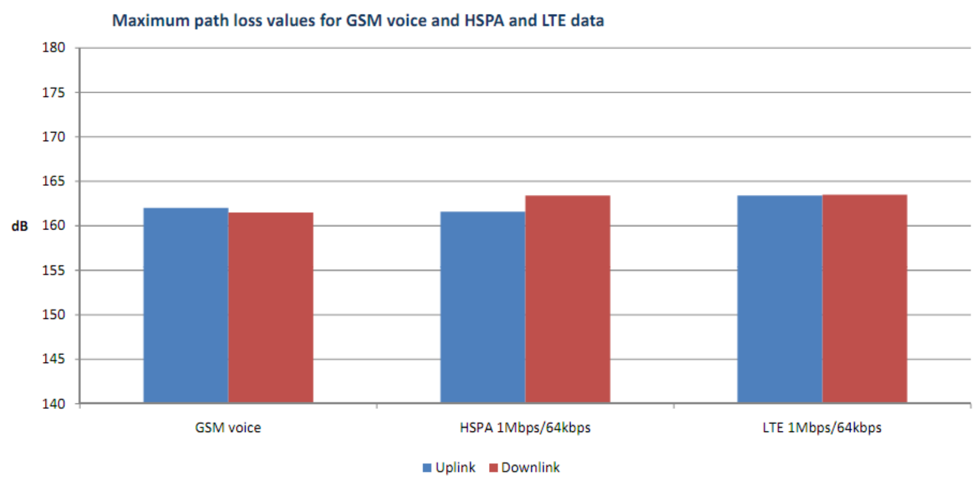


Figure 2.31 Link Budget comparison GSM/LTE/HSPA [1]

Link budget is defined for 64 Kbps uplink .This is not a very true high data rate for broadband service. If high data rates have to be achieved- low frequency deployment is necessary with additional sites and some additional antenna. At lower frequency the wave propagation is better as compared to higher frequency. A comparison is shown in following table considering 900 MHz and 2600 MHz, however a small loss with the use of lower frequency band is that antenna gains tend to be lower and to increase the antenna gain we need to use larger antenna which is not always feasible at UE side. So, for an optimum solution with lower frequency, we can use around 2.5 m antenna at eNode B side and external antenna at terminal, which will a fixed wireless case.

The typical cell ranges has been calculated based on the Okumura- Hata model (with parameters in following table). The cell range is calculated for 900, 1800 2100 and 2600 MHz frequency bands.

Table 2.8 Okumura–Hata propagation model parameters [1]

	Urban indoor	Suburban indoor	Rural outdoor	Rural outdoor fixed
Base station antenna height (m)	30	50	80	80
Mobile antenna height (m)	1.5	1.5	1.5	5
Mobile antenna gain (dBi)	0.0	0.0	0.0	0.0
Slow fading standard deviation (dB)	8.0	8.0	8.0	8.0
Location probability	95%	95%	95%	95%
Correction factor (dB)	0	−5	−15	−15
Indoor loss (dB)	20	15	0	0
Slow fading margin (dB)	8.8	8.8	8.8	8.8
Max path loss at 1800/2100/2600 (dB)	163	163	163	163
Max path loss at 900 (dB)	160	160	160	160

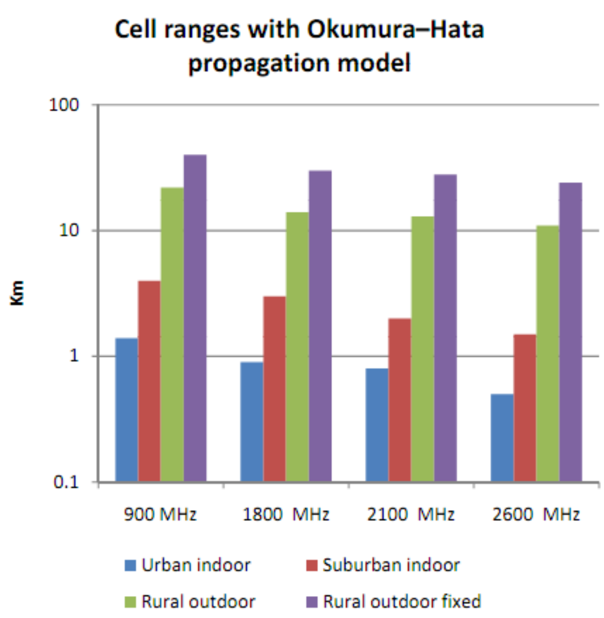


Figure 2.32 Cell ranges with Okumura –Hata propagation model [1]

For urban areas LTE provides the same coverage as for GSM i.e (0.6Km to 1.4Km)

Range for suburban varies from 1.5 km to 3.4 km. In rural areas due to less sources of multipath and scattering higher cell ranges of upto 26 km is achieved with mobile operation and even up to 50 km for fixed installation at 900 MHz.

CHAPTER 3

PHYSICAL LAYER PROCEDURES

The Main Physical layer procedures in LTE system are HARQ, Power control, timing advance and random access. We will start discussing all the procedures one by one in brief.

3.1 HARQ Procedure

In LTE, HARQ is based on stop and wait HARQ procedure. UE gets a packet from the enode B and provides the feedback in PUCCH channel. For a NACK, enode B will send a retransmission. Upon receiving this retransmission, UE combines this with the original transmission and runs the turbo decoding again .If the decoding is successful, UE will transmit Positive ACK. Now, upon receiving this ACK, eNodeB will be sending a new packet for this HARQ process done. To enable a continuous data flow, one will need to have continuous HARQ procedures because this is stop and wait way of operating. In LTE, the number of process is fixed to be 8, let us see how this particular number is derived.

The number of HARQ N_{HARQ} process can be given as:

$$N_{HARQ} = \left\lceil \frac{2T_p + T_{sb} + T_{uep} + T_{ack} + T_{nbp}}{T_{sb}} \right\rceil$$

where the propagation time between eNB and the UE is denoted by Tp , T_{sb} is the subblock transmission time, T_{uep} denotes UE processing time which includes the decoding times, T_{ack} ACK/NACK will be the transmission time and lastly eNB processing time is taken care by T_{nbp}. The relationship between these parameters is shown in Figure 3.1.

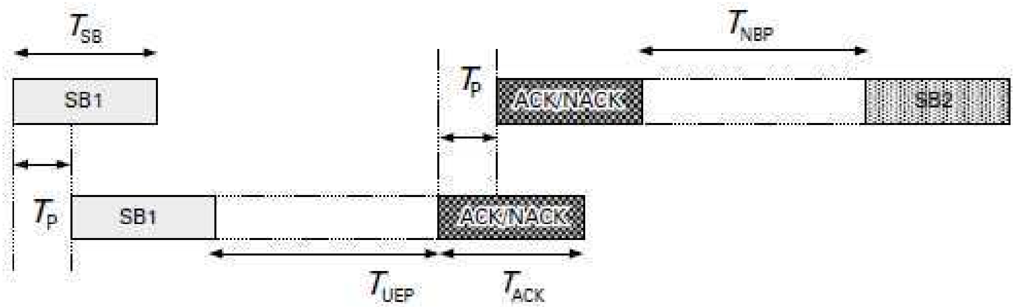


Figure 3.1 Stop-and-wait hybrid ARQ round-trip time (RTT) [3]

The propagation time T_p is generally very small compared to the sub block transmission time and can be ignored. The sub block transmission time is selected to be only 1 ms in LTE as a compromise between latency and signaling overhead. T_{uep} is the UE processing time which involves the total amount of time which is required to process and decode the sub block. The turbo decoding delays is the major component in UE process time. The value for UE processing time is selected as a compromise between complexity and latency and in LTE it is 3 sub frames (3 ms). For reliability reasons, T_{ack} which is time period in which the ACK or NACK type of feedback is sent cannot be very short. This is because if the ACK/NACK transmission time will be shorter that means smaller the amount of ACK/NACK signal energy for a given transmit power. As the UE transmit power is obviously smaller compared to eNB, the required ACK/NACK reliability can limit the uplink coverage for short *T*ack. [3]. LTE system assumes the ACK/NACK transmission time to be one sub frame (1 ms). The eNodeB processing time T_{nbp} includes the time the eNB takes to decode ACK/NACK and to make scheduling decision for new transport blocks. As per specification it is assumed to be 3 ms.

Putting all these values in the above equation, we get

$$N_{HARQ} = \left\lceil \frac{(0+1+3+1+3)}{1} \right\rceil = 8$$

To put all the values in table format for ease to depict, we form a table:

Table 3.1 Hybrid ARQ RTT parameters for the LTE System [3]

Parameter	Symbol	Value
Propagation time	T_p	Negligible
Subblock transmission time	T_{sb}	1 ms
UE processing time	T_{uep}	3 ms
ACK transmission time	T_{ack}	1 ms
eNB processing time	T_{nbp}	3 ms

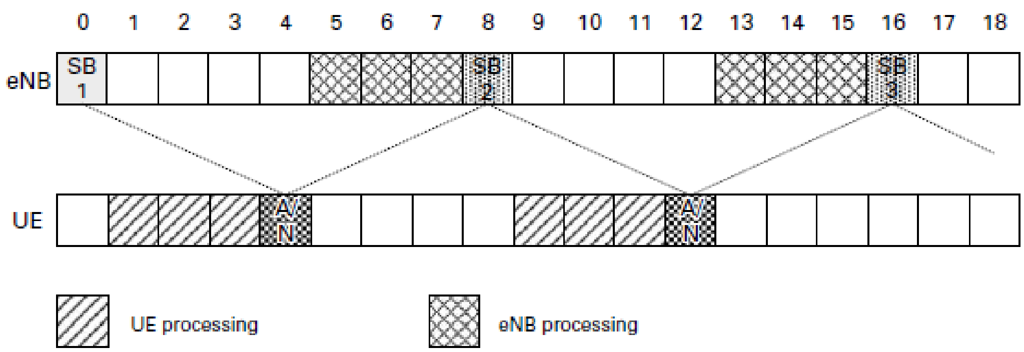


Figure 3.2 An illustration of a hybrid ARQ process in the LTE system [3]

3.2 Power Control

The goal of power control is to have adequate amount of power necessary for certain data rate. Too much of power causes interference and very little power will result in poor energy/signal and which in effect increase the error rate and to combat that retransmission will be required and thus delays come into picture and average data rate drops.

In Case of WCDMA, we had non orthogonal uplink transmission where cell centered UEs dominate the cell edged UEs and created the near far affect. Thus, we had to use very extensive power control mechanism based on fast closed –loop power control.

In LTE , as we do have SC-FDMA access, near far problem is not there but some degree of interference from neighboring cells are still present which are enough to limit the uplink coverage. We encounter increased Interference over Thermal (IoT), which limits the uplink coverage at the desired cell. Hence we need to have some kind of power control; however it need not be as extensive and elaborate as we have in WCDMA. Even If we perform slow power control on each UE uplink transmission, we get success in reducing the average inter –cell interference at eNodeB.

Due to data rate changes, the bandwidth will also vary and the values of absolute power transmitted by UE will also change. Uplink power control in LTE does not change the absolute power at user rather it controls the power spectral density (PSD), power per HZ, for a particular UE.

The basic principal of Uplink power control is described in Figure 3.3 where even if the data rate changes the PSD remains constant but according to the data rate variation, the total transmission power is adjusted.

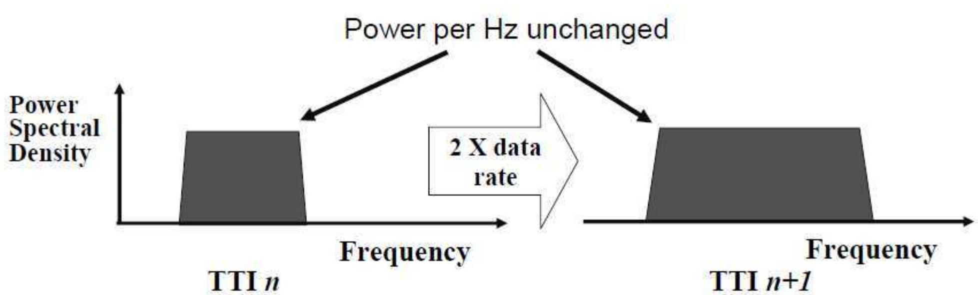


Figure 3.3 LTE uplink power with data rate change [1]

One has to estimate the path loss, consider cell specific parameters etc. to derive the actual power control and then applying the accumulated value of correction factor from enodeB.

Depending on the higher layer parameter settings, the power control command is either 1 dB up or down or then the set of [−1dB, 0, +1dB, +3 dB] is used. [1] .In LTE we have slightly smaller- total dynamic range of power control compared to WCDMA. In LTE devices now have a minimum power level of −41 dBm and in WCDMA, it is-50 dbm.

There are two possibilities of power control command:

1) Part of scheduling decision
   a) Downlink assignment (PUCCH) - In this case, we include 2 bits of power control in PUCCH.
   b) Uplink grants (PUSCH).
2) Separate power control command (DCI format 3/3A) - It is also possible to send the power control command only and not as the part of scheduling decision. This type of power control may be used if one decides to use a periodic power control scheme for example sending control message every 10 ms or so.

The first option is aperiodic method, where there is no periodicity. In LTE system first option is used most popularly. We can say that we have event based power control unlike WCDMA that is we need not send TPC at regular interval. Now let's see uplink power control on PUCCH and PUSCH.

3.2.1 Uplink power control on PUCCH

$$P_T = \min\{P_{max}, P0+PL_{DL}+\Delta_{Format}+^{\delta}\}$$

Where, Pmax is the maximum power that can be transmitted by the UE. P0 is the cell specific parameter and is specified in the system information; it controls the received SIR for PUCCH. PLDL is the measured path loss in DL which UE keep measuring. $\Delta_{\text{Format is}}$ included to handle different SIR requirements by different PUCCH formats. For example if you have PUCCH format 1, we transmit 1 or 2 bits and if we have PUCCH format 2 , we transmit multiple bits. Obviously with multiple bits, we need a larger transmitted power. $^{\delta}$ represents accumulated power control bits .It can be a part of downlink assignment where it may take values -1.0 , 0 ,+1,+3 etc.

3.2.2 Uplink power control on PUSCH

The formula for Uplink PUSCH power control is almost the same except few changes.

$$P_T = \min\{ P_{max}, P_0+\alpha PL_{DL}+ 10 \log_{10}(M)+\Delta MCS+^{\delta} \}$$

We have an extra term α added which compensates for Fractional path loss. If we set α equal to 1 then we compensate completely for the path loss, and if we set it less than 1 (0.4,0.5,0.6,0.7,0.8,0.9) , we compensate partially which means we transmit less power and thereby reducing the interference for the other cell. M is is the size of the PUSCH resource assignment expressed as the number of resource .In order to assure the same power spectral density irrespective of the number of resource blocks allocated for uplink transmission blocks ,the transmit power shall be increased proportional to M. The other different term is ΔMCS which is specified to handle different SNR requirements for different MCS. For example depending upon what type of modulation we are using 16 QAM, QPSK or 64 QAM, we need different level of powers.

Let's see this in more detail by segregating the power control methods in two options.

3.2.3 Open loop power control

Open loop power control is capability of the UE transmitter to set its uplink transmit power to a specified value suitable for receiver. It can be noted that $^{\delta}$ is signaled by enodeB to any UE after it sets its initial power so it does not have any contribution in the initial setting of the UE transmit power. [7] So the above equation gets reduced to

$$P_{OL}= \min\{P_{max}, P0+\alpha PL_{DL}+ 10 \log_{10}(M) \} \text{ [dbm]}$$

Following block diagram shows steps that are involved in setting uplink transmission power where it is worth noting that the path loss is measured as per reference symbol received power (RSRP). Then above equation can be used to calculate transmission power.

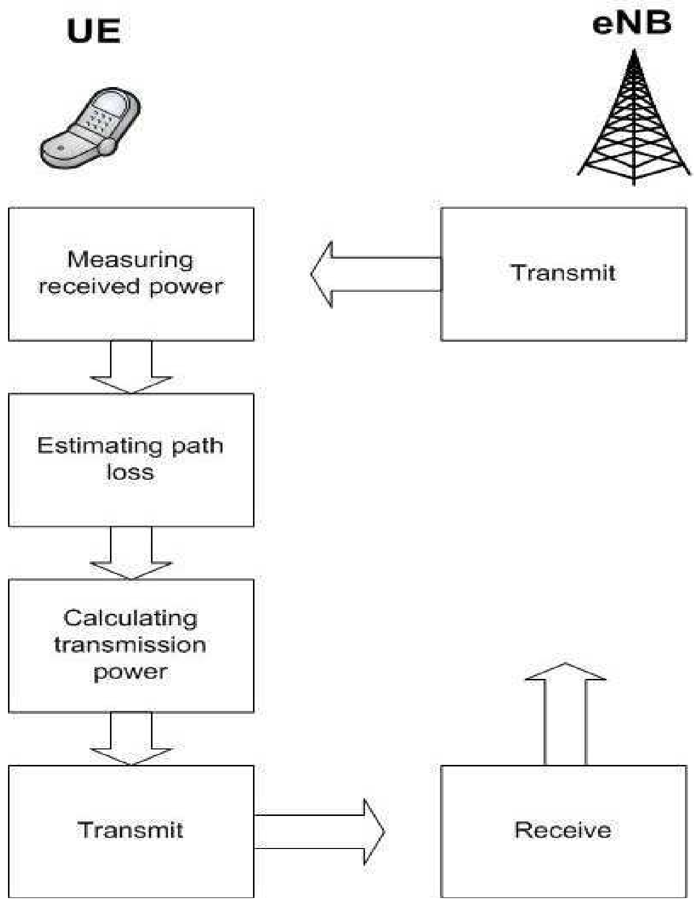


Figure 3.4 Block diagram of steps involved in setting uplink power using open loop power control [7]

3.2.4 Closed loop power control

In this type of power control methodology, UE can adjust its transmission power as per the closed loop correction value also known as transmit power control (TPC) commands. eNodeB compares the received SINR and compares it with target SINR and generates TPC commands to send it across to UE.

The LTE closed loop power control works around the open loop point of operation. When the UE is involved in setting uplink power using open loop power control method, it can also adjust its power based on TPC that enodeB sends. The boxes which are shaded defines closed loop power component.

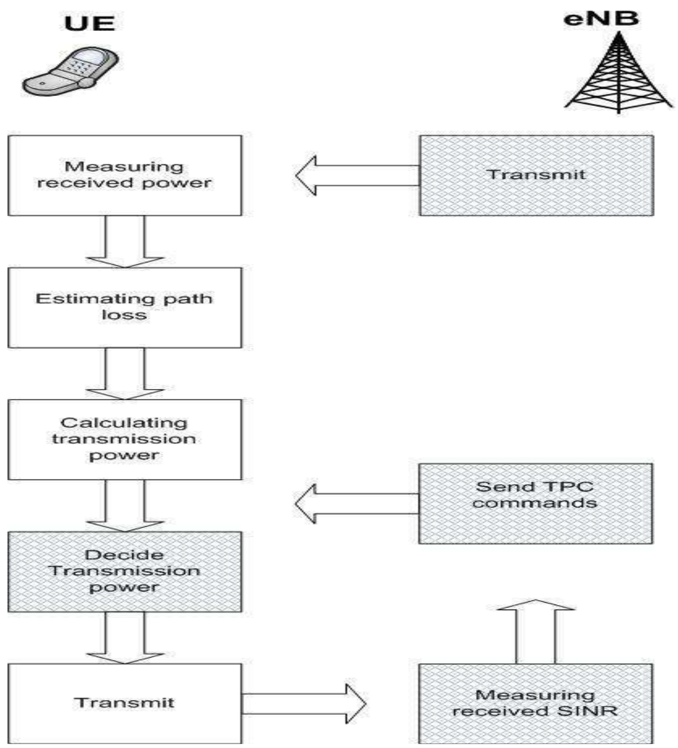


Figure 3.5 Block diagram of steps involved in adjusting open loop point of operation Using closed loop power control [7]

3.3 Random Access

Random Access may be needed when UE comes from a sleep mode, performs HO with another cell or when sometimes it loses the synchronization on uplink. It should be noted that we always assume that the UE is downlink synchronized with eNodeB while performing the Random access. For an example, whenever the UE comes out of a sleep mode, it has to first extract (PSS & SSS) along with some System information which may contain Random access specific parameters. When UE is done with acquiring the downlink timing synchronization, it can start the random access by sending random access preamble. Upon receiving this, eNodeB sends the random access response along with timing advance information (TA) and uplink resource allocation information to the UE. UE can determine whether or not the preamble was successfully received by comparing the preamble number contained in the random access response message obtained from the eNodeB. If UE determines that the preamble number matches, it goes ahead with adjusting the uplink timing with help of TA (receive in response) from eNodeB. This is how a UE acquires the uplink timing and now it can proceed with sending the resource request on uplink using the resources allocated in random access response message. Figure 3.6 explains the above procedure:

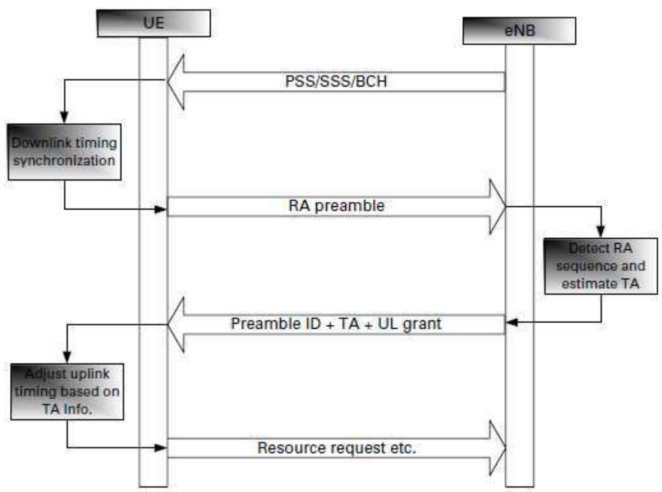


Figure 3.6 An example of random access procedure [3]

3.3.1 Random Access Preamble formats

As Random access procedure is performed by UE when it is not synchronized on uplink, a guard time (GT) is needed to avoid the collision with any other transmission that is going on. The guard timing should be such that it should take into account the round trip delay and is dependent on the cell size which is supported, as shown in Figure 3.7.:

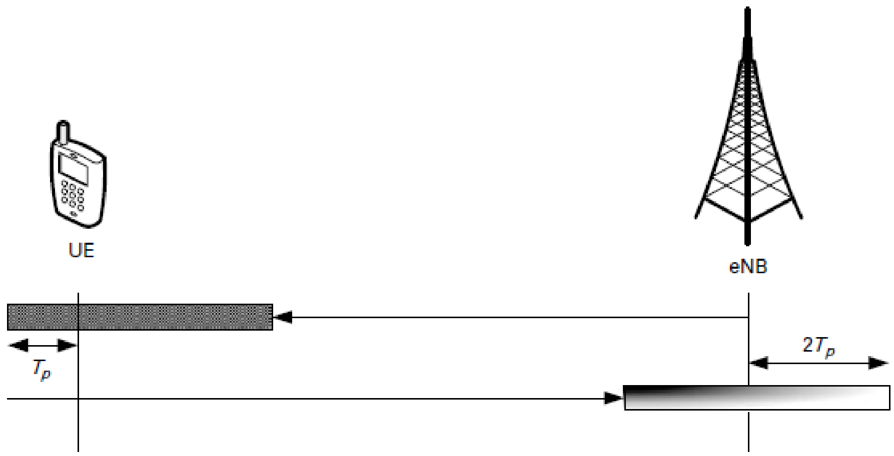


Figure 3.7 Round trip propagation time [3]

If the propagation speed is 1 km/3.33μs, we need approximately 6.7μs of GT per kilometer to accommodate the round-trip time. With the cell size of up to 100 km as required for LTE, the guard time should be around of 670 μs. But sometimes this big GT may result in extra overhead and is not much compatible with smaller cell sizes which may be the case in some cities. So, to handle this different preamble formats have been designed as shown below in the Figure 3.8:

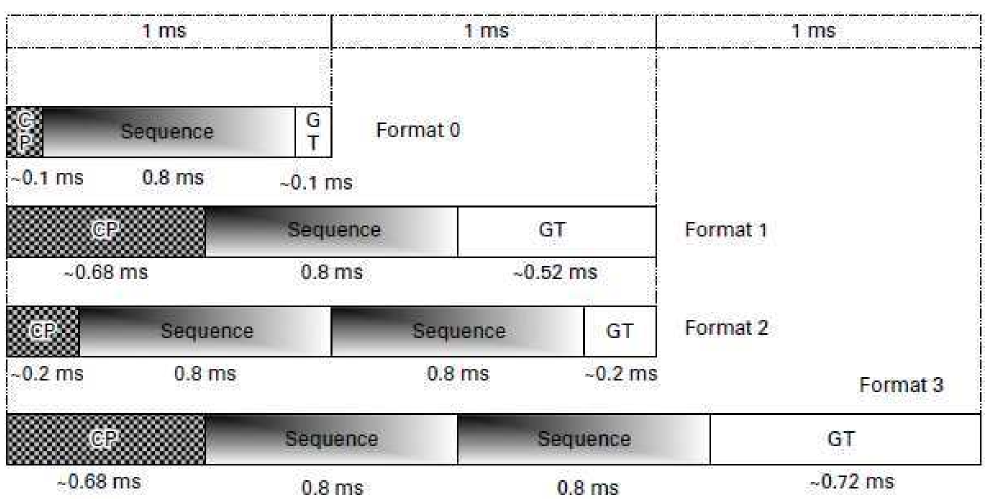


Figure 3.8 Random access preamble formats [3]

In order to enable simple frequency-domain processing, the random access preamble also uses a cyclic prefix [3]. It can be seen that the preamble length is always 0.8ms. In format 0, the size of the GT and CP both are ~0.1ms which will be enough to support cell with a size of 15Km. Format 1 has CP as 0.68ms and GT as 0.52ms, which will be sufficient to support the cell size of 70 Km. Sometimes one matter of concern is that whether the preamble length of 0.8ms has enough energy to be heard by the base station or not.

To handle such scenarios, 2 more formats were defined in which the preamble is repeated twice. In format 2, both CP and GT have length of .2ms and it will be enough to support the cell with range of 30 Km. For format 3, CP and GT are fixed to be 0.68ms and 0.72ms respectively which will support the cell size of 100 Km. Following table summarizes the discussion.

Table 3.2 Random access preamble parameters [3]

Preamble format	T_{CP}	T_{SEQ}	T_{GT}	$T_{CP} + T_{SEQ}$ $+T_{GT}$
0	$3168 \cdot T_s \approx 0.1$ ms	$24576 \cdot T_s = 0.8$ ms	$2976 \cdot T_s \approx 0.1$ ms	$3072 \cdot T_s = 1$ ms
1	$21024 \cdot T_s \approx 0.68$ ms	$24576 \cdot T_s = 0.8$ ms	$15840 \cdot T_s \approx 0.52$ ms	$2.3072 \cdot T_s = 2$ ms
2	$6240 \cdot T_s \approx 0.2$ ms	$2.24576 \cdot T_s = 1.6$ ms	$6048 \cdot T_s \approx 0.2$ ms	$2.3072 \cdot T_s = 2$ ms
3	$21024 \cdot T_s \approx 0.68$ ms	$2.24576 \cdot T_s = 1.6$ ms	$21984 \cdot T_s \approx 0.72$ ms	$3.3072 \cdot T_s = 3$ ms

3.3.2 Random Access MAC procedures and formats

3.3.2.1 Random Access MAC Procedures

Random access procedure can be performed in two ways, either by a PDCCH (physical downlink control channel) order or by the MAC sub layer. In a case where UE sends data on uplink and eNodeB comes to know that UE has gone out of sync, PDCCH order is used. In rest of the cases, it is the MAC which will initiate the random access procedure. There are some of the parameters which UE may have access to before beginning the random access .This can include set of PRACH resources and their corresponding RA-RNTIs (random access radio network temporary identifiers), the groups of random access preambles and the set of available access preambles in each group, the thresholds required for selecting one of the two groups of preambles, the parameters required to derive the TTI window, the power-ramping factor POWER_RAMP_STEP, the parameter PREAMBLE_TRANS_MAX, the initial preamble power PREAMBLE_ INITIAL_RECEIVED_TARGET_POWER, etc. [3] . The random access procedure is initiated by setting PREAMBLE_TRANSMISSION_COUNTER =1 and setting back off parameter =0. After this UE sees whether the random access preamble and PRACH resource is explicitly assigned by eNodeB or UE has to select it out from the two preamble groups. In the first case of explicit assignment, UE can directly go ahead and transmit the preamble. In second case, it selects the group out of 2 based on the size of message to be transmitted on uplink and also taking into account the channel conditions. Once the group is selected, UE can randomly select the preamble from that group. After this Preamble transmit power is set by UE as:

$$\text{PREAMBLE\_RECEIVED\_TARGET\_POWER} = \text{PREAMBLE\_INITIAL\_RECEIVED\_TARGET\_POWER} + (\text{PREAMBLE\_TRANSMISSION\_COUNTER} - 1) \times \text{POWER\_RAMP\_STEP}$$

If the Maximum number of preamble transmission attempts is reached, MAC layer notifies upper layer about the random access problem. Alarming situation is raised if:

$$\text{PREAMBLE\_TRANSMISSION\_COUNTER} = \text{PREAMBLE\_TRANS\_MAX} + 1$$

3.3.2.2 Random access MAC PDU format

In response to the UE random access, a random access response PDU is sent by eNodeB which may consist of one or more MAC random access response (MAC-RAR) along with a MAC header. This MAC header size may vary and therefore we have a field called extension field (E). It’s a one bit flag indicating whether more fields are there in the MAC header or not. Another field (T) that is Type field indicates whether sub header has Random access ID(RAID) or back off indicator(BI).

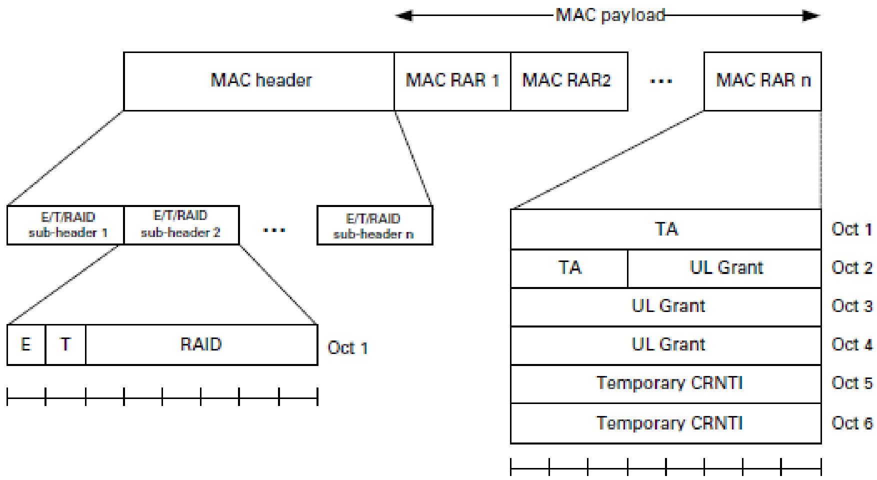


Figure 3.9 MAC PDU consisting of a MAC header and MAC RARs [3]

The MAC RAR fields have 3 more contents. First is TA, which is necessary for uplink timing synchronization as discussed in previous paragraphs. UL Grant field accounts for the resource to be used in uplink. C-RNTI (cell radio network temporary identifier) is used by UE until another RA procedure is initiated.

Table 3.3 Random access MAC header and MAC RAR fields [3]

Subheader/payload	Field	Bits
E/T/RAID (8-bits)	Extension	1
	Type	1
	Random access ID (RAID)	6
E/T/R/R/BI (8-bits)	Extension	1
	Type	1
	Reserved	2
	Backoff indicator (BI)	4
MAC RAR (48-bits)	Timing advance (TA)	11
	Uplink (UL) grant	21
	T-CRNTI	16

3.4 Cell Search

Cell search is done by UE whenever it powers on and also when it has to select candidate cells while it is travelling inside the network area. So, by a cell search process, UE basically tries to derive the time frequency synchronization and detect the cell identity.

In LTE each cell has a physical layer cell identity and it corresponds to a specific reference signal sequence. We have 504 different cell identities which are grouped into 168 cell identity groups with 3 cell identifiers per group as shown in Figure 3.10.

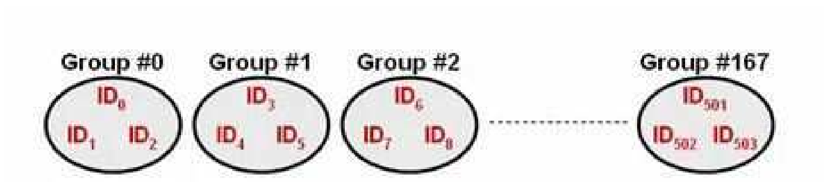


Figure 3.10 Group of cell identities [8]

To obtain the cell identity and downlink timing synchronization, LTE relies on two synchronization signals-Primary synchronization signal and Secondary synchronization channel. Primary synchronization signal can consist of one of the three different sequences. The primary synchronization signal transmitted in a cell is one of these 3 sequences that are possible for PSS.

Figure 3.11 PSS possibilities [8]

When UE performs cell search, it correlates with all 3 sequences that are possible for PSS and tries different timing offset and eventually gets a correlation peak with one of them. Thus on obtaining the peak it knows which identity within the physical layer cell identity group. It still does not know which group but it knows a fixed identity within the group. It also obtains the timing on 5 ms basis as PSS is identical in all the sub frames where it is transmitted. But still frame timing is unknown to UE.

Once PSS is obtained by UE, it tries to find the Secondary synchronization signal (SSS). The SSS is located at well specified location in relation to primary one. Its located next to PSS in FDD mode. So as we have timing information from PSS, we know in time exactly where to correlate for SSS. There are 168 different sequences possible for SSS. So it tries to correlate with all the 168 sequences and once a peak is found it knows which exact group the cell identity belongs to. Is should be noted that the SSS is different in the two sub frames of a frame. It gets frame timing from SSS detection.

Figure 3.12 SSS possibilities [8]

Thus by deriving PSS and SSS, the cell identity is known and it can start reading the BCH (broadcast channel) to get the system information (SI).

In LTE, all the sub frames carry cell specific reference signal. First and third last OFDM symbol within a slot carry the reference signal for antenna port 0 and 1 (R0 and R1).The reference signal for the other two antenna ports (R2 and R3) are carried in second OFDM symbol within a slot.

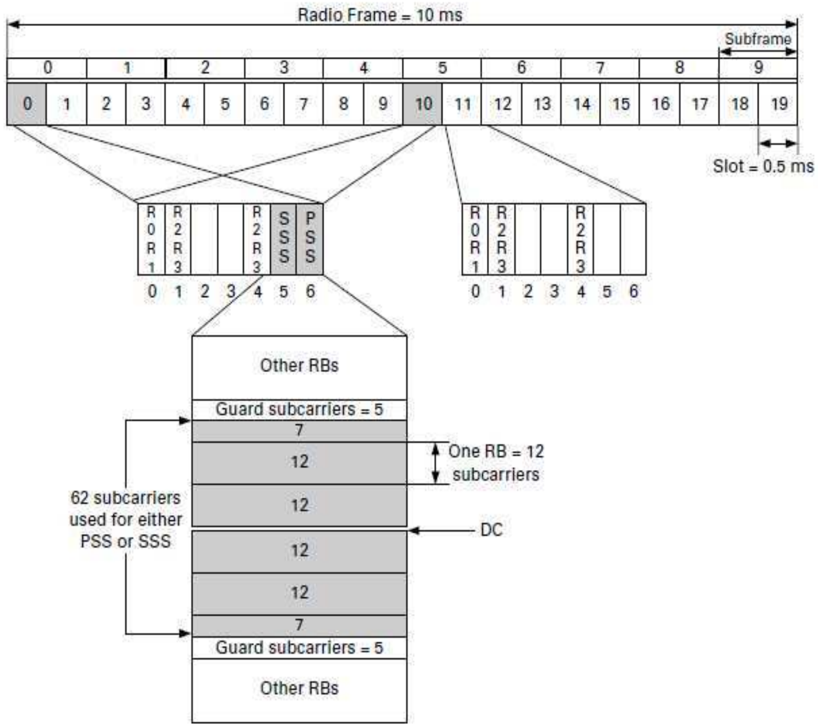


Figure 3.13 Downlink frame structure and location of PSS and SSS [7]

The PSS and SSS are located in last and second last OFDM symbols respectively in slot 0 and slot 10. Out of 72 available subcarriers (in 1.08 MHz BW), only 62 subcarriers are used for PSS and SSS. It should be noted that the DC subcarrier is not transmitted. Also 5 sub carries on each side serve as guard subcarriers.

CHAPTER 4

SMART ANTENNA TECHNOLOGY

4.1 MIMO basics

Many Universities and Labs have been working on multiple antenna techniques for decades and have tried to combine it with some advanced signal processing to improve what is called as smart antenna technology, widely referred as Multi-input multi-output (MIMO). 3GPP has standardized MIMO schemes and made eNodeB scheduler capable of selecting /switching between different MIMO schemes depending upon the channel conditions of the mobile. The very basic method is Spatial multiplexing(SM), where many information streams can be transmitted simultaneously. SM can be augmented with other schemes such as open loop transmit diversity and beam forming , if the radio condition is not good for SM operation. This is the main focus in LTE release 8 –to adapt to channel optimal MIMO. Figure 4.1 illustrates the basic principle of MIMO.

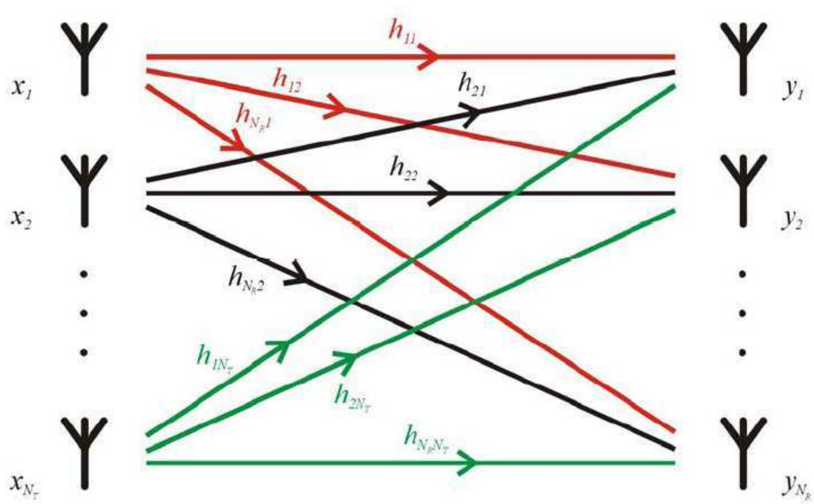


Figure 4.1 MIMO scheme [6]

To separate different antennas from each other, reference symbols are used at the receiver. The receiver has to deal with the impact of channel on individual sub-carriers that have experienced frequency dependent phase and amplitude changes. To make sure that transmission from one antenna should not interfere with antenna, proper channel estimation is needed for separating the different MIMO streams. For this the reference symbols have to map alternately between antennas as shown in Figure 4.2.

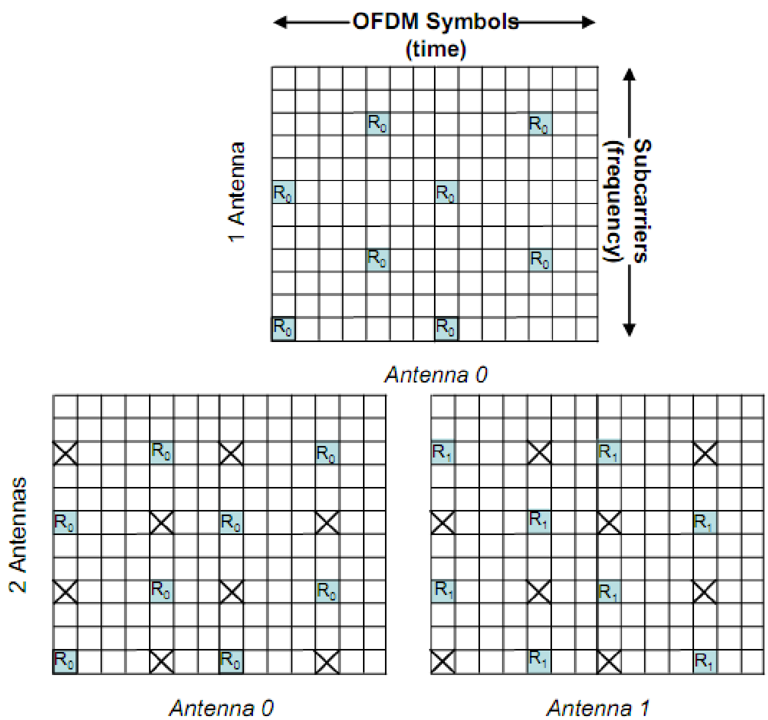


Figure 4.2 Reference Signal Mapping [18]

Reference signals are transmitted on every 6th subcarrier and within first and third last OFDM symbol of each slot. Also other ports of antenna in the cell remain idle when reference signals are being transmitted from one particular antenna.

4.1.1 *Principles*

There are two main aims of having multi antenna transmission

1) Improving SINR

2) Sharing SINR

Improving SINR- The main aim is to transmit the energy in the direction of receiver. Beam forming falls into this category, where effort is made to adjust the phase of the signal transmitted in different antennas so that they can add up at the destination end.

Another scheme which serves for this purpose is transmit diversity using Alamouti space – frequency block code (SFBC) and space time block code (STBC). Actually, it does not improve the SINR rather can help in reducing the variation in SINR that is experienced by the user.

Sharing SNR- Sometimes when SINR level is too high, the throughput increase saturates as shown below in the Figure 4.3:

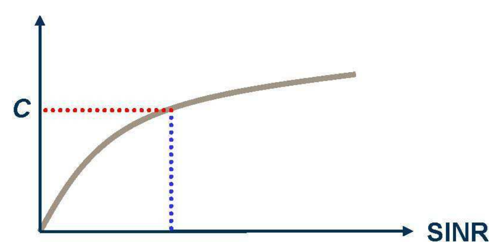


Figure 4.3 Throughput curve versus SINR saturates at high SINR value [12]

So if we use multiple antennas at transmitter and receiver side, we get multiple parallel channels, which share the overall SINR and above mentioned saturation can be avoided.

Basically, such technology is called Spatial Multiplexing, where if we separately encode and modulate the two blocks of information, SINR will be shared.

4.1.2 *Peak rate or coverage*

In real world scenarios, interference occurs from neighboring cell too. This inter-cell interference will be high for the cell edge users compared to the cell center users. These cell edge users operate in the linear part of the above curve, and hence improving the SINR by means of beam forming will be more suitable compared to cell center users who generally operates at high SINR and MIMO transmission using spatial multiplexing will be suitable for them. To put it in another words, for cell edge user, we can make use of rank one transmission and for cell center user's spatial multiplexing (rank larger than one) can be used. Figure 4.4 shows the tradeoff between coverage and throughput for single and multi-rank transmission [12]

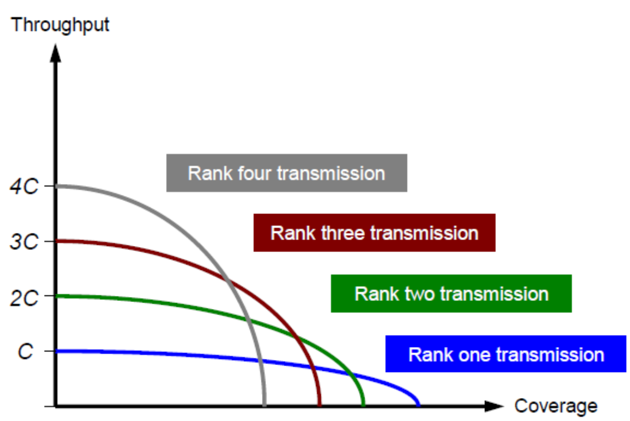


Figure 4.4 Throughput versus coverage for a 4x4 MIMO wireless link [12]

4.1.3 *Precoding*

There are many ways in which the modulated symbols can be put on different transmit antennas. For beam forming case here we define a channel dependent vector "w" which describes the antenna specific phase adjustment, which when multiplied with single symbol s1 gives following transmitted vector:

$$\mathbf{x} = \mathbf{w}s_1 = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_{N_T} \end{bmatrix} s_1 .$$

These phase adjustments are made is such a way that signals which are transmitted from different antennas will add up constructively at the receiver side, so that SINR and hen coverage enhancement is achieved. As the number if transmit antennas is increased, the SINR increases. Figure 4.5 shows the behavior of throughput –vs.-coverage.

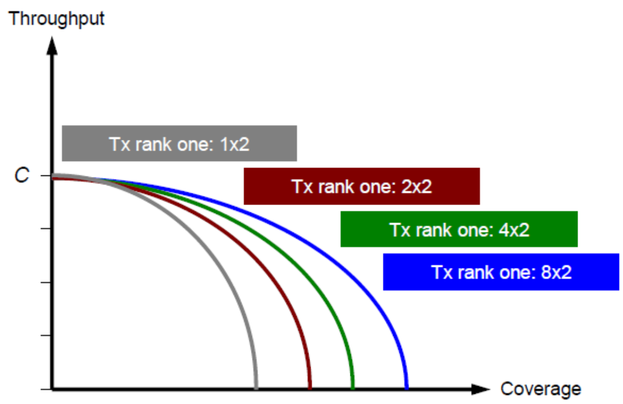


Figure 4.5 Throughput Vs. coverage curves- how the array gain from the use of beamforming improves the throughput on the cell edge [12]

4.1.4 *Choice of Transmission scheme*

There are many factors like UE mobility, Path loss, polarization of the signal, shadowing effect and antenna configuration at the transmitter and receiver will affect the properties of MIMO channels. A large separation between the antennas will result in less correlation between the channels of antennas for fixed angular spread. Also, if the signals transmitted from different antennas have different polarization, correlation is less.

Some of the possible combinations of these configurations of antenna result in following schemes:

-Beam forming: Where Strong spatial correlation is achieved on the transmitter side by having small inter-antenna distance and co polarized antennas.

- Transmit diversity: Using Alamouti coding, we obtain low spatial correlation at transmitter side, by using orthogonally polarized antennas and/or large inter-antenna distance.

- Spatial multiplexing (Single User MIMO): we obtain low spatial correlation on both the transmitter and receiver side transmit/receive antenna pairs provided by either

a) Co-polarized antennas on both transmitter and receiver side with large inter-antenna distances on both sides.

b) Orthogonally polarized antennas on transmitter side and receiver side.

4.2 Antenna configurations

4.2.1 UE antenna configurations

The two most important points to keep in mind while designing the antenna for a UE are antenna volume which will affect UE terminal size and its battery life. Some of the factors that make antenna design in a hand held device more complicated are [12].

-RF complexity and placement

- Correlation with other MIMO antennas

-Coupling with other MIMO antennas, battery, displays etc.

- The position and number of other antennas that support 802.11, Bluetooth, GPS, FM Radio, and other cellular services

- Multiple-band support (e.g., 0.7, 2.1 and 2.6 GHz)

-Polarization, interaction with mechanics (display, battery), ESD and EMC requirements (harmonics), and mass-production limitations all affect antenna design in small, handheld form factors

-SAR and HAC compliance

-Even attenuation caused by hand and head effects can have a large impact on performance

Processing multiple streams with MIMO means demodulating a large amount of data volume and which will result in higher current drain from the battery.

It has been researched that MIMO operates best if the antenna spacing is of the order of 0.5 of a wavelength of the operating frequency. So, for operating in the band of 2.6 GHz may not be much of a problem and may be manageable but with operating frequency in the range of 700 MHz BW will be much of a challenge and a new approached has to be adopted for such low bands of operations which is discussed in following paragraphs.

Following graph shows some of the challenges/complexities with different frequency if operations.

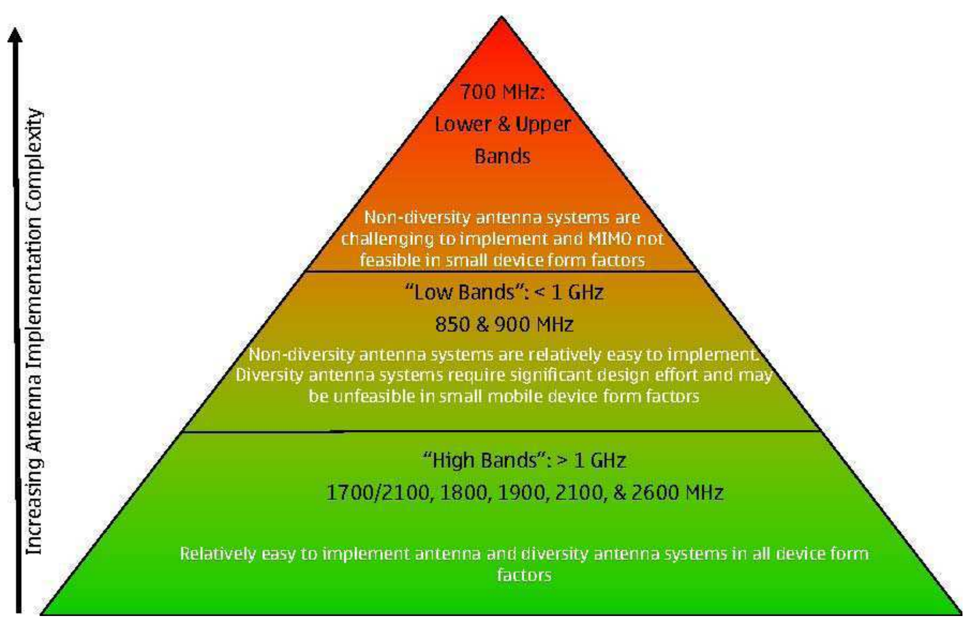


Figure 4.6 Antenna Complexities and Frequency Band [12]

In handheld device-as the antenna spacing becomes smaller, coupling will become greater and antenna pattern will start distorting, which will result in loss in the efficiency of antenna and its correlation is impacted.

Table 4.1 Summary of UE challenges in UE-MIMO Implementation [12]

Network Scenario	Relative Difficulty	Device Antenna Parameters	Practical Effects on the Mobile Device
Interference Mitigation in interference limited scenarios with strong to medium signal levels.	Low	• Envelope Correlation < 0.7 • Antenna BPD in the range of 10dB (quite "loose")	Small increase in antenna volume in device (e.g. ~ 10-25 %). Diversity antenna does not have to perform nearly as well as the "main antenna"
MIMO usage in strong to medium signal level environments.	Medium/ High	• Envelope Correlation < 0.3 for good MIMO "gain" • Envelope Correlation < 0.5 in worst case • "Medium" to low "BPD" is required	Difficult to implement in low (< 1 GHz bands) in small handheld devices. Device antenna volume increase from ~ 30% - 100%
SNR improvements in noise-limited weak signal environments (e.g. range extension).	High	• Low BPD is needed (ideally 0 dB) – the main and diversity antennas need to have the same performance	Device antenna volume doubles. Diversity antenna performance gets closer to that of the main antenna.

Now days, mobiles are stuffed with electronics like GPS, Wi-Fi, Bluetooth, battery, displays etc. These things again create additional coupling resulting in degradation in efficiency.

4.2.1.1 Impact of multiple antennas on UE size

Taking into account the fact that antenna size is inversely proportional to the operating frequency, an 11 cm hand held device will be needed to operate in 700 MHz band and which will be too much in comparison with the current UE sizes in the market. Now, implementing MIMO with this band means more space in dimension in UE to accommodate multiple antennas. A UE (with MIMO) operating in 700 MHz band will be 30% more in volume in comparison to a device without MIMO-which is too much. So, if we have to go with market trend and cannot compromise on size, we have to compromise and sacrifice the efficiency and correlation. But also, the care should be taken that these losses don't hamper the gains we get with propagation friendly 700 MHz band.

4.2.1.2 Battery consumption of multiple antennas

Multiple antennas mean dedicated component and circuitry for each of them and each will require separate RF processing. This means we need to have comparatively more energy to operate each component and chain. This condition gets worse if you have many bands supporting MIMO. With a simple Rx diversity case, battery consumption increases by 25% so for a MIMO implementation it can be expected to much more.

4.2.1.3 Advanced antenna concepts for UE application

If multiple antennas have to be used, they will have to be closer in UE (for achieve small volume) and which will result in pattern distortion and impact correlation. Of course spatial multiplexing cannot be an option in UE to combat correlation and coupling as it has limited size, so developers considered other diversity options to combat these issues. Two latest patterns developed are pattern diversity and polarization diversity.

In pattern diversity, each antenna is directional and they have to be positioned in such a way that they point in different directions; this will help in reducing the coupling.

In polarization diversity we combine pairs of antennas with orthogonal polarizations (i.e. horizontal/vertical, ± slant 45°, Left-hand/Right-h and CP etc.). Depending on the media the reflected signals will undergo polarization changes. Figure 4.7 shows the illustration of the two types.

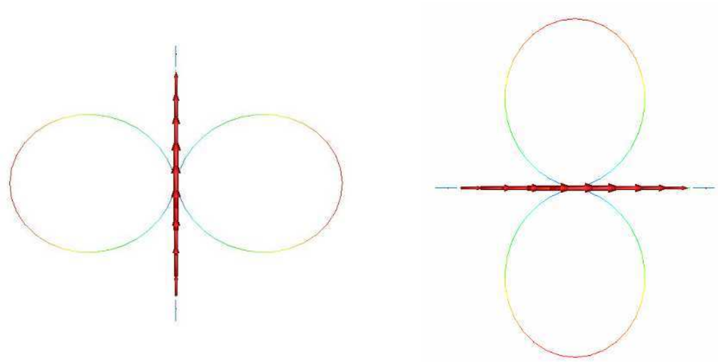
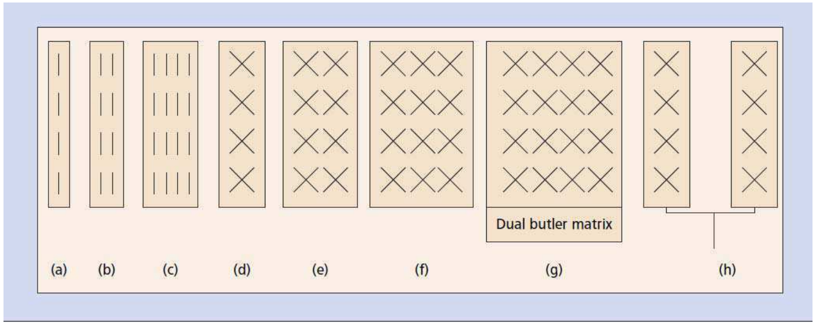


Figure 4.7 A simple illustration of pattern and polarization diversity obtained by using two orthogonal half-wavelength dipoles [12]

The arrows seen in middle of each pattern indicates the polarity of the antenna. Hence, if we keep two dipoles in a handheld device in this manner it will allow for both polarization and pattern diversity.

4.2.2 *BS antenna Configurations*

Figure 4.8 shows typical BS antenna configurations that can be deployed in LTE networks, for example using twelve or less RF cables due to cost and frequency band constraints. With this, a 3 sector cell can support 4 antennas per sector and 2 antennas per sector for a 6 sector cell.



Antenna configuration	Fig.	Description
1V	(a)	1 column with vertical polarization (V-pol)
ULA-2V	(b)	2 closely spaced V-pol columns
ULA-4V	(c)	4 V-pol columns
DIV-1X	(d)	1 column with dual-slant polarization (X-pol)
CLA-2X	(e)	2 closely spaced X-pol columns
CLA-3X	(f)	1 X-pol middle column with two closely spaced columns of +45-pol
BM-4X	(g)	4 X-pol columns with dual Butler matrix
DIV-2X	(h)	2 widely spaced X-pol columns

Figure 4.8 Antenna configurations as BS for 12 RF cables per BS constraint [12]

Here CLA means having two pairs of antenna which are cross polarized and spaced half a wavelength with beam forming on each pair.

4.3 Introduction to LTE MIMO techniques

To meet the demand of better cell coverage and better data rate Multiple input multiple output (MIMO) has been treated as an one of the emerging technology ,without increasing frequency bandwidth and average transmit. It happens so because MIMO can create many spatial layers where multiple data streams can be delivered on a given frequency-time resource thereby increasing the capacity. In LTE, MIMO provides wide range of benefits such as improved average cell throughput, peak throughput rate and wide cell coverage.

LTE adopted many MIMO techniques to get above mentioned objectives like Transmit diversity, single user (SU)-MIMO, multiuser (MU)-MIMO, closed-loop rank-1 precoding, and dedicated beamforming. Let us discuss them one by one.

4.3.1 Downlink SU-MIMO in LTE

The scheme is generally used for the Physical Downlink Shared Channel (PDSCH), which carries the information data from the network side to the UE. With SU-MIMO spatial multiplexing, and using 2 transmit antennas the peak rate of 150 Mbps and with 4 transmit antennas 300 Mbps is achievable. SU-MIMO spatial multiplexing works in two modes: the closed-loop spatial multiplexing mode and the open-loop spatial multiplexing mode.

4.3.1.1 Closed Loop spatial multiplexing

In the closed-loop spatial multiplexing mode, UE sends back the pre-coding matrix indicator to eNodeB to indicate the spatial channel experienced by it. eNodeB can then apply the spatial domain pre coding on the transmitted signal so that the transmitted signal matches with the channel experienced by the UE. UE needs to report two things to eNodeB to support closed loop MIMO-PMI and CQI.

Rank indicator is nothing but the number of spatial layers that UE can support at that time depending upon the channel condition. Channel Quality indicator (CQI) tells eNodeB that what kind of modulation scheme and channel coding rate it should use to make sure that the

BEP(Block error probability) at UE will be less than 10%. Figure 4.9 shows closed-loop spatial multiplexing with M layers and N transmit antennas (N≥M).

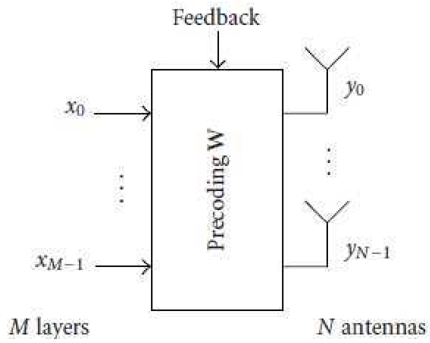


Figure 4.9 Closed-loop spatial multiplexing with N antennas and M layers [13]

In closed-loop spatial multiplexing, precoding is defined by

$$y=Wx$$

where $y=[y0,\ldots,yN-1]^{T,}$ yn denotes the complex symbol transmitted on the nth antenna, x=[x0,…,xM-1]T, xm denotes the modulation symbol transmitted on the mth layer, and W denotes the N×M precoding matrix.[13] .

Table 1 is used for selecting the precoding matrix for two antenna transmissions and Table 2 is used for four antenna transmissions

In Table2, $W_i^{\{c1\ldots cm\}}$ denotes the matrix defined by the columns $c_1 \ldots c_m$ of the matrix

$W_i=I_{4\times4}-2u_i\, u_j^{H}/u_j^{H}u_i$.

Table 4.2 Precoding codebook for transmission on two antennas [13]

Codebook index	Number of layers M	
	1	2
0	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$	—
1	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$	$1/2\begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}$
2	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\j\end{bmatrix}$	$1/2\begin{bmatrix}1 & 1\\j & -j\end{bmatrix}$
3	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-j\end{bmatrix}$	—

Table 4.3 Precoding codebook for transmission on four antennas [13]

Codebook index	$\mathbf{u}_i$	Number of layers M			
		1	2	3	4
0	$\mathbf{u}_0 = [1\ -1\ -1\ -1]^T$	$W_0^{\{1\}}$	$W_0^{\{14\}}/\sqrt{2}$	$W_0^{\{124\}}/\sqrt{3}$	$W_0^{\{1234\}}/2$
1	$\mathbf{u}_1 = [1\ -j\ 1\ j]^T$	$W_1^{\{1\}}$	$W_1^{\{12\}}/\sqrt{2}$	$W_1^{\{123\}}/\sqrt{3}$	$W_1^{\{1234\}}/2$
2	$\mathbf{u}_2 = [1\ 1\ -1\ 1]^T$	$W_2^{\{1\}}$	$W_2^{\{12\}}/\sqrt{2}$	$W_2^{\{123\}}/\sqrt{3}$	$W_2^{\{3214\}}/2$
3	$\mathbf{u}_3 = [1\ j\ 1\ -j]^T$	$W_3^{\{1\}}$	$W_3^{\{12\}}/\sqrt{2}$	$W_3^{\{123\}}/\sqrt{3}$	$W_3^{\{3214\}}/2$
4	$\mathbf{u}_4 = [1\ (-1-j)/\sqrt{2}\ -j\ (1-j)/\sqrt{2}]^T$	$W_4^{\{1\}}$	$W_4^{\{14\}}/\sqrt{2}$	$W_4^{\{124\}}/\sqrt{3}$	$W_4^{\{1234\}}/2$
5	$\mathbf{u}_5 = [1\ (1-j)/\sqrt{2}\ j\ (-1-j)/\sqrt{2}]^T$	$W_5^{\{1\}}$	$W_5^{\{14\}}/\sqrt{2}$	$W_5^{\{124\}}/\sqrt{3}$	$W_5^{\{1234\}}/2$
6	$\mathbf{u}_6 = [1\ (1+j)/\sqrt{2}\ -j\ (-1+j)/\sqrt{2}]^T$	$W_6^{\{1\}}$	$W_6^{\{13\}}/\sqrt{2}$	$W_6^{\{134\}}/\sqrt{3}$	$W_6^{\{1324\}}/2$
7	$\mathbf{u}_7 = [1\ (-1+j)/\sqrt{2}\ j\ (1+j)/\sqrt{2}]^T$	$W_7^{\{1\}}$	$W_7^{\{13\}}/\sqrt{2}$	$W_7^{\{134\}}/\sqrt{3}$	$W_7^{\{1324\}}/2$
8	$\mathbf{u}_8 = [1\ -1\ 1\ 1]^T$	$W_8^{\{1\}}$	$W_8^{\{12\}}/\sqrt{2}$	$W_8^{\{124\}}/\sqrt{3}$	$W_8^{\{1234\}}/2$
9	$\mathbf{u}_9 = [1\ -j\ -1\ -j]^T$	$W_9^{\{1\}}$	$W_9^{\{14\}}/\sqrt{2}$	$W_9^{\{134\}}/\sqrt{3}$	$W_9^{\{1234\}}/2$
10	$\mathbf{u}_{10} = [1\ 1\ 1\ -1]^T$	$W_{10}^{\{1\}}$	$W_{10}^{\{13\}}/\sqrt{2}$	$W_{10}^{\{123\}}/\sqrt{3}$	$W_{10}^{\{1324\}}/2$
11	$\mathbf{u}_{11} = [1\ j\ -1\ j]^T$	$W_{11}^{\{1\}}$	$W_{11}^{\{13\}}/\sqrt{2}$	$W_{11}^{\{134\}}/\sqrt{3}$	$W_{11}^{\{1324\}}/2$
12	$\mathbf{u}_{12} = [1\ -1\ -1\ 1]^T$	$W_{12}^{\{1\}}$	$W_{12}^{\{12\}}/\sqrt{2}$	$W_{12}^{\{123\}}/\sqrt{3}$	$W_{12}^{\{1234\}}/2$
13	$\mathbf{u}_{13} = [1\ -1\ 1\ -1]^T$	$W_{13}^{\{1\}}$	$W_{13}^{\{13\}}/\sqrt{2}$	$W_{13}^{\{123\}}/\sqrt{3}$	$W_{13}^{\{1324\}}/2$
14	$\mathbf{u}_{14} = [1\ 1\ -1\ -1]^T$	$W_{14}^{\{1\}}$	$W_{14}^{\{13\}}/\sqrt{2}$	$W_{14}^{\{123\}}/\sqrt{3}$	$W_{14}^{\{3214\}}/2$
15	$\mathbf{u}_{15} = [1\ 1\ 1\ 1]^T$	$W_{15}^{\{1\}}$	$W_{15}^{\{12\}}/\sqrt{2}$	$W_{15}^{\{123\}}/\sqrt{3}$	$W_{15}^{\{1234\}}/2$

Depending on the transmission rank that is scheduled by eNodeB , multiple codewords may be mapped to multiple layers .

Table 3 refers to how codewords are mapped to layers in LTE. Here $d_K(i)$ denotes the ith modulation symbol of the kth codeword, $x_l(i)$ denotes the ith modulation symbol of the *l*th layer, S_{layer} denotes the number of modulation symbols of each layer, and Sk denotes the number of modulation symbols of the kth codeword. [13].

Table 4.4 Codeword-to-layer mapping for spatial multiplexing [13]

Number of layers	Number of codewords	Codeword-to-layer mapping $i = 0, 1, \ldots, S_{layer} - 1$	
1	1	$x_0(i) = d_0(i)$	$S_{layer} = S_0$
2	2	$x_0(i) = d_0(i)$ $x_1(i) = d_1(i)$	$S_{layer} = S_0 = S_1$
2	1	$x_0(i) = d_0(2i)$ $x_1(i) = d_0(2i+1)$	$S_{layer} = S_0/2$
3	2	$x_0(i) = d_0(i)$ $x_1(i) = d_1(2i)$ $x_2(i) = d_1(2i+1)$	$S_{layer} = S_0 = S_1/2$
4	2	$x_0(i) = d_0(2i)$ $x_1(i) = d_0(2i+1)$ $x_2(i) = d_1(2i)$ $x_3(i) = d_1(2i+1)$	$S_{layer} = S_0/2 = S_1/2$

If there is one layer, there is one codeword. If there are two layers, the basic mode of operation is to carry a codeword for each layer. The case of transmitting a single codeword using two layers is only applicable for the eNodeB having four transmit antennas when its initial transmission contained two codewords and a codeword mapped onto two layers needs to be retransmitted. In case of three-layer transmission, the first layer carry the first codeword while the second and the third layers carries the second codeword, in which case the second codeword has two times modulation symbols than the first one. When four layers are scheduled, two codewords are transmitted, each of which is transmitted using two layers. As can be seen in Table 3, the modulation symbols of a codeword are equally split into two layers when the codeword is mapped to two layers.

In case of closed loop spatial multiplexing , eNodeB lets UE know about what precoding matrix is being used with the use of TPMI (transmit precoding matrix indication). It's a part of DL control information in which 3-bit field is used for 2 antenna system and 6-bit information field is used for 4 transmit antenna system. Sometimes due to channel variation, the use of

Spatial multiplexing may not be feasible and in that case enodeB can instantaneously use transmit diversity even though UE has been configured for spatial multiplexing operation. Again TPMI will indicate the use of transmit diversity.

4.3.1.2 Open Loop spatial multiplexing

When UE speed is not too slow and feedback overhead on UL is high, open-loop spatial multiplexing is used in LTE system because reliable PMI feedback is not possible at the eNodeB. Such an open loop spatial multiplexing is shown in Figure 4.10 with N transmit antennas and M layers (N>=M). RI and CQI constitute the feedback and unlike closed loop spatial multiplexing system a fixed set of precoding is applied. It is done in cyclic manner across the subcarriers in frequency domain.

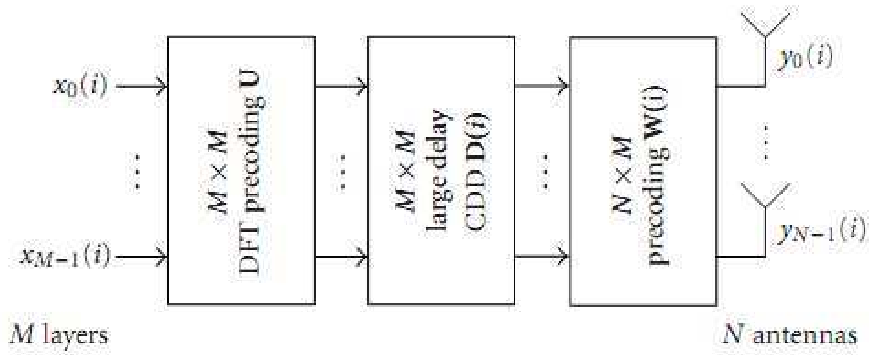


Figure 4.10 Open-loop spatial multiplexing with N antennas and M layers [13]

For an open loop spatial multiplexing, the pre coding can be defined as

$$y(i) = W(i)D(i)Ux(i)$$

where $y(i) = [y0(i), \ldots , yN-1(i)]^T$, yn(i) indicates the i^{th} complex symbol transmitted on the nth antenna, the size of precoding matrix W(i) is N × M, $x(i) = [x0(i), \ldots , xM-1(i)]^T$, xm(i) refers to the i^{th} modulation symbol transmitted on the m^{th} layer. The size of the DFT precoding matrix U is size M × M and the matrix D(i) of size M × M supporting the large delay cyclic delay diversity (CDD) are defined in following tables.

Table 4.5 DFT Precoding matrix U [13]

Number of layers M	$M \times M$ matrix $\mathbf{U}$
2	$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & e^{-j2\pi/2} \end{bmatrix}$
3	$\frac{1}{\sqrt{3}}\begin{bmatrix} 1 & 1 & 1 \\ 1 & e^{-j2\pi/3} & e^{-j4\pi/3} \\ 1 & e^{-j4\pi/3} & e^{-j8\pi/3} \end{bmatrix}$
4	$\frac{1}{2}\begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & e^{-j2\pi/4} & e^{-j4\pi/4} & e^{-j6\pi/4} \\ 1 & e^{-j4\pi/4} & e^{-j8\pi/4} & e^{-j12\pi/4} \\ 1 & e^{-j6\pi/4} & e^{-j12\pi/4} & e^{-j18\pi/4} \end{bmatrix}$

Table 4.6 Large Delay CDD Matrix D(i) [13]

Number of layers M	$\mathbf{D}(i)$
2	$\begin{bmatrix} 1 & 0 \\ 0 & e^{-j2\pi i/2} \end{bmatrix}$
3	$\begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{-j2\pi i/3} & 0 \\ 0 & 0 & e^{-j4\pi i/3} \end{bmatrix}$
4	$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & e^{-j2\pi i/4} & 0 & 0 \\ 0 & 0 & e^{-j4\pi i/4} & 0 \\ 0 & 0 & 0 & e^{-j6\pi i/4} \end{bmatrix}$

For two transmit antenna,

$$W(i) = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

For four antennas for transmission ,there is extra robustness needed to combat the spatial channel charatersitics and therefore W(i) is assigned a set of precoding matrix cyclically as index i increases

$$W(i) = C_k$$

Where k =((i/M)⁻ mod 4) + 1 and C_k (k=1,2,3,4) for different rank values given in following table:

Table 4.7 Precoding matrix Ck(k = 1, 2, 3, 4) for the open-loop spatial multiplexing[13]

	Number of layers M		
	2	3	4
$\mathbf{C}_1$	$\mathbf{W}_{12}^{\{12\}}/\sqrt{2}$	$\mathbf{W}_{12}^{\{123\}}/\sqrt{3}$	$\mathbf{W}_{12}^{\{1234\}}/2$
$\mathbf{C}_2$	$\mathbf{W}_{13}^{\{13\}}/\sqrt{2}$	$\mathbf{W}_{13}^{\{123\}}/\sqrt{3}$	$\mathbf{W}_{13}^{\{1324\}}/2$
$\mathbf{C}_3$	$\mathbf{W}_{14}^{\{13\}}/\sqrt{2}$	$\mathbf{W}_{14}^{\{123\}}/\sqrt{3}$	$\mathbf{W}_{14}^{\{3214\}}/2$
$\mathbf{C}_4$	$\mathbf{W}_{15}^{\{12\}}/\sqrt{2}$	$\mathbf{W}_{15}^{\{123\}}/\sqrt{3}$	$\mathbf{W}_{15}^{\{1234\}}/2$

4.3.2 Transmit Diversity in LTE

While the other MIMO technology are only applied to Physical downlink shared channel (PDSCH), transmit diversity is applicable to all the physical channels like Physical Broadcast Channel (PBCH), Physical Control Format Indicator Channel (PCFICH), Physical Downlink Control Channel (PDCCH), and Physical Hybrid ARQ Indicator Channel (PHICH).

The different transmit diversity schemes for LTE downlink is shown in Figures 4.11 to Figure 4.12. If there are two antennas at eNodeB, the space frequency block code (SFBC) is used as showing in Figure 4.11(a). For 4 transmit antenna a combination of SFBC and frequency –switched transmit diversity (FSTD) is used as shown in Figure 4.11(b).

$$\begin{array}{c c} & \xrightarrow{\text{Subcarrier}} \\ \begin{array}{c}\text{Antenna 0}\\ \text{Antenna 1}\end{array} & \begin{bmatrix} S_0 & S_1 \\ -S_1^* & S_1^* \end{bmatrix} \end{array}$$

(a)

$$\begin{array}{c c} & \xrightarrow{\text{Subcarrier}} \\ \begin{array}{c}\text{Antenna 0}\\ \text{Antenna 1}\\ \text{Antenna 2}\\ \text{Antenna 3}\end{array} & \begin{bmatrix} S_0 & S_1 & 0 & 0 \\ 0 & 0 & S_2 & S_3 \\ -S_1^* & S_0^* & 0 & 0 \\ 0 & 0 & -S_3^* & S_2^* \end{bmatrix} \end{array}$$

(b)

Figure 4.11 (a) SFBC with two transmit antennas on downlink (b) SFBC + FSTD with four transmit antennas on downlink [13]

As with the four channels implementation, the correlation between the channels due to this setup is matter of consideration and using the combination of SFBC and FSTD serves as robust for combating the correlation. However for PHICH channel, the different transmit diversity scheme has to be used as shown in Figure 4.12. In this, orthogonal signals are used to multiplex four ACK/NACK signals and spreading factor of 4 is used over the group of four subcarriers and this resulting group should be repeated four times. If there are multiple PHICHs to be transmitted, we can use type 1 and type 2 alternatively so that uniform distribution of power is maintained over base station transmit antennas.

$$
\text{Type1:}\quad
\begin{array}{l}
\\
\text{Antenna 0}\\ \text{Antenna 1}\\ \text{Antenna 2}\\ \text{Antenna 3}
\end{array}
\underbrace{\overset{\xrightarrow{\text{Subcarrier}}}{\begin{bmatrix} S_0 & S_1 & S_2 & S_3 \\ 0 & 0 & 0 & 0 \\ -S_1^* & S_0^* & -S_3^* & S_2^* \\ 0 & 0 & 0 & 0 \end{bmatrix}}}_{\text{1st repetition}},
\underbrace{\begin{bmatrix} 0 & 0 & 0 & 0 \\ S_0 & S_1 & S_2 & S_3 \\ 0 & 0 & 0 & 0 \\ -S_1^* & S_0^* & -S_3^* & S_2^* \end{bmatrix}}_{\text{2nd repetition}},
\underbrace{\begin{bmatrix} S_0 & S_1 & S_2 & S_3 \\ 0 & 0 & 0 & 0 \\ -S_1^* & S_0^* & -S_3^* & S_2^* \\ 0 & 0 & 0 & 0 \end{bmatrix}}_{\text{3rd repetition}}
$$

(a)

$$
\text{Type2:}\quad
\begin{array}{l}
\\
\text{Antenna 0}\\ \text{Antenna 1}\\ \text{Antenna 2}\\ \text{Antenna 3}
\end{array}
\underbrace{\overset{\xrightarrow{\text{Subcarrier}}}{\begin{bmatrix} 0 & 0 & 0 & 0 \\ S_0 & S_1 & S_2 & S_3 \\ 0 & 0 & 0 & 0 \\ -S_1^* & S_0^* & -S_3^* & S_2^* \end{bmatrix}}}_{\text{1st repetition}},
\underbrace{\begin{bmatrix} S_0 & S_1 & S_2 & S_3 \\ 0 & 0 & 0 & 0 \\ -S_1^* & S_0^* & -S_3^* & S_2^* \\ 0 & 0 & 0 & 0 \end{bmatrix}}_{\text{2nd repetition}},
\underbrace{\begin{bmatrix} 0 & 0 & 0 & 0 \\ S_0 & S_1 & S_2 & S_3 \\ 0 & 0 & 0 & 0 \\ -S_1^* & S_0^* & -S_3^* & S_2^* \end{bmatrix}}_{\text{3rd repetition}}
$$

(b)

Figure 4.12 Modified SFBC + FSTD for PHICH with four transmit antennas on downlink [13]

Sometimes the eNodeB may have to signal the change in transmission scheme to UE using control signaling and which may not be possible because of current channel condition or in other words it may not be favorable to the current transmission scheme. In such case eNodeB shall always use transmit diversity to deliver the control information irrespective of fact that UE may be configured for SU-MIMO,MU-MIMO or closed loop rank-1 precoding etc. This is necessary to ensure the reliable change of transmission scheme.

4.3.3 Closed –Loop Rank-1 Precoding in LTE

In this smart antenna scheme, operation is same as that of closed loop spatial multiplexing with cell –specific reference signal but the limitation is that only rank-1 precoding matrix is selected and without relying on the UE –specific reference signal. The advantage of this technology is that the DL control signaling is pretty less and thus saves some overhead in the system.

4.3.4 MU-MIMO in LTE

This scheme is supported for both UL and DL. In Uplink, it is possible for eNodeB to schedule more than one UE in the same time-frequency resource as shown in Figure 4.13.

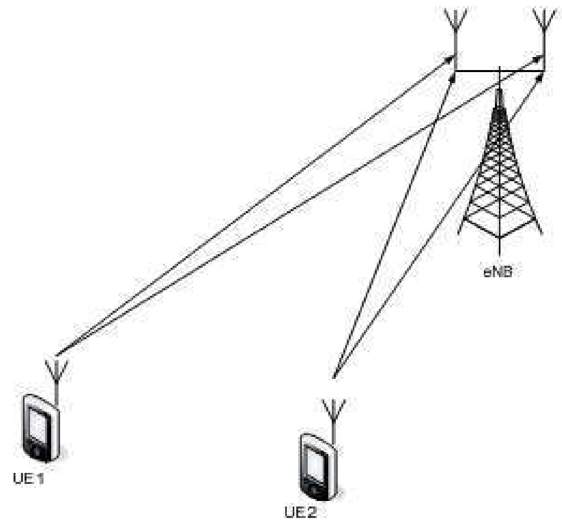


Figure 4.13 UL Multiuser MIMO [12]

For distinguishing between these UEs on uplink, eNodeB gives a cyclic shift value in the control signaling to all UEs. UEs can then apply these cyclic shift values with the base Zadoff-chu sequence to form the uplink reference signal and thus it is orthogonal to the other UE's reference signal. Figure 4.14 shows the UL slot structure in which 4th symbol is used to transmit reference signal.

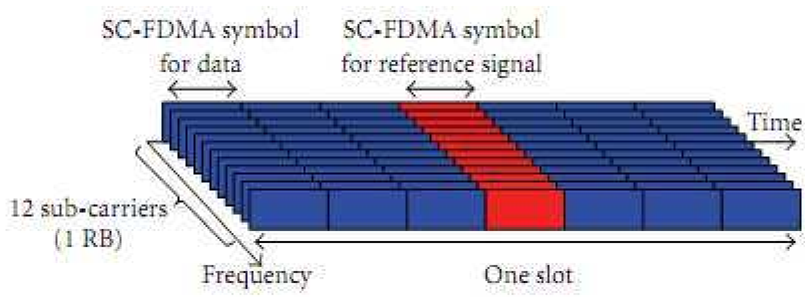


Figure 4.14 Multiplexing of data and reference signal on uplink[13]

In Downlink, only rank -1 transmission can be used if UE is configured in MU-MIMO transmission mode. eNodeB uses rank-1 precoding matrix from above table depending on whether 2 or 4 transmission antennas are implemented. Here the antennas at eNodeB side are half wavelenght apart and thus create a hogly correlated channel scenario. So the UEs that are well separated in physical directions can be co-scheduled . The interfence can be kept low by focussing the narrow beam towards each user. The UEs can be configured in single rank channel dependent precoding scheme. One noticble problem with MU-MIMO in DL is that of power ratio between the refernce signal and data signal to assit inr demodulation. This power ratio is a problem because there are multiple UEs sharing the same resource and therefore have to share the finite power at Pas of eNodeB. For QPSK, UE may not have to rely on knowing the power ratio but for higher oder modulation like 16QAM and 64QAM, the UE has to be signaled about the power ratio. A1 bit signaling is done to indicate if there is 3dB power reduction if UE is configured in MU-MIMO mode.

Another problem with MU-MIMO is that the coscheduling of UEs is possible only if there beams are well seperated. This makes the scheulder task little tough as now scheuler has to match those UEs which have reported compatible beams and are well seperated. MU-MIMO will be more beneficial if there is large system load because then probability that schduler can find many UEs which can be coscheuled on beams and also the intra cell interfence will be less. Also shoulbe be noted a point here that in MU-MIMO UE calculate s PMI/CQI feedback where it has no clue about the UEs which are shceduled at the same time and hence the PMI/CQI generated may not be the true PMI/CQI as it does not take into account the other user's interfernce.

4.3.5 Single layer dedicated beamforming in LTE

It is possible to have a transmission mode in which UE demodulated the data using UE specific reference signal. It is possible to use 4 antenna element or 8 antenna elements for beamforming, depending upon the eNodeB implementation. Having 8 antenna array elements provides some advantages though such as increase in the throughput as it provides double array gain and hence SNR. Also, with large antenna array elements , inter cell interference can be reduced as more narrower beams will be formed.

Another approach can be- to use more sectors and implement 4 antennas. This setup is already a standard supported and also provides MU-MIMO capability as UEs can be co-scheduled in different sectors. So, many factors should be taken into account in choosing the above mentioned alternatives including antenna size and typical traffic situation.

4.4 Real world implementation/trails and Performance analysis of MIMO techniques

4.4.1 Field Trial of LTE with 4x4 MIMO

Ericsson tried a measurement campaign in a LTE test bed in a business district in northern Stockholm, Sweden. The test bed comprised of a eNode B and a UE with 4x4 MIMO in the downlink. The Figure 4.15 shows the aerial view of the setup and its parameter description for this test bed is given in following table.

Figure 4.15 The drive routes in Sector 1 (red) and Sector 2 (yellow) each sector as seen from behind the antenna installations [14]

Table 4.8 Parameters of the Ericsson Research LTE test bed [14]

PARAMETER	DESCRIPTION
Carrier frequency	2.6GHz
System bandwidth	10MHz, UE always scheduled over entire bandwidth
Link adaptation, closed loop operation (3GPP mode 4)	Rank, PMI and channel-quality indicator (CQI) feedback on millisecond timescale. Time between channel measurement and transmission of the resulting transport format is around 5ms
Hybrid automatic repeat request (HARQ)	HARQ with chase combining
Receiver	Minimum mean square error (MMSE) receiver
LTE duplex mode	FDD
Number of antennas (downlink)	eNB: 1, 2 or 4. UE: 2 or 4

In this trial UE was taken through two different routes in 2 different sectors. Sector 1 consisted of a suburban area where there were low height building and mostly flat area. Sector 2 was a urban area with high rise buildings .The distance between the UE and eNodeB was at max 720 meter. Also the trial was done with 2 power settings.

-34dbm and 18dbm in sector 1 and

-34dbm and 24 dbm in sector 2

Tests were done with two antenna configurations- correlated configuration and uncorrelated configuration. In correlated configuration with 4x4 MIMO , the four columns forming an antenna were co-polarized placed closely to each other (0.7λ ~8cm) and is denoted with [a] and for 4x2 it is denoted by [l]. In uncorrelated configuration with 4x4 MIMO, we used dual polarized columns placed widely apart (25 λ),denoted by[c] and for 4x2 it is denoted by [k].

For all of the four cases above UE antenna comprised of both horizontal and vertically polarized antenna two of each kind in setup with 4 antennas and one of each kind in case of 2 antenna setup at UE side. UE antennas were mounted on a roof top of a van in square shape with 20 cm antenna.

Performance for correlated and uncorrelated setup is shown in Figure 4.16. At the top left corner, we have graphs showing the sector 2 setup with low power setting and on top right corner we have sector two graphs with high power setting.

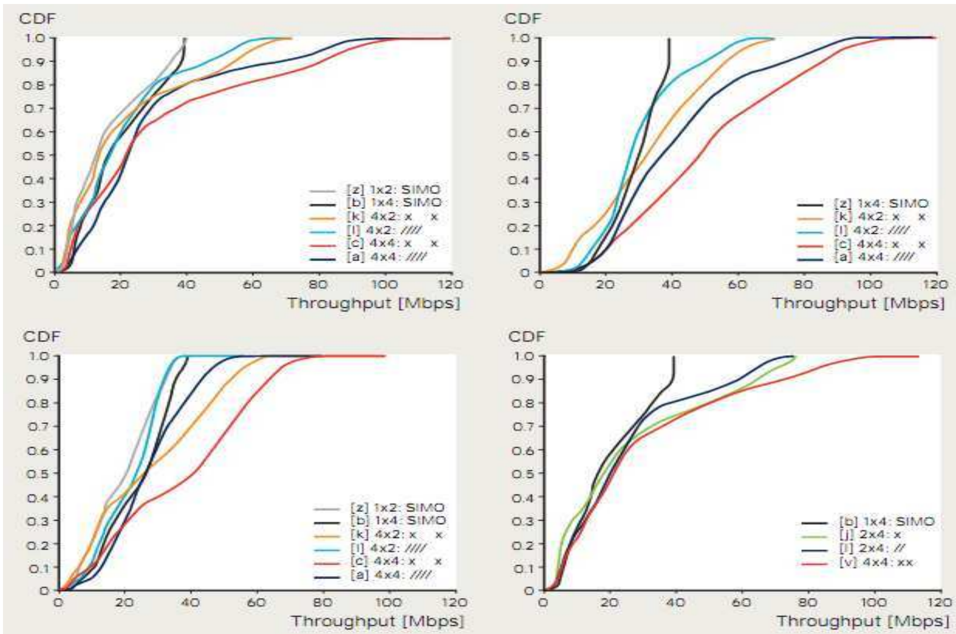


Figure 4.16 Selection of cumulative distribution functions (CDFs) of throughput achieved during test drives along the measurement routes. [14]

We can clearly see that for all the two 4x2 configure; the corresponding CDFs intersect while for 4x4 there are few cases of intersection. With uncorrelated antenna setup, best performance can be achieved above the intersection point in higher throughput region while for correlated setup, best performance is achieved below the intersection point in low throughput region. Also, another observation that can be made is that for lower setting the intersection occurs at comparatively higher point than the high power setup and test drive case. The reason for this may be the fact that if we supply more received power to UE operating with low SNR; increase in throughput is more notable than the UEs which are already working with high SNR.

In comparison with uncorrelated antenna setup, correlated configuration results in higher power gain. It is more beneficial to transmit multiple layers for operation in high power region and for this uncorrelated setup gives better channel support. We see , for this reason, the curves intersect at higher points in sector 2 drive case than sector 1 drive case.

Also, we get CDFs intersection at lower points with 4 UE antennas compared to 2 UE antennas setup case. In two antenna setup at UE, the ability to improve SNR by combining the signal coherently from multiple antennas is less and therefore correlated setup is best for this case because it gives more received power at UE. In contrast, for 4 antenna setup at UE, correlated setup is more apt because it will improve the ability of channel to support multiple layers. [14]

4.4.2 Performance Analysis of Closed and Open Loop MIMO in LTE

To illustrate the concept of open loop and closed loop MIMO, Figure 4.17 depicts that in closed loop MIMO, the UE sends a precoding matrix indicator (PMI) and channel quality indicator(CQI) which will enable appropriate transmitter precoding matrix for further transmission of data. In open loop MIMO, the UE need not send any feedback and a fixed precoding matrix has been reserved.

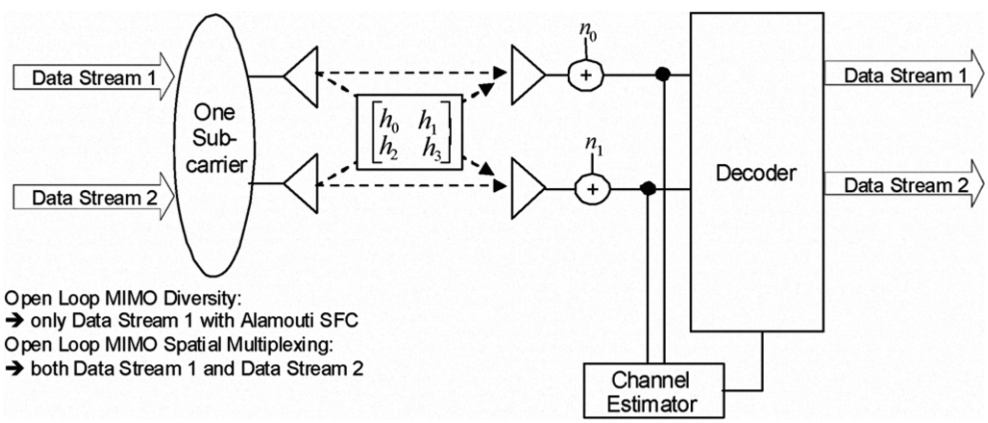


Figure 4.17 Open loop 2x2MIMO without feedback [15]

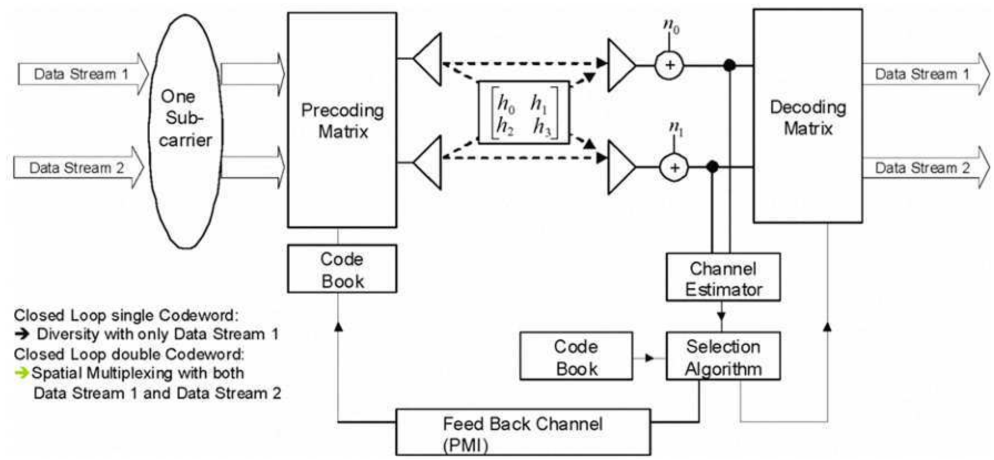


Figure 4.18 Closed loop 2x2MIMO with PMI feedback [15]

It is seen that for lower SINR, the diversity case is better and for higher SINR, spatial multiplexing case is better. So, it will be a good idea to switch between MIMO algorithms depending upon the SINR. To illustrate this, a simple algorithm is presented.

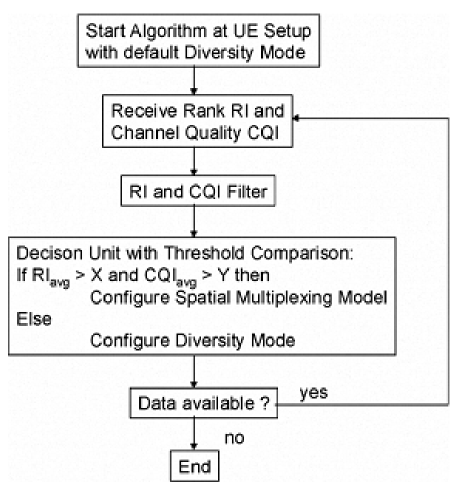


Figure 4.19 Optimum dynamic MIMO switch defined by the throughput envelopes for open Loop MIMO spatial multiplexing and MIMO diversity; 20MHz bandwidth, spatially uncorrelated VehA 30krn/h assumed [15]

In LTE case , typically this switching point is located at 15-18 dB(depending on the UE speed- in this case UE speed of 30 Km.hr is considered) as shown in Figure 4.20.

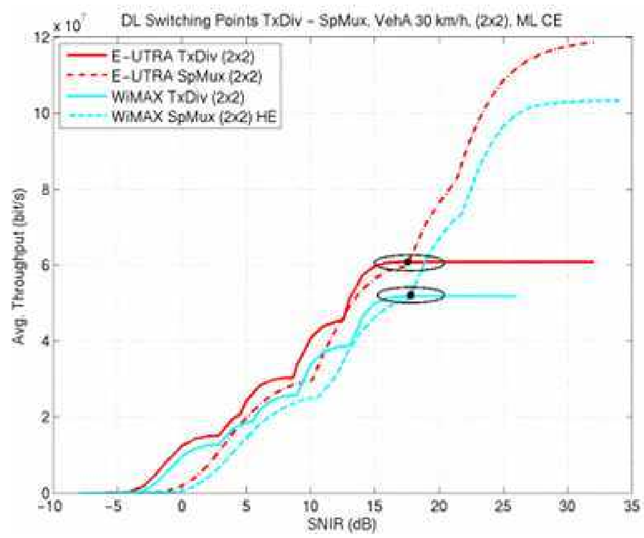


Figure 4.20 Threshold based dynamic MIMO Switch Algorithm based on filtered Rank and CQI Measurements [15]

To simulate a urban area deployment, a hexagonal regular cell layout is considered with frequency BW of 10 MHz. The simulation area consists of 21 cells with K users in all meaning K/21 users in average per cell. K was varied from 2 to 1050 to model different system load. A traffic model was with FTP of 300 Kbytes file download and a slow UE speed was considered.

Following result shows the performance of closed loop MIMO with two parameters as PMI granularity (PMI BW in terms of number of PRBs) and PMI error. The OL MIMO is considered as the reference.

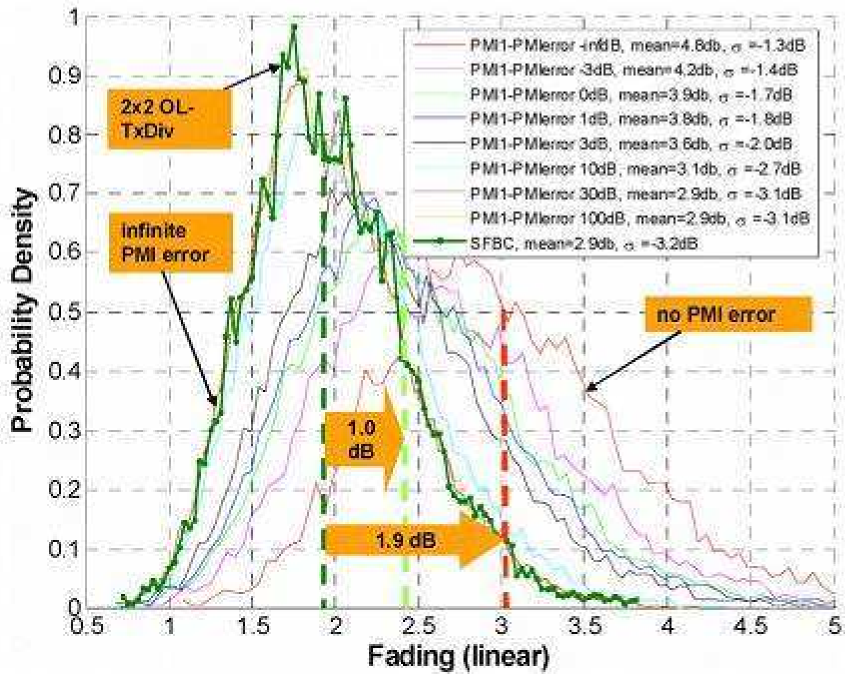


Figure 4.21 PDF of the "equivalent" fast fading for 2x2 CL diversity depending on measurement error assuming ~180 kHz PMI bandwidth (single PRB basis), TU-3 channel model [15]

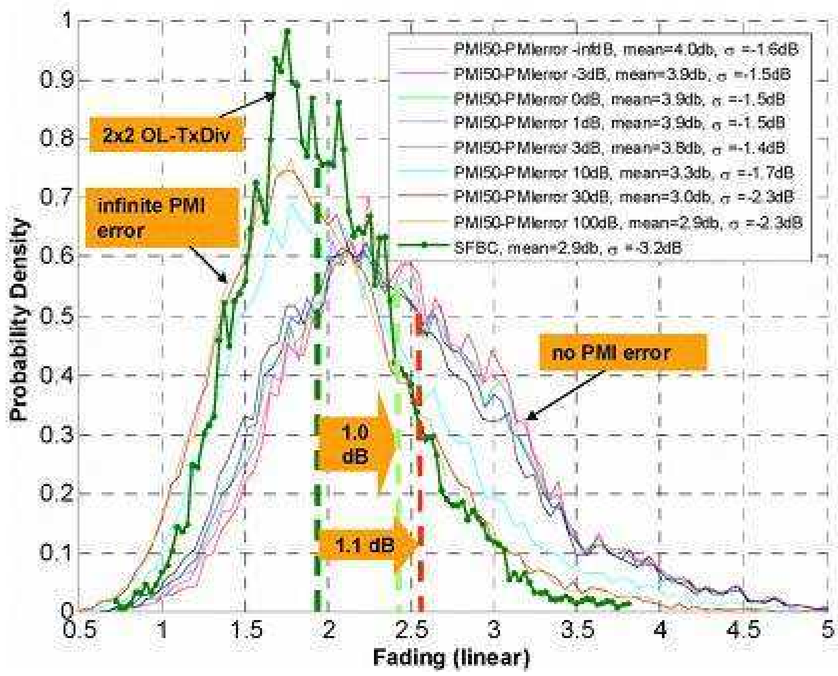


Figure 4.22 PDF of the "equivalent" fast fading for 2x2 CL diversity depending on measurement error assuming wideband PMI (10 MHz BW) [15]

Figure 4.21 shows results where PMI feedback is sent for every PRB (high feedback capacity).It shows that with no PMI error CL MIMO has almost 2 dB (4.8 dB vs. 2.9 dB) gain than OL MIMO. As PMI error increases the performance of CL MIMO becomes comparable to open loop MIMO. As shown Figure 4.22 with wideband PMI which is more realistic gain over OL MIMO gets reduces to 1.1dB (4.0 dB vs. 2.9 dB) . Again with wide band PMI also the performance approaches that of OL MIMO with higher PMI errors.

Also the performance of CL MIMO was seen in terms of cell throughput and user throughput vs system load (in terms of number of users). This simulation results were obtained for diversity technique as well as for dynamic MIMO switching.

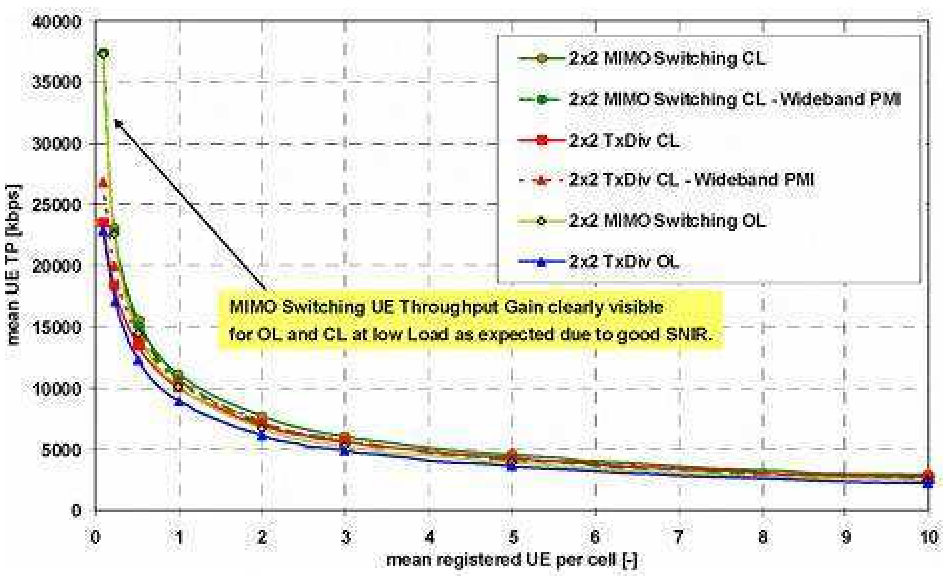


Figure 4.23 Mean user throughput vs. system load assuming 10 MHz BW [15]

For the cell throughput case CL MIMO achieves a gain of 20 % (11Mbps) over OL MIMO (9 Mbps) both at full load. Wideband PMI gives only 10% increase (10 Mbps). Dynamic switching of MIMO only gives some considerable gain at lower loads but with high loads, the performance of dynamic MIMO is negligible. Also in Figure 4.23 we compare the performance of CL MIMO with respect to user throughput. It is seen that at lower loads dynamic switching MIMO for CL and OL achieves almost double throughput.

4.4.3 LTE performance for initial deployments by Nokia Siemens Network

Two test routes were selected by Nokia Siemens network.

(1) A route on the Nokia Siemens Network campus in Munich within about 300 meters of the base station antenna.

(2) A wide area route on public streets within about 1000 meters of the Munich test site antenna.

Only 1 UE was used for (1) and 4 UE were used for trying (2) case. Out of these 2 terminals were placed in van (UE2 and UE3) and 2 were placed (UE1 and UE4) inside the building to analyze the indoor performance.

Figure 4.24 Measurement Vans with LTE UE [17]

Carrier frequency	2.6 GHz (UMTS Extension band)
Duplex	FDD
Scalable bandwidth	20 MHz, 10 MHz, 5 MHz
Data rate @ 20 MHz	>150 Mbps (DL), >50 Mbps (UL)
Transmission Time Interval (TTI)	1 ms
Tx power DL	40 dBm
Tx power UL	23 dBm
Modulation schemes:	
• Downlink	OFDMA (64QAM, 16QAM, QPSK)
• Uplink	SC-FDMA (16QAM, QPSK)
Antenna techniques:	
• Downlink	2x2 MIMO
• Uplink	SDMA, Rx-Diversity
CQI based link adaptation (DL)	Time, Frequency, Space
Setup	single Cell – multi user
Number eUE per Node B per Sector	4

Figure 4.25 Features of LTE development platform for FDD mode [17]

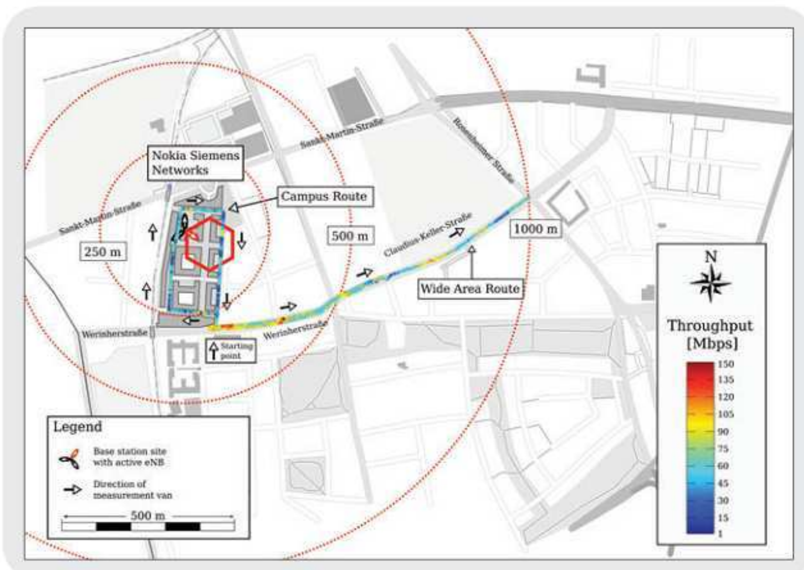


Figure 4.26 Data rates along campus and wide area routes in Munich [17]

4.4.3.1 Campus route results

In this route there were buildings of height between 17 and 23 m and trees of 5-8 meter height which created a scenario of typical urban area with extensive shadowing of antenna signals by building. With UE speeds between 10-20Km/hr, L1 throughput of 60 to 100 Mpbs was observed with NLOS. There were few instances on street crossing where probably line of sight reception occurred which resulted in throughput to shoot to 140 Mbps but very hardly it was achieved. This is shown in the Figure 4.27.

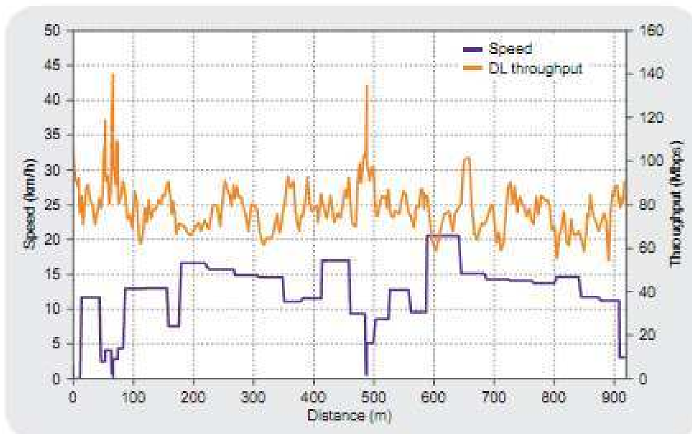


Figure 4.27 DL throughput on campus route [17]

4.4.3.2 Wide Area route results

This route was between 350 and 1000 meter away from eNodeB. There were medium size buildings and apartment of max height up to 10-20 meter. This created a scenario of a typical sub urban area. This test was done in two scenarios a) using single UE and b) multiuser scenario.

In single user case the UE speed was upto 40 Km/hr. . As in this case route had many crossings and traffic lights (stops), it resulted in highly varying performance where L1 data rate was between 14-83 Mbps. This high variation may be attributed to different shadowing conditions along the drive test route. However more interestingly even at the distance of 1000 m from eNodeB, 30 Mbps was achievable easily.

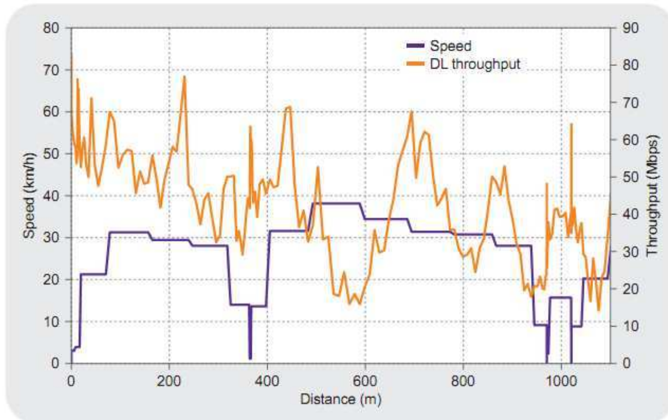


Figure 4.28 DL single user throughput along wide area route [17]

In multiuser case UE2 and UE 3 were placed in the van which created a scene of varying SNR due to changing channel conditions. UE 4 was kept close to the window of the lab to get good SNR and UE 1 was kept inside the lab (4 meter away from the window). The distance between the lab and eNodeB is 282 meter.

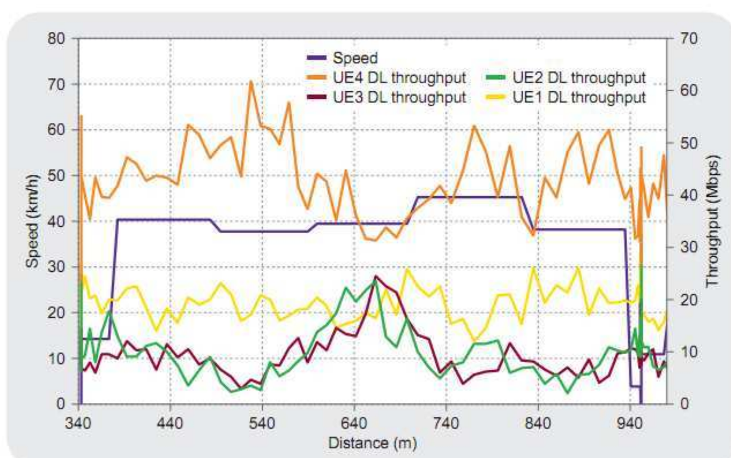


Figure 4.29 DL multiuser throughput along wide area route [17]

UE4 which was kept close to window maximum throughput (30 -60 Mbps). UE1 kept inside the lab was second best in the line delivering L1 throughput of 12-25 Mbps. However UE2 and UE3 showed data rate in the range of 5-25 Mbps depending on the channel conditions.

CHAPTER 5

CONCLUSION

Considering MIMO as future generation technology, it is important to understand every aspect of it as this novel wireless communication system involves many new methodology and techniques to enhance the performance so that the end user is happy with the quality of service. In this thesis, we concentrated mostly on the air interface part of LTE which is the domain with maximum changes compared to the legacy system.

Multipath results in Inter Symbol Interference and this has been the most common drawback in legacy communication systems resulting in detection problem and increases bit error probability (BER). In LTE, researchers came up with a new technology called Orthogonal division multiple access (OFDMA) which greatly solved the multipath problem. Using OFDMA with cyclic prefix resulted in almost zero ISI as discussed in previous sections. However, the care has to be taken that the subcarriers are sampled at exactly its center frequency.

For uplink, OFDMA could have been used but as it results in High Peak to average power ratio and this requires larger power amplifier for linearity and this was not feasible at user terminal side. To solve this problem, SC-FDMA was suggested which gives all good properties from OFDMA and also keeps the UE terminal size low.

We also saw that different smart antenna techniques are suitable under different conditions. For example, for the user near the cell edge beam forming technique is best and for the cell center user spatial multiplexing suits the best. To schedule different user (spatially apart enough) in same time frequency resource MU-MIMO can be used. Transmit diversity is most robust and can be applied while sending control signals which cannot be afforded to be corrupt.

It basically provides coding gain instead of any increase in throughput. For increase in throughput techniques like spatial multiplexing can be used and to achieve the optimum performance according to the current channel, closed loop spatial multiplexing is the best choice. Another variation of closed loop SU-MIMO is rank-1 precoding method which will save some signaling overhead as the rank of transmission is fixed to 1. Thus we see that there are variety of transmission schemes available in the LTE system and can be used accordingly depending on the conditions (with a flexibility of dynamic MIMO switching), which was not the case in previous wireless systems and this enhances the performance of the LTE.

We have presented some real world implementation and simulations of smart antenna methods and some results can be concluded from that. Comparing the performance of open loop ad closed loop MIMO, we saw that CL MIMO gives 2dB gain over OL MIMO if there are no PMI errors considered which means it results in 20 % higher spectral efficiency. The realistic wideband PMI however achieves little less gain ~1 dB and hence provides with only 10% higher spectral efficiency.

Also it is seen that switching MIMO at lower loads provides the double throughput gain. For lower loads the gain in throughput may not be dramatic. So, for the cell where cell load is expected to be low or medium, dynamic MIMO switching may be implemented to enhance the user as well as cell throughput.

Test conducted by Nokia Siemens Network reveal that even at the speed of 40 Km/hr. data throughput of almost 30Mbps was observed even at distance of 1Km from the eNodeB. In typical urban kind of environment at the speed of ~20 Km/hr. the data rate in the range of 60 to 100 Mbps is achievable in NLOS condition. If there is line of sight this throughput up to ~140 Mbps can be achieved which is phenomenal.

APPENDIX A

LIST OF ACRONYMS

3GPP – Third generation partnerShip Project
ACK – Acknowledgement
BCCH - Broadcast Control Channel
BCH - Broadcast channel
BEP –Bit Error Probability
BER – Bit Error Rate
BS – Base Station
CCCH - Common Control Channel
CDD - Cyclic Delay Diversity
CDMA – Code Division Multple Access
CLA – Cluster Linear Array
CM- Cubic Meter
CP – Cyclic Prefix
DCCH - Dedicated Control Channel
DCI – Downlink Control Information
DFT – Discrete Frequency Transform
DL – Downlink
DL_SCH - Downlink shared channel
DMRS - .Demodulation Reference Signal
DRX – Discontinuous Reception
DTCH- Dedicated Traffic Channel
EPC - Evolved Packet Core
E-UTRAN – Evolved UMTS Terrestrial Radio Access
FDM – Frequency Division Multiplex
FFT – Fast Frequency Transform
FSTD – Frequency Switch Transmit Diversity
GGSN – Gateway GPRS Support Node
GMSK – Gaussian Minimum Shift Keying
GPS – Global Position System
GSM – Global System for Mobile Communication
GT – Guard Time
HARQ – Hybrid Automatic Repeat Request
HLR – Home Location Register
HSDPA – High Speed Downlink Packet Access
HSUPA- High Speed Uplink Packet Acess
ICI – Inter Carrier Interference
IFFT – Inverse Fast Frequency Transform
IoT – Interference over Thermal
ISI – Inter Symbol Interference
L1- Layer 1

LFSR - Linear feedback shift registers

LMMSE- Linear minimum mean square error

LO – Local Oscillator

LTE – Long Term Evolution

MAC – Medium Access Control

MCCH - Multicast control channel

MCH - Multicast channel

MIB – Master Information Block

MIMO- Multiple Input Multiple Output

MME – Mobile Management Entity

MU-MIMO – Multiuser MIMO

OFDMA – Orthogonal Frequency Division Multiple Access

PAPR – Peak to Average Power Ratio

PBCH - Physical Broadcast Channel

PCCH - Paging Control Channel

PCH - Paging channel

PDCCH - Physical Downlink Control Channel

PDCP - Packet Data Convergence Protocol

PDN – Packet Data Network

PDSCH - Physical Downlink Shared Channel

PHICH - Physical Hybrid ARQ Indicator Channel

PMCH - Physical Multicast Channel

PMI – Precoding Matrix Indicator

PN –Pseudo Random Noise

PRB – Physical Resource block

PSD – Power Frequency Density

PSK – Phase Shift Keying

PSS – Primary Synchronization Signal

QAM – Quadrature Amplitude Modulation

QPSK – Quadrature Phase Shift Keying

RACH – Random Access Channel

RAR – Random Access Response

RA-RNTI - Random Access Radio Network Temporary Identifiers

RE – Resource Element

RF – Radio Frequency

RFPA – RF Power Amplifier

RLC – Radio Link Controller

RNC – Radio Network Controller

RRC – Radio Resource Controller

RRM- Radio Resource Management

RSRP – Reference Symbol Received Power
SAE – System Architecture Evolution
SC-FDMA – Single Carrier- frequency division multiple access
SFBC – Space Frequency Block Code
SGSN – Serving GPRS Support Node
S-GW – Serving Gateway
SINR – Signal to Interference plus Noise Ratio
SRS - Sounding reference signal
SSS – Secondary Synchronization Signal
STBC – Space Time Block Code
SU –MIMO – Single user MIMO
TA – Timing Advance
TDM – Time Division Multiplex
TPC - Transmit Power Control
TPMI - Transmit Precoding Matrix Indication
TTI – Transmit Time Interval
UE – User Equiment
UL – Uplink
UMTS- Universal Mobile Telecommunication System
VLR – Visitor Location Register
WCDMA – Wideband Code Division Multiple Access

REFERENCES

[1] Harri holma and Antti Toskala, “LTE for UMTS –OFDMA and SC-FDMA Based Radio Access”, Jhon Wiley & Sons Ltd, 2009

[2] T.Zemen ,”OFDMA_SCFDMA basics for LTE (EUTRA)”, 2008

[3] Farooq khan, “LTE for 4G mobile broadband Air interface and Performance”, Cambridge University Press, 2009

[4] Goldsmith,A.,“Wireless Communications”, Cambridge University Press, UK, 2005

[5] Prasad Ramjee,“OFDM for wireless Communications system”, Artech House Publishers, August 2004

[6] Mackowiak,M., “Geometrically Based Multibounce MIMO Channel Models”, M.Sc. Thesis, IST- UTL, Lisbon, Portugal, 2007

[7] Bilal Muhammad, “Closed loop power control for LTE Uplink”, Thesis -Blekinge Institute of Technology School of Engineering, Nov 2008

[8] Stefan Parkvall, “LTE Radio Access –Physical layer Stefan Parkvall” LTE Resource Guide - Anritsu

[9] Stefan Kohler, “LTE from A-Z Technology and concepts of the 4G 3GPP Standard” INACON GmbH,2009

[10] 3GPP LTE Channels and MAC Layer 2009 EventHelix.com Inc

[11] 3GPP, Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN), 3GPP, TS 36.300 V.8.0.1, June 2007

[12] 3G America’s –MIMO transmission schemes for LTE and HSPA networks, June 2009

[13] Juho Lee, Jin-Kyu Han and Jianzhong (Charlie) Zhang, “MIMO Technologies in 3GPP LTE and LTE-Advanced” ,Hindawi Publishing Corporation ,2009

[14] Johan Furuskog, Karl Werner, Mathias Riback and Bo Hagerman, “Field trials of LTE with 4×4 MIMO”

[15] Carsten F. BallI, Robert Mullner, Johann Lienhart and Hubert Winkler, “ Performance Analysis of Closed and Open Loop MIMO in LTE” ,2009

[16] Stefenia sesia ,Issam Toufik , Mathew Baker, “ LTE –The long term evolution from theory to practice” Jhon Wiley & Sons Ltd, 2009

[17] LTE Performance for initial deployments by Nokia Siemens Network-White Paper

[18] Jim Zyren, “ Overview of the 3GPP Long Term Evolution Physical Layer”–Free scale Semiconductor, 2009

[19] 3GPP, Technical Specification 24.008 ‘Mobile radio interface Layer 3 specification; Core network protocols’, V.8.3.0

[20] B. Hassibi and B. M. Hochwald, “High-rate codes that are linear in space and time,” IEEE Transactions on Information Theory

[21] 3GPP TR 25.996 v6.1.0, “Spatial Channel Model for MIMO simulations.”

[22] Winters, J. H., “Optimum combining in digital mobile radio with cochannel interference,” IEEE Journal on Selected Areas in Communications, vol. SAC-2, no. 4, July 1984

[23] 3GPP TS 36.201 – v1.0.0, LTE Physical Layer – General Description

[24] Jim Zyren, "Overview of the 3GPP Long Term Evolution Physical Layer," White paperfrom FreeScale Semiconductor, July 2007

[25] Dongzhe Cui- Alcatel Lucent , “LTE Peak Rates Analysis”

[26] 3GPP TS 36.213 3rd Generation Partnership Project, Technical Specification Group Radio Access Network: Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Layer Procedures. Release 8

[27] Johansson, B. & Sundin, T., 2007. LTE test bed. Ericsson Review

[28] 3GPP, Technical Report 25.820 ‘3G Home NodeB Study Item Technical Report’, V.8.1.1

[29] D.G. Brennan, “Linear Diversity Combining Techniques”, Data Communications via Fading Channel, IEEE Press, 1975.

BIOGRAPHICAL INFORMATION

Prashant Srivastava was born on September 26th, 1983 in India. He achieved his Bachelor of Engineering in Electronics and Telecommunications from Fr.C.Rodrigues Institute of Technology, Mumbai University, India in June 2005. After doing his Bachelor, he worked with Reliance Communication, Ltd, India as a RF engineer for more than 2 years. In fall 2008 he came to University of Texas at Arlington to pursue Master's in Electrical Engineering. His research interests include wireless communications and data networks.