TAMPERE UNIVERSITY OF TECHNOLOGY

SYED NUMAN RAZA

LTE PERFORMANCE STUDY

Master of Science thesis

Examiners: M.Sc. Tero Isotalo,
PhD Jarno Niemelä

Examiners and topic approved by the Faculty Council of the Faculty of Computing and Electrical Engineering on 09 February 2012.

ABSTRACT

TAMPERE UNIVERSITY OF TECHNOLOGY: International Master's Degree Programme in Information Technology.
SYED NUMAN RAZA: LTE PERFORMANCE STUDY.
Master of Science Thesis, 69 pages, Appendix pages
March 2012
Majors: Wireless Communications
Supervisors: M.Sc. Tero Isotalo, PhD Jarno Niemelä.
Key words: LTE, 3GPP, performance, outdoor, urban, sub urban, rural, measurements.

Long Term Evolution (LTE) has been designed with new architecture and features to meet user's high data rates demand for a longer term in the future. 3rd Generation Partnership Project (3GPP) has set the goals and targets for LTE with better performance and data rates close to fixed networks.

In this thesis outdoor measurements have been conducted in three different environments macro/rural, urban and suburban. This thesis study has been done with single user measurements and performance analysis scenario. The idea of measurements was to analyze LTE performance in three different types of environments. Performance analysis has been done using few key performance indicators and parameters including RSRP, RS SNR, MAC downlink throughput, timing advance and CQI. Vendor/operator specific key performance indicators and parameters were unknown.

The results and analysis of this thesis give an idea about LTE performance in three different outdoor environments. The output of this thesis study can be beneficial in understanding LTE behavior and performance in different environments, which can be further useful in planning and deployment phases for LTE.

PREFACE

This Master of Science Thesis has been written for the completion of my Master of Science Degree in Information Technology, in Tampere University of Technology (TUT). The research work has been carried out in RNG group in the Department of Electrical Engineering at Tampere University of Technology (TUT) during winter and spring season of 2011-12.

First of all, I would like to express my acknowledgments to my supervisors and examiners PhD. Jarno Niemelä and M.Sc. Tero Isotalo for providing me the topic for my master thesis. Their continuous guidance and supervision led this thesis work to completion. I am particularly thankful to my colleagues Rohit and Usman in RNG group at TUT for proof reading stage. I would like to express my gratitude to my sister, brother and most importantly to my wife for her patience and support during my work. I would like to pay my highest regards to my mother who is credible for my every success in life. In the end I would like to thank TAYS orthopaedic doctors and nurses for taking care of me and enabling me to walk again on my feet and start a new life.

Syed Numan Raza
raza.syednuman@gmail.com
Tel. +358452080660

TABLE OF CONTENTS

LIST OF SYMBOLS

Δf	Subcarrier spacing
Δf_{coh}	Coherence bandwidth
λ	Wavelength
Φ	Incident angle
$\overline{\Phi}$	Mean angle
B	Bandwidth
B_p	Break point
D	Frequency reuse distance
G_r	Receiver gain
G_t	Transmitter gain
Δh	Height difference of surface
h_{BTS}	Height of base station
h_{MS}	Height of mobile station
i_{other}	Other to own cell interference
K	Boltzman constant
M	Number of cells in a single cluster
N	Number of resource blocks
N_s	Noise
N_t	Thermal noise
$P(\Phi)$	Angular power distribution
$P_{\Phi total}$	Angular total power
P_L	Path loss
P_r	Receievd power
P_t	Transmitted power
r	Cell radius
r_d	Distance between transmitter and receiver
S	Delay spread
S_{Φ}	Angular spread
$SINR_{req.}$	Signal to interference and noise ratio required

LIST OF ABREVIATIONS

1G	1st Generation
2G	2nd Generation
3G	3rd Generation
3GPP	3rd Generation Partnership Project
4G	4th Generation
AMC	Adaptive Modulation and Coding
AMPS	Advanced Mobile Phone systems
BLER	Block Error Rate
CAPEX	Capital Expenditure
CDMA	Code Division Multiple Access
CN	Core Network
CP	Cyclic Prefix
C-Plane	Control Plane
CQI	Channel Quality Indicator
CS	Circuit Switching/Switched
dB	Decibel
dec	Decade
EDGE	Enhanced Data rates for GSM Evolution
eNB	eNodeB
EPC	Evolve Packet Core
EPS	Evolved Packet system
E-UTRAN	Evolved Universal Terrestrial Radio Access Network
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
FFT	Fast Fourier Transform
FST	Frame Structure Type
GERAN	GSM/EDGE Radio Access Network
GGSN	Gateway GPRS Support Node
GSM	Global System for Mobile Communications
GPRS	General Packet Radio Service
HARQ	Hybrid Automatic Repeat Request
HSCSD	High Speed Circuit Switched Data
HSDPA	High Speed Downlink Packet Access
HSPA	High Speed Packet Access
HSPA+	High Speed Packet Access Plus/Evolution
HSS	Home Subscriber Server

HSUPA	High Speed Uplink Packet Access
ICI	Inter Carrier Interference
ICIC	Inter Cell Interference Coordination
IMS	IP Multimedia Services
IMT	International Mobile Telecommunications
IP	Internet Protocol
ISI	Inter-symbol Interference
bps	bits per second
LOS	Line of Sight
LTE	Long Term Evolution
MBMS	Multicast Broadcast Multimedia Services
MCS	Modulation and Coding Scheme
MIMO	Multiple Input Multiple Output
MIB	Master Information Block
MME	Mobility Management Entity
MU-MIMO	Multi User Multiple Inputs Multiple Outputs
NLOS	Non Line Of Sight
OFDMA	Orthogonal Frequency Division Multiple Access
OPEX	Operational Expenditure
P-GW	PDN Gateway
PAPR	Peak to Average Power Ratio
PBCH	Physical Broadcast Channel
PCEF	Policy Control Enforcement Function
PCFICH	Physical Control Format Indicator Channel
PDCP	Packet Data Convergence Protocol
PCRF	Policy Control and Charging Rules Function
PDCCH	Physical Downlink Control Channel
PDN	Packet Data Network
PDSCH	Physical Downlink Shared Channel
PMI	Pre-coding Matrix Indicator
PHICH	Physical HARQ Indicator Channel
PRACH	Physical Random Access Channel
PS	Packet Switching/Switched
PSD	Power Spectral Density
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
QoS	Quality of Service
RA	Routing Area
RAT	Radio Access Technology/Technologies
RB	Resource Block
RE	Resource Element
RI	Rank Indicator

RLC	Radio Link Control
RNC	Radio Network Controller
RS	Reference Signal
RTT	Round Trip Time
S-GW	Serving Gateway
SAE	System Architecture Evolution
SC-FDMA	Single Carrier Frequency Division Multiple Access
SGSN	Serving GPRS Support Node
SIB	System Information Block
SINR	Signal to Interference and Noise Ratio
SRS	Sounding Reference Signal
SU-MIMO	Single User Multiple Inputs Multiple Outputs
TA	Tracking Area
TCP	Transmission Control Protocol
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TM	Transmission Mode
TPC	Transmit Power Control
UMTS	Universal Mobile Telecommunication System
U-Plane	User Plane
UTRA	Universal Terrestrial Radio Access
UTRAN	Universal Terrestrial Radio Access Network
VoIP	Voice over Internet Protocol
WCDMA	Wideband Code Division Multiple Access

1. INTRODUCTION

The word performance has been used a lot in every walk of life now a days. It is used widely in business sense as well. What does it mean and where it has come from. According to [1], performance word was originated from ‘performen', borrowed from the old French 'parfornir', which means to do. In many dictionaries it has been described as accomplishment of work or task. How performance word is used in my thesis and what is the relevance of it with my thesis title? We are living in a commercial world and every business has its own targets and performance goals. Most common goals in all businesses are customer satisfaction and profit for the business owner. In this case business owner is a mobile phone operator and customers are human beings with personal communication devices. Mobile user’s satisfaction comes with higher capacity, better coverage and Quality of Service (QoS) with cheapm rates. Mobile operator’s satisfaction comes with higher profit which is achievable only with high number of users and their satisfaction.

We all know that human beings have a strange behavior for satisfaction, which is never constant. It can be described as more and more with time. This is the same behavior which mobile users are showing towards mobile phone industry in form of high data rates demand. Users have become much more mature day by day. They are not any more users who are just satisfied with a voice call or text message. Users of today want to make video calls and run real time applications, i.e. video streaming and playing online games etc. and all they want it within their handheld small mobile phone devices. These demands have driven mobile phone operators and manufacturers to move forward towards new mobile broadband technologies. The goal is to provide higher user data rates making the mobile broadband services throughputs closer to fixed land line broadband and that too with mobility. UMTS Long Term Evolution (LTE) has come with some promises to fulfill the demands of high data rates for mobile broadband users, which are investigated further in thesis. This thesis study is based on outdoor measurement results from LTE network. These measurement campaigns were conducted in three different environments macro/rural, urban and suburban in Tampere and Nokia cities of Finland. Results from measurements have been analyzed to study the performance of LTE in three different types of environments and antennas heights. A comparison based analysis is done using LTE key performance indicators and parameters.

Motivation to this thesis study was the thirst of learning and understanding the performance and behavior of LTE in field measurements based practical scenario. When I wanted to choose a thesis for my master’s degree there were simulations based performance studies and literature available for LTE but I could not find any appreciable literature or study for LTE performance based on field measurements. In my opinion measurements based study is much more beneficial to understand a system's behavior and performance as compared to simulations because simulations might lack some practical issues and show errors as compared to field measurements based results.

This thesis can be divided in two parts. First part includes theoretical background study and second part presents measurement plan and results. Chapters from 2 to 4 belong to theoretical study part. In Chapter 2, wireless communication principles are discussed for the basic understanding of a mobile radio communication system. Chapter 3 gives idea about historical background of mobile communication systems. LTE overview is given with basic requirements to achieve LTE system goals following with short discussion on LTE architecture. Chapter 4 presents the idea of LTE radio interface design, radio frame structure and physical layer procedures of LTE. LTE downlink performance has been discussed on the basis of already existing theory. It shall help to understand LTE performance as compared to LTE targets given in chapter 3. In Chapter 5 measurement campaigns have been presented and results have been discussed with supporting figures from measurements. Results and analysis meaning, possible utilization and error analysis is done following with limitations to analysis. In Chapter 6 conclusion is given with discussion on the basis of results and analysis from Chapter 5 following with short discussion on future possible research potential in the end.

2. WIRELESS COMMUNICATION PRINCIPLES

This chapter gives the basic knowledge about wireless communication principles. At first cellular network concept and frequency reuse has been discussed for LTE. Then basic multiple access schemes have been discussed shortly following with propagation environment and factors which affect propagation of a wireless signal. This chapter lays the basis for further study and understanding of this thesis.

2.1. Cellular network concept

Cellular network concept was introduced and used by Bell labs in 1970 for the first time [2]. It is famous for its use in 2nd generation mobile communication systems most famous Global System for Mobile communications (GSM). The idea of a cellular network concept is to divide an area called cluster into many small cells each cell uses different frequencies than its neighboring cells. Single base station is used to serve several cells with regular or irregular shape, most commonly used cell shape is hexagon but square, rectangle and circle shapes can also be used. All frequencies used in a cluster can be reused in other clusters maintaining that neighboring cells among different clusters also use different frequencies to avoid co-channel interference but adjacent channel interference is still an issue in GSM because of imperfect filters. Mobility management through handovers among adjacent cells is necessary for continuity of service in case of supporting user mobility over long distance travelling. [2]

This concept is used by mobile operators to provide coverage and mobility in large geographical area, like in a country because operators are bounded with their licensed spectrum and limited amount of available frequencies. Cellular concept enables them to reuse their frequencies to enhance capacity and coverage. It also helps to reduce the coverage or cell size of a base station transceiver which enables reduction in power consumption for transmissions in both uplink and downlink directions. This is how mobile station benefits with longer battery life. A typical cellular layout is described below in Figure 2.1.

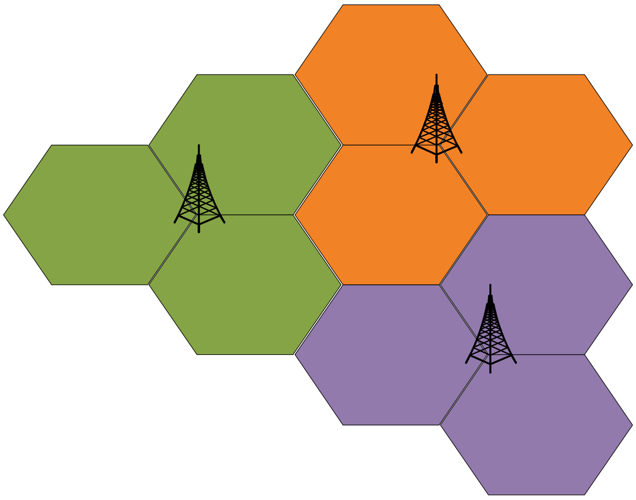

Figure 2.1. *Cellular layout with three base stations.*

Frequency reuse factor is defined as 1/M, where M is amount of cells in a single cluster which cannot have same frequencies. Common values of frequency reuse factor are 1/3, 1/4, 1/7, 1/9 and 1/12. For M number of cells in a single cluster with cell radius r, reuse distance D can be calculated with the formula given below. [2]

$$D = r\sqrt{3M} \tag{2.6}$$

In FDMA signals are distinguished by using different frequencies in adjacent neighboring cells. In CDMA frequency reuse factor is 1 and signals for different users are distinguished by pseudo random noise codes.
In LTE inter cell interference coordination and scheduling techniques enable frequency reuse factor of 1. There are 2 types of frequency reuse schemes available for LTE to facilitate Inter Cell Interference Coordination (ICIC) and scheduling procedures.

- Fractional frequency reuse.
- Soft frequency reuse.

Before fractional and soft frequency reuse schemes, it will be worth to discuss hard frequency resuse scheme which will form basis for understanding these frequency reuse schemes in LTE. In hard frequency reuse scheme in a cell those physical resource blocks or bandwidth are not allocated at all to the cell edge users which are being used by neighboring cell and have high interference level as shown in the Figure 2.2. [3]

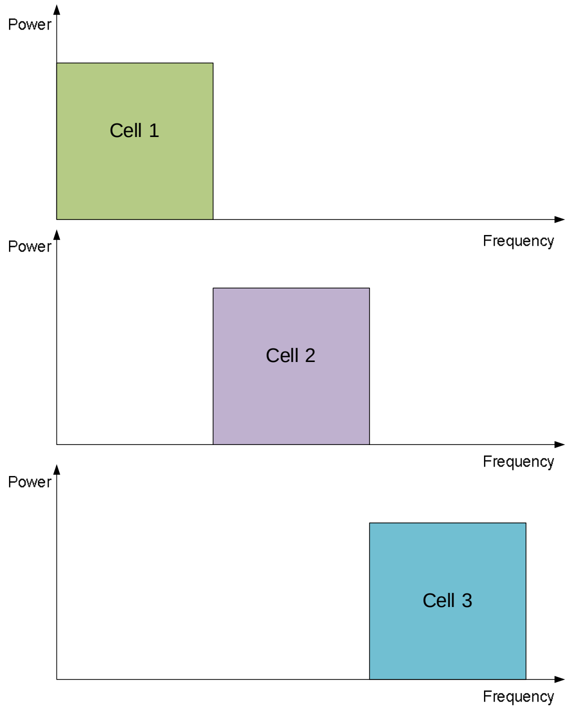

Figure 2.2. *Hard frequency reuse scheme for LTE [3].*

For fractional and soft frequency reuse schemes each cell is logically divided into 2 parts as shown in Figure 2.3. The inner or central part is used for cell centered users with frequency reuse factor 1. In the outer or cell edge part users are scheduled resources using ICIC and power allocation methods [4]. So in reality in a whole LTE cell frequency reuse 1 can not be used. On cell edge either fractional or soft frequency reuse scheme has to be employed to avoid intercell interference.

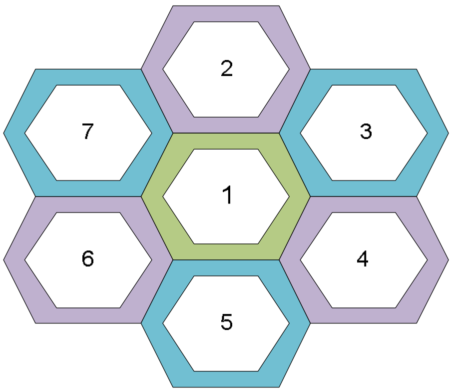

Figure 2.3. *Frequency reuse and power allocation in cell [4].*

In fractional frequency reuse cell edge users are scheduled in the complementary frequency bands using hard frequency reuse technique taking into consider neighboring cell interference as shown in Figure 2.4. [3]

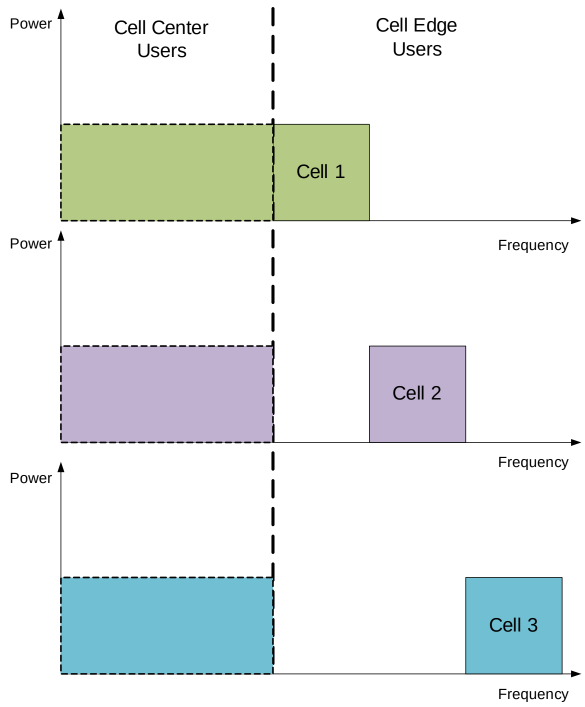

Figure 2.4. *Fractional frequency reuse for LTE [3].*

In soft frequency reuse scheme all resource blocks and full bandwidth are utilized but very low power is allocated to the physical resource blocks for cell edge users as shown in Figure 2.5.[3]

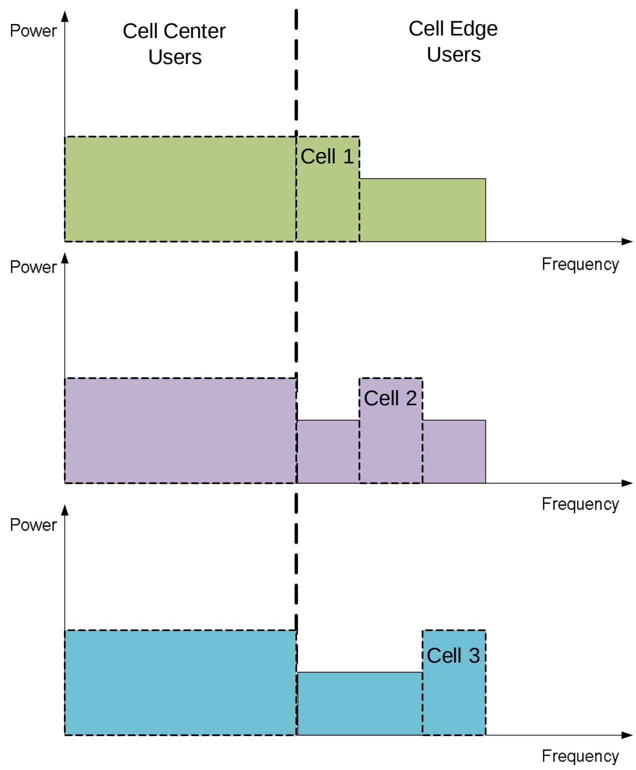

Figure 2.5. *Soft frequency reuse for LTE [3].*

2.2. Multiple access techniques

A multiple access technique is used to enable multiple users to share the radio resources in a system but still keeping users separate from each other on radio interface. There are three basic multiple access techniques available for this purpose.

- FDMA
- TDMA
- CDMA

2.2.1. FDMA

FDMA stands for Frequency Division Multiple Access. This scheme divides available spectrum into a group of frequencies called channels. Each user is assigned different channel for uplink and downlink. These channels after assigning to a user cannot be used by any other user in the system which makes it inefficient when those channels are not being used by assigned user. These channels are separated by guard bands. FDMA have very poor performance from system capacity and throughput point of view. However user equipment complexity is very low for supporting FDMA.
Orthogonal Frequency Division Multiple Access scheme is a variant of FDMA which uses multiple orthogonal carriers to exploit channel conditions to maximize user throughput. [5] OFDMA (Orthogonal Frequency Division Multiple Access) is discussed in detail in Chapter 4, Section 4.1.3.

2.2.2. TDMA

TDMA stands for Time Division Multiple Access. In this scheme the available spectrum is divided into time domain slots and users are allocated these time slots for transmitting or receiving data. TDMA scheme has discontinuities in transmission which causes bursts in channel and hence the data buffering is required at the receiver side. TDMA system needs good synchronization to avoid adjacent channel interference. [5]

2.2.3. CDMA

CDMA stands for Code Division Multiple Access. This scheme uses spread spectrum technology and a special coding scheme to separate different users to allow multiple users to be multiplexed over the same physical channel. A spreading code is used to convert a narrowband message signal into a wideband signal. The spreading codes are pseudo random noise code sequences with a chip rate higher than the message signal. Each user is assigned its own spreading code which is approximately orthogonal to all other spreading codes assigned to other users in the system. UMTS uses CDMA with a frequency reuse factor 1. [5]

2.3. Wireless propagation mechanisms

When wireless signals propagate in an environment, it is affected by environment depending on its type. To understand these environmental effects on a wireless signal, wireless propagation mechanisms are given below.

2.3.1. Free space propagation

When there are no obstacles in the propagation path between transmitter and receiver, then propagation is considered to be free space propagation and medium is considered as free space loss medium. Received power at receiver P_r can be calculated using Friis formula: [2]

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi r_d}\right)^2, \tag{2.1}$$

where P_t is transmitted power, G_t transmitter gain, G_r receiver gain, λ wavelength and r_d is distance between transmitter and receiver.

2.3.2. Reflection and transmission

Reflection occurs when a plane wave propagating from one medium, incidents on the boundary of second medium and bounces back into the first medium. On the contrary if wave is able to enter into second medium it is called transmission. Reflection and transmission both can be partial as well as full. Signal propagation depends on phase shifts, the angle of reflection, refracted signal and polarization. [2]

2.3.3. Scattering

As compared to specular reflection which occurs from smooth surface, if the surface of second medium is rough, the incident wave energy is scattered into random directions in the first medium depending on angle of incident and wavelength. This is called scattering. For a surface to be rough, it must satisfy the Rayleigh criterion: [2]

$$\Delta h < \frac{\lambda}{8\cos\Phi}, \tag{2.2}$$

where a signal surface with wavelength of λ and incident angle of Φ can be considered as rough for which $\Delta\theta \geq \frac{\pi}{2}$.

2.3.4. Diffraction

Diffraction is a phenomenon which occurs, when propagating wave incidents on a knife edge and needle head like objects. Diffraction phenomenon helps signals to propagate in non line of sight (NLOS) places like shadow regions. [2]

2.4. Multi-path propagation

When line of sight (LOS) is not available or partially available and there are obstacles on the propagation path between transmitter and receiver, then there is possibility of receiving several replicas of same signal with amplitude and phase variations due to different propagation mechanisms discussed above. This kind of propagation is called multi-path propagation which is characterized by angular spread, delay spread, coherence bandwidth and the propagation slope. [6]

2.4.1. Angular spread

Angular spread S is the deviation of signal incident angel. It affects on the performance of diversity reception and adaptive antennas. It is higher in indoor (up to 360 degree) and smaller in outdoor macro (up to 5- 10 degrees for macro and 45 degrees for micro) environments. The angular spread S_Φ can be calculated using following formula: [6]

$$S_\Phi = \sqrt{\int_{\Phi-180}^{\Phi+180} (\Phi - \overline{\Phi})^2 \frac{P(\Phi)}{P_{\Phi total}} d\Phi}, \qquad (2.3)$$

where Φ is incident angel, $\overline{\Phi}$ is the mean angle, $P(\Phi)$ is the angular power distribution, and $P_{\Phi total}$ is the total power.

2.4.2. Delay spread

Delay spread is the amount of variation and delay in time between first and last multi-path received components. It is higher in outdoor (10 – 15 μs for macro and 1-5 μs for micro) environment as compared to indoor (10 – 200 ns). It affects performance of frequency hopping and 3G radio interfaces. [6]

2.4.3. Coherence bandwidth

Coherence bandwidth is a function of delay spread. It is the maximum bandwidth in which channel response is considered flat over all frequencies. It can be calculated using following formula which also describes the relationship of delay spread S and coherence bandwidth Δf_c: [6]

$$\Delta f_c = \frac{1}{2\pi S}, \qquad (2.4)$$

2.4.4. Propagation slope

Propagation slope is a measure of attenuation between transmitter and receiver. Attenuation factor of propagation slope is higher in urban areas (40 dB/dec slope) as compared to free space (20 dB/dec slope). Path loss can be calculated using power law: [5]

$$L = 10n\log_{10}(r) + K, \qquad (2.5)$$

Where L is path loss, n is path loss exponent which depends on antenna height and propagation environment, r is distance and K is clutter correction factor.

According to two ray reflection model after break point distance, propagation attenuation corresponds to the propagating environment. Break point B_p can be calculated using following formula: [6]

$$B_p = 4\frac{h_{BTS}h_{MS}}{\lambda}, \qquad (2.6)$$

where h_{BTS} and h_{MS} are heights of base station and mobile station. Wavelength is λ.

2.5. Radio propagation in outdoor environment

For understanding radio propagation it is necessary for one to understand radio environment in which radio signals propagate. It is the environment which effects and defines propagation for a signal along with the signal nature and characteristics itself.

Outdoor environment can be categorized into macro, micro/urban, sub-urban and rural environments based on their geographical area and population density. Macro and rural environments are considered where population and buildings are not dense and scattered over longer distance. Antenna heights of base stations are considered larger than average building heights and foliage presence. Larger coverage is the essence of macro and rural environments. In these environments delay spread is longer and angular spread is smaller. [6]

Micro/urban environments are those where population and buildings are denser and their concentration is higher in many countries. Antenna heights of base stations are lower as compared to average buildings height which makes these environments multipath propagation environments with fast fading and with shorter delay spread but with higher angular spread as compared to macro/rural environments. Higher capacity with large amount of users is main target in micro/urban environments. Suburban environment is an average environment with some characteristics common both from rural and urban environments. A medium size city with good number of population is a good example of suburban environment [2; 6]

When a signal wave propagates through a medium, it suffers with fading which results in signal envelop variations. Fading can be of two types, slow fading/shadowing and fast fading.

Slow fading is the variation of local mean signal level over a wide area due to large obstacles in the signal propagation path of a moving mobile. [6]

Local mean is the mean value of the fast fading component which is due to multipath propagation characteristics. Fast variations are caused by scatterers in the multipath propagation environment. [6]

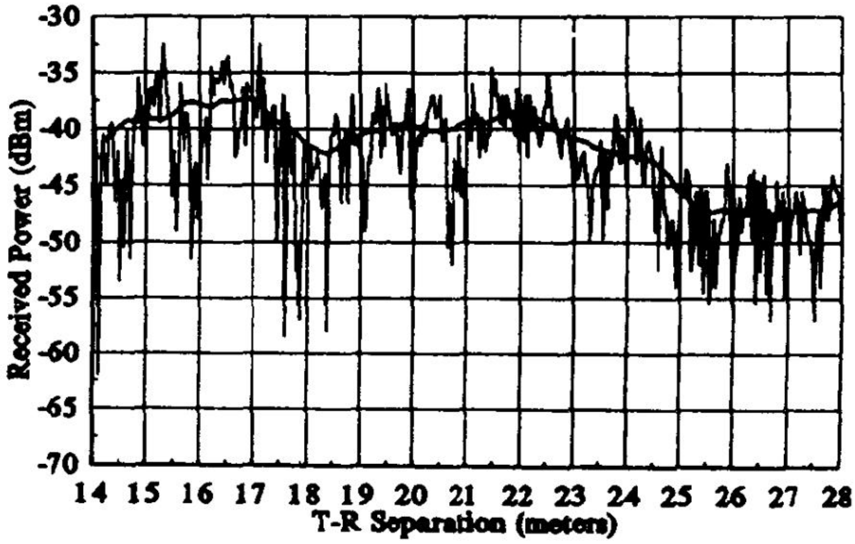

Figure 2.6. *Slow and fast fading [2].*

In Figure 2.6, thick black curve is representing slow fading/shadowing and thin black curve is representing fast fading fluctuations.

3. HISTORY AND LTE OVERVIEW

In this chapter first mobile communication history has been discussed shortly which is followed by LTE overview providing basic understanding of LTE goals and targets. LTE architecture has been discussed briefly in the later part of this chapter.

3.1. History of mobile communication systems

The world saw its first successful mobile communication system in 1980's. It was analogue communication based system which is now called 1st generation (1G) of mobile phone systems. In different parts of the world independent analogue systems were developed and used AMPS (Advanced Mobile Phone Systems) in USA, TACS (Total Access Communication Systems), NMT (Nordic Mobile Telephone Systems) in Europe and J-TACS (Japanese Total Access Communication System) in Japan and Hong Kong. These systems used FM (Frequency Modulation) and FDMA (Frequency Division Multiple Access) techniques. Cellular concept was used to enhance capacity and handover was used to support mobility. These systems did not earn big success because they were restricted within their boundaries. Amount of users were not large because equipment was expensives and heavy with short battery life. There were security leakages due to lack of encryption. Anyone could overhear conversation of other users just tuning to particular frequencies, and only voice calls were possible. [2]
The second generation (2G) of mobile communication systems were digital and includes systems such as GSM (Global Service for Mobile communications), PDC (Personal Digital Cellular technology), IS (Interim Standard)-136 based on TDMA (Time Division Multiple Access), iDEN (integrated Digital Enhanced Network), IS-95 based on CDMA (Code Division Multiple Access). First commercial GSM network was successfully launched in Finland in 1991. In Europe 900 and 1800 MHz bands have been used for GSM system. GSM became much stronger and prevailing system in the whole world as compared to its counter parts in 2G. Being a digital system, GSM over ruled 1G analogue systems completely and became worldwide accepted, because of its roaming service. It introduced SMS (Short Messaging Service) text messaging which became very popular. Being digital system GSM was more immune to noise as compared to 1G system. Battery life extended much longer and due to digital systems development which helped GSM mobile phones to get smaller in size and lighter as compared to old

er generation mobile phones. Security was improved because of digital encryption. Amount of users grew huge because of frequency reuse techniques. In GSM basic data rates were only 9.6 kbps. [2]

GSM is based on circuit switching and provides higher data rates and internet access by HSCSD (High Speed Circuit Switched Data), GPRS (General Packet Radio Service) and EDGE (Enhanced Data rates for GSM Evolution) technologies, which were introduced later. GPRS and EDGE (Enhanced Data rates for GSM Evolution) introduced packet switched services with circuit switching for GSM users. [2]

The third generation mobile communication systems use packet switching along with traditional circuit switching from 2G systems. These systems provide high data rate services and applications like real time TV streaming, video conferencing, GPS navigation and other multimedia services. The program was led by International Telecommunication Union under the project IMT-2000; standards were developed for 3G systems which are defined as UMTS (Universal Mobile Telecommunication Systems). 3G technology systems include UMTS, CDMA2000, DECT (Digital Enhanced Cordless Telecommunications) and EDGE. There are different sets of frequencies being used for 3G systems in all over the world. These are 850, 900, 1700, 1900, 2100 MHz. Earlier in many countries standard bands availability was a problem for UMTS. UMTS is a CDMA based system with peak data rates for pedestrian user up to 384 kbps and for vehicle user up to 144 kbps theoretically. The operators had to face some problems adapting UMTS, like huge cost and availability of standard bands. Moreover new hardware and sites were also expensive to have in larger amount as compared to traditional GSM to provide enough coverage with 2100 MHz, for providing high data rate services. [2]

Later on HSDPA (High Speed Downlink Packet Access) and HSUPA (High Speed Uplink Packet Access) were introduced in Release 5 and Release 6 respectively based on WCDMA (Wideband Code Division Multiple Access). Maximum data rates up to 14 Mbps in downlink and 5.76 Mbps in uplink were achieved. New transport and physical layer channels were introduced for HSDPA. HARQ, fast packet scheduling and adaptive modulation and coding schemes helped to reduce latency and improve data rates for downlink user. Uplink enhanced channel E-DCH (Enhanced Dedicated Channel) is used by HSUPA. Packet scheduler is also used but on request-grant principle, which means user equipment requests its transmission from scheduler. HSUPA also introduces new physical channels and uses shorter TTI (Transmission Time Interval), incremental redundancy and HARQ (Hybrid Automatic-Repeat-Request) to improve data rates but unlike HSDPA it does not use orthogonal transmissions to each other. [3]

HSPA+ or Evolved HSPA was introduced in Release 7. It improves data rates in downlink up to 84 Mbps and 22 Mbps in uplink (theoretically) using higher modulation schemes and MIMO techniques. HSPA+ can also use all IP based structure connected to base stations. HSPA+ should not be confused with LTE because LTE introduces new air interfaces. New improvements continued in HSPA+ in coming releases. [3]

LTE Long Term Evolution was introduced in Release 8. It was based on a pure all IP based flat architecture and introduced new interfaces, reduced elements with more simplicity and low latency which will be discussed later in detail. 2600 MHz frequency band is considered to be suitable to interwork with existing UMTS, however other low frequency bands are also being considered for LTE in different circumstances. LTE promises peak data rates up to 170 Mbps in downlink and 85 Mbps in uplink theoretically. LTE provides many delay sensitive services like VoIP and real time applications. Latency is an important issue for performance and efficiency assessment for wireless services. With pre-allocated resources round trip delay can be lower than 15 ms. With scheduling delay round trip delay can be 20 ms. These round trip delays are low enough to support delay sensitive real time application services.
LTE can interwork with 3G systems. Further improvements in LTE are brought in LTE Advanced which is backward compatible with LTE and was introduced in Release 10. [3]

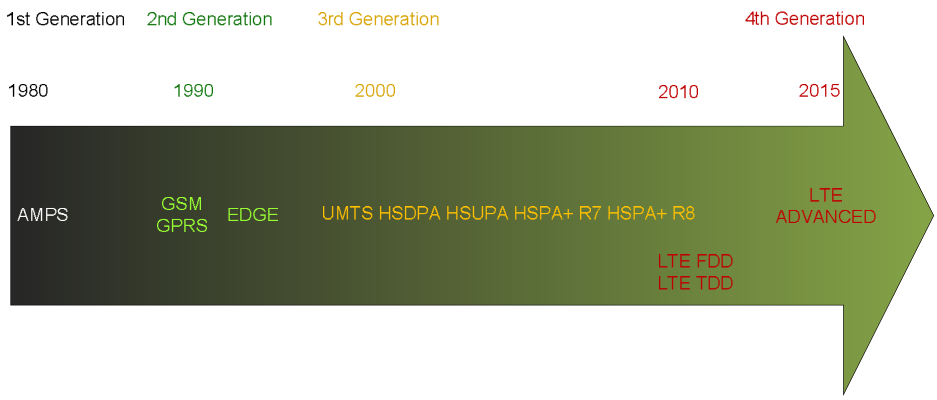

Figure 3.1.*Mobile communication evolution path [3].*

3.2. 3rd Generation Partnership Project: 3GPP

3rd Generation Partnership Project was created in 1998. The main purpose was to produce technical specifications and technical reports for a 3G Mobile System based on evolved GSM core networks and the radio access technologies that they support i.e., Universal Terrestrial Radio Access (UTRA) both Frequency Division Duplex (FDD) and Time Division Duplex (TDD) modes. Later on maintenance and development of the GSM Technical Specifications (TS) and Technical Reports (TR) including evolved radio access technologies (e.g. General Packet Radio Service (GPRS) and Enhanced Data rates for GSM Evolution (EDGE) were included in 3GPP work. LTE and LTE Advanced standards, specifications and technical reports are also designed and developed under 3GPP now [3; 7].
LTE was formed by the collaboration of regional development standard organizations. ATIS from North America, ETSI from Europe, CCSA from China, TTA from Korea,

ARIB and TTC from Japan helped forming initially 3rd Generation Partnership Project shown in Figure 3.2. Later on over 300 different individual companies all over the world joined 3GPP. 3GPP has done appreciable work for the evolution of mobile communication technologies since its foundation.

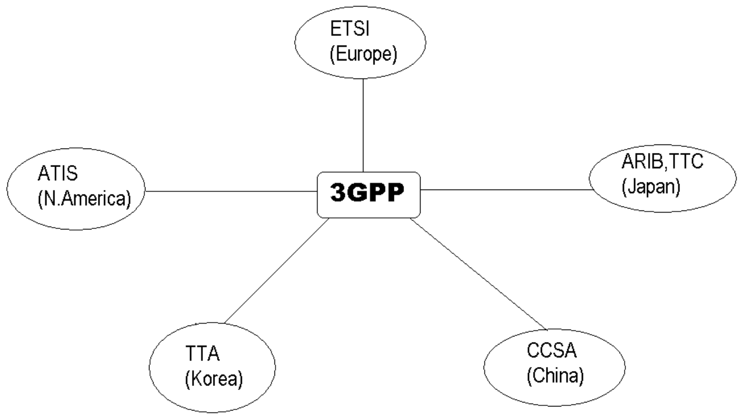

Figure 3.2. *3rd Generation Partnership Project early formation [8].*

We have seen since 1980, a new mobile phone technology after every 10 years. The 3GPP objectives behind each technology evolution has been to achieve reduced latency, higher data rates, improved system capacity, better coverage and reduced cost for operators. To achieve these objectives an evolution to system architecture and radio interfaces was necessary.
Keeping these objectives in mind, LTE was standardized and developed to provide long term competitiveness. LTE provides a smooth upgrade path from previous technologies as shown in Figure 3.3. A GSM operator can upgrade to LTE without routing through 3G technologies. It is designed to co-exist with 2G and 3G technologies. New radio interfaces, flat and all IP architecture help it to achieve targets. [3]

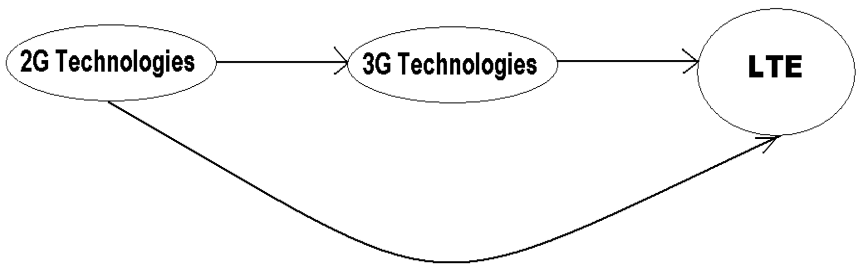

Figure 3.3. *LTE upgrade paths and options.*

3.3. LTE deployment scenarios

There are many deployment scenarios for LTE but exact deployment scenario for an operator shall be determined on the requirements of particular case and inter-working, demand of mobile services and competitive environment. A high level E-UTRAN

(Evolved UMTS Terrestrial Radio Access Network) should at least support following two deployment scenarios. [8]

- Standalone deployment scenario: where there is no inter-working with UTRAN/GERAN (GSM/EDGE Radio Access Network), whether it exists already or does not. This is called standalone wireless broadband application.
- Integration with UTRAN/GERAN deployment scenario: UTRAN and GERAN exist already with full or partial geographical coverage and can have different levels of maturity. LTE supports inter-working and mobility with legacy 3GPP and non-3GPP technologies.
  It means in such case, LTE coverage planning and choice of frequency spectrum band selection is affected by already existing UTRAN/GERAN 3GPP or non-3GPP systems parameters for an operator.

3.4. Targets for Long Term Evolution

For understanding a system it is very necessary to understand its goals and targets. For Long Term Evolution, goals and targets are described in 3GPP [9] are given below briefly.

- Significantly increased peak data rates e.g. 100 Mbps in downlink and 50 Mbps in uplink with increase in data rates for cell edge users too.
- Significantly improved spectrum efficiency 2 to 4 times better than Release 6 and reduced radio access latency up to 10 ms and control plane latency less than 100 ms excluding downlink paging delay.
- Scalable bandwidth from 1.25 to 20 MHz, with possibility to allow flexibility in narrow band spectral allocations.
- Support for inter working with existing 3G systems and non 3GPP specified systems with backward compatibility desire.
- Support of enhanced IP Multimedia Services (IMS) and core network with support of various other types of Packet Switched services e.g. Voice over IP.
- Support for enhanced Multicast Broadcast Multimedia Services (MBMS).
- Reduced CAPEX and OPEX including backhaul cost with cost effective migration from Release 6 UTRA radio interface and architecture.
- Reasonable system and terminal complexity, cost, and power consumption.
- Support for high speed mobility with reliability for example in high speed trains up to 500km/h.
- LTE typical cell radius is 5 km but possible operational cell range should be 100 km to support wide area deployments.

3.5. LTE user equipment capabilities

3GPP Release 8 has defined five user equipment categories for LTE in [10]. Capabilities including downlink/uplink peak data rates, maximum bits received/transmitted per Transmission Time Interval (TTI), maximum available Radio Frequency (RF) system bandwidth, highest modulation scheme available in downlink/uplink and MIMO schemes available for each user equipment category are given in Table 3.4. TTI is related to the size of the data blocks transfered from higher network layers to radio link layer. MIMO is used for all categories except category one mobiles. For this thesis only category 3 mobile is used in measurements. Purpose of this section is to give the idea about capabilities and limitations of user equipment used during measurements.

Table 3.4. *LTE user equipment categories [10].*

	Cat. 1	**Cat. 2**	**Cat. 3**	**Cat. 4**	**Cat. 5**
Downlink peak data rates (Mbps)	10	50	100	150	300
Uplink peak data rates (Mbps)	5	25	50	50	75
Max. bits received within TTI	10296	51024	102048	149776	299552
Max. bits transmitted within TTI	5160	25456	51024	51024	75376
RF system bandwidth (MHz)	20	20	20	20	20
Modulation downlink	64QAM	64QAM	64QAM	64QAM	64QAM
Modulation uplink	16QAM	16QAM	16QAM	16QAM	64QAM
MIMO downlink	Optional	2 x 2	2 x 2	2 x 2	4 x 4

3.6. Comparison of LTE and Release 6

When LTE was being designed, its performance targets were set by 3GPP in [7] comparatively to most advanced version of UMTS at that time which was Release 6. LTE provides more than 3 times performance efficiency gain over HSDPA Release 6 and in uplink gives more than 2 times efficiency gain over HSUPA [3]. There are 4 major factors for LTE downlink spectral efficiency gain over HSPA Release 6.

- HSDPA suffers from intra-cell interference in rake receivers. HSDPA terminals use equalizer for rake receivers to remove intra-cell interference. But LTE uses OFDM which removes intra cell interference due to orthogonal subcarriers and about 70% gain is achieved over HSDPA Release 6 depending on multipath profile. [3]

- In single carrier HSDPA there is no frequency domain packet scheduling but in LTE due to OFDM frequency domain scheduling a gain of about 40% is achieved over HSDPA Release 6. In dual carrier HSDPA in later Release 7 there is some frequency domain scheduling gain possible. [3]
- In HSDPA Release 6 MIMO was not introduced. 1 × 2 antenna scheme was used in HSDPA. In LTE with 2 × 2 MIMO about 15% efficiency gain is achieved over HSDPA Release 6. [3]
- Inter cell interference rejection combining is used in LTE which works better with OFDM and gives about 10% efficiency gain over HSDPA Release 6. [3]

Efficiencies comparison of different systems is shown in Figure 3.5, these results are obtained after simulations performed in [3].

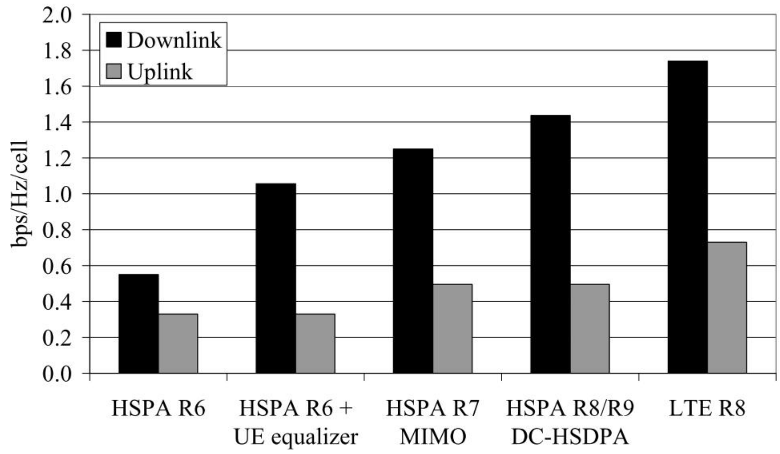

Figure 3.5. *Spectral efficiency comparison of HSPA and LTE [3].*

3.7. All IP based, flat LTE network architecture

LTE network architecture is designed to be flat and all IP based structure, which means LTE has been designed to support only packet switched services. Flat architecture helps to reduce delays in User Plane (U-Plane) and Control Plane (C-Plane)s which improves data rates. It provides seamless connectivity between user equipment and packet data network (PDN) without any disruption to the communications during mobility. LTE has brought System Architecture Evolution (SAE). SAE consists of Evolved Packet Core (EPC) network. Together LTE and SAE comprise Evolved Packet System (EPS). As shown in Figure 3.6, EPS provides user equipment, IP connectivity to a PDN for accessing Internet. Packets between user equipment and a gateway in PDN are routed by EPS through IP bearers, which are usually associated with a QoS. A user can also download a file during a VoIP call because EPS can establish multiple bearers to support different QoS streams by connecting to different PDNs. Sufficient security and privacy is also provided in the network to the users. Core Network (CN) elements and their functions are shown in Figure 3.6, which are described in core network section. [3; 8; 11]

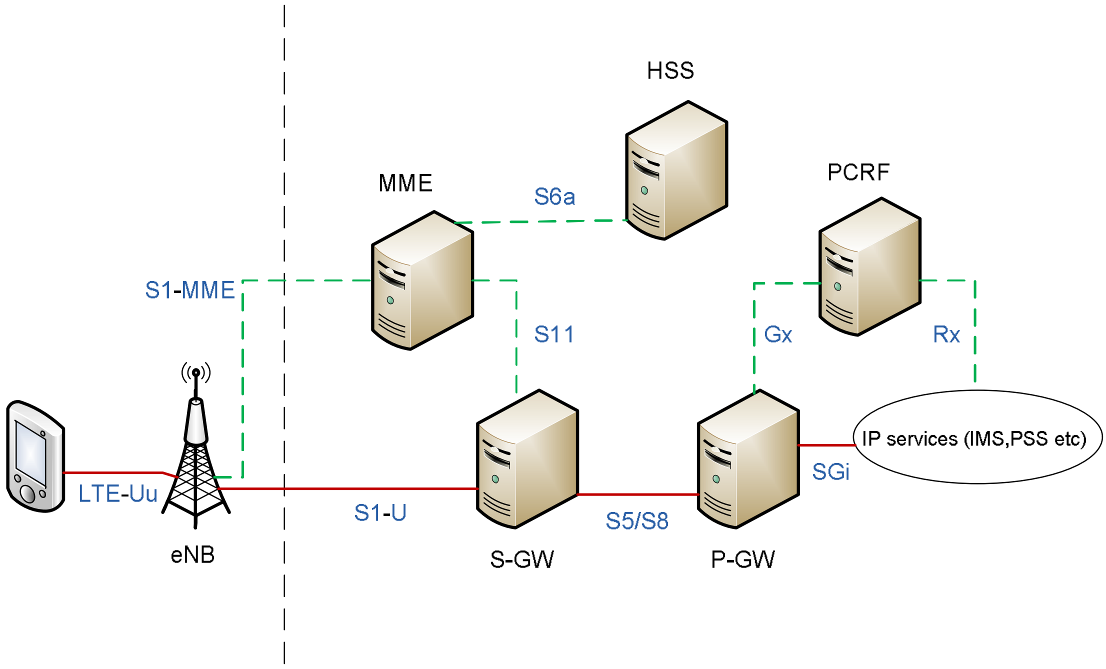

Figure 3.6. *EPS Network architecture [11].*

3.7.1. LTE core network

The CN or EPC in LTE controls the user equipment and manages the establishment of bearers. There are three main logical nodes of EPC.

- PDN Gateway (P-GW)
- Serving Gateway (S-GW)
- Mobility Management Entity

There are other logical nodes such as Policy Control and Charging Rules Function (PCRF) and Home Subscription Server (HSS). The functions of these nodes are described in [8].

PCRF is responsible for policy control decision making and controlling flow based charging in the Policy Control Enforcement Function (PCEF) which resides in P-GW. PCRF provides QoS authorization which helps PCEF how to treat a certain data flow according to user's subscription profile.

HSS contains user's SAE subscription data such as EPS subscribed QoS profile and roaming restrictions. It holds information how and to which PDN a user can connect. It holds other dynamic information such as identity of MME to which user is currently registered. It can integrate with authentication center which generates authentication and security keys.

P-GW is responsible for IP address allocation for user equipment, QoS enforcement and flow of charging according to the rules of PCRF, filtering of downlink IP packets into different QoS based bearers based on Traffic Flow Template (TFT). It serves as mobility anchor for inter-working with non-3GPP technologies.

S-GW is used for the transferring of IP packet data of all users. It serves as a mobility anchor for inter-working with other 3GPP technologies. It also serves as mobility anchor for data bearers when user equipment moves between eNBs. It retains the information about bearers when user equipment is in idle mode it temporarily buffers downlink data, while MME initiates paging of user equipment to re-establish the bearers. S-GW also performs some administrative functions in the visited network such as charging and legal interception.

MME is a control node and processes the information between CN and user equipment. Protocols running between user equipment and CN are known as Non-Access Stratum (NAS) protocols. MME handles establishment, maintenance and release of bearers by management layer in NAS. It also handles establishment of connection and security between user equipment and network by connection or mobility management layer in NAS.

NAS procedures are same as in UMTS but EPS allows concatenation of some procedures and makes faster connection and radio bearer establishment. Basic EPS structure for LTE is already given above in Figure 3.6.

3.7.2. The access network

In Figure 3.7, overall E-UTRAN architecture is shown as produced by 3GPP. This is a flat architecture without controllers (RNC in UMTS). It only consists of eNBs and EPC nodes. Through X2 interface eNBs are connected with each other, while with EPC node (MME/S-GW) through S1 interface. The protocols which run between eNBs and user equipment are Access Stratum (AS) protocols. [8]

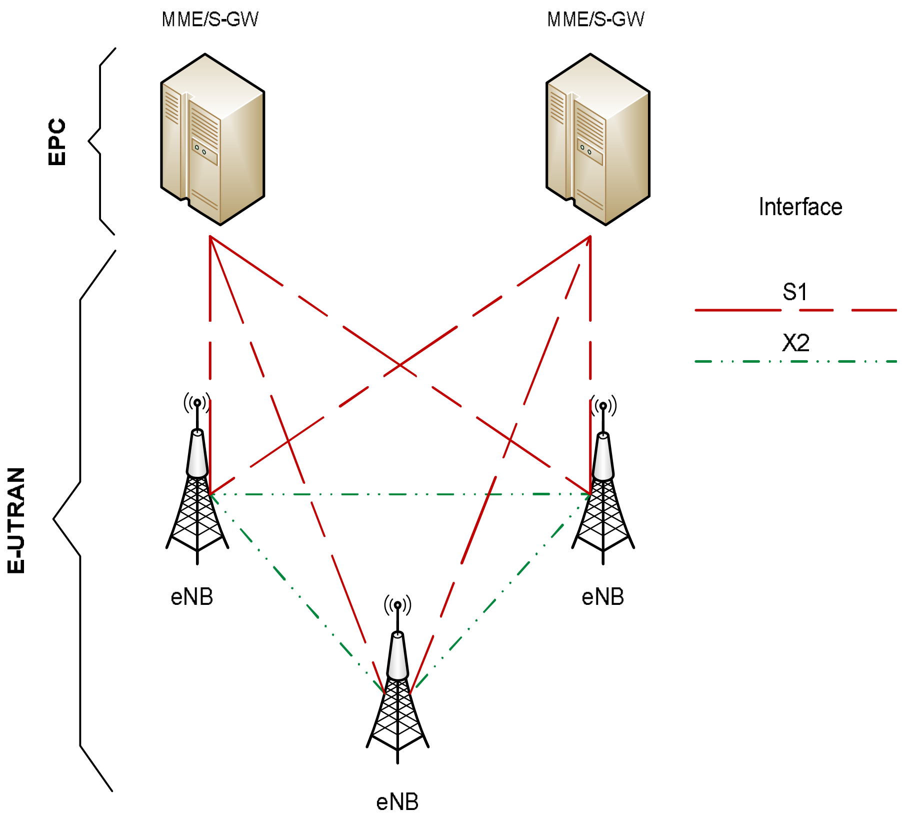

Figure 3.7. *Overall E-UTRAN architecture [11].*

E-UTRAN with a flat architecture is responsible for all radio related functions such as radio resource management, header compression, security, connectivity to EPC and S1 flex mechanism, which supports redundancy load sharing of traffic across network elements in CN.

Radio Resource Management (RRM**)** functions include Radio Bearer (RB) control, radio admission control, radio mobility control, scheduling and dynamic allocation of resources to user equipment in both uplink and downlink.

A function split between E-UTRAN and EPC is shown below in Figure 3.8.

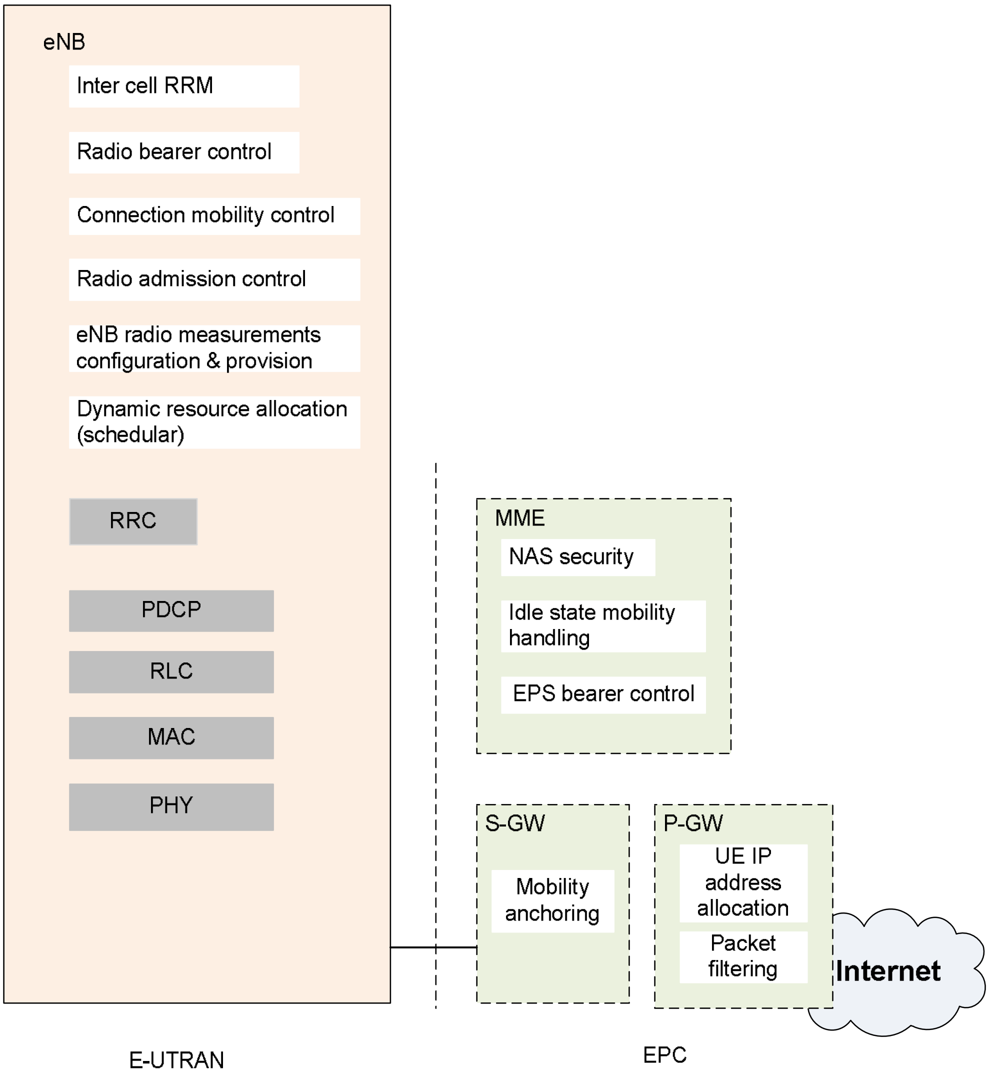

Figure 3.8. *Functional split between E-UTRAN and EPC [11].*

4. LTE PHYSICAL LAYER

To meet challenges and targets which were set for Long Term Evolution design, there was a need of evolution in the radio technology too. LTE radio interface design has been shaped by two fundamental technologies which are

- Multicarrier Technology
- Multiple Antenna Technology

Without above technology changes achieving LTE targets and goals was not possible. In this chapter first multicarrier technology and multiple antenna technology has been discussed. Then physical channels and LTE resource structure has been discussed shortly following with some physical layer functions. LTE downlink performance has been discussed on the basis of already existing theory and simulations. Downlink peak data rate calculation with the parameters has been given. A modified formula of LTE capacity and a comparative LTE link budget has been discussed.

4.1. Multicarrier technology

During LTE design phase initially the choices for downlink were Orthogonal Frequency Division Multiple Access (OFDMA) and Multiple Wideband Code Division Multiple Access (WCDMA), and for uplink Single Carrier Frequency Domain Multiple Access (SC-FDMA), OFDMA and Multiple WCDMA. Although Multiple WCDMA had the advantage of reusing existing technology from UMTS systems, but as intention for LTE was long term competitiveness. OFDMA was a stronger candidate and was considered for LTE downlink due to its flexibility, low receiver complexity and better performance in time dispersive channels. However OFDMA was not suitable for uplink because transmitter design for OFDM is costly due to its high cubic metric Peak to Average Power Ratio (PAPR) which results into a need of high linear RF power amplifier. On eNB side for downlink this cost issue was not a problem. The choice only left was SC-

FDMA. To keep user equipment's cost low SC-FDMA was considered as a better choice for uplink as compared to other techniques. [8]

4.1.1. OFDM principle and characteristics

OFDM is a multicarrier technique. In a single carrier technique high-rate data stream is transmitted on a single channel but in OFDM, channel is divided into more than one channel using multiple orthogonal subcarriers. We can use water filling interpretation to explain multicarrier technique advantage, where we have more than one water pipes. Some pipes can be bigger in diameter with more capacity than others, so more water can run through those pipes as compared to other pipes with less capacity. Wireless channels are usually frequency selective which means each subcarrier can have different radio fading conditions and each subcarrier or sub channel has different capacity. Different modulation schemes can be used for individual subcarriers. Higher redundant coding schemes can be used to mitigate channel frequency selectivity effect.

In OFDM, Inter Symbol Interference (ISI) is reduced by simply adding guard interval or Cyclic Prefix (CP) to OFDM symbol. CP should be longer than the multipath delay spread of the channel. Frequency selective fading is avoided simply by increasing the number of subcarriers or reducing subcarrier spacing. Contrary to avoid inter carrier interference caused by Doppler spread of the OFDM signals, in case of mobility and fast fading subcarrier spacing should be increased. So we need optimum parameter values to avoid such situation. Orthogonality between subcarriers helps to avoid spectrum wastage and reduces receiver complexity. Fast Fourier transform makes the implementation of OFDM efficient by employing different and existing multiple access methods to allow multiple users to access the available channel. OFDM is utilized in various wireless network technologies e.g. Wireless Local Area Network (WLAN), Wireless Metropolitan Area Network (WMAN), Digital Video Broadcasting (DVB), because of these attractive features OFDM is a stronger candidate for future wireless technologies which also support smart and multiple antennas. Each sub-carrier becomes flat faded and the antenna weights can be optimized per subcarrier basis. In addition, OFDM enables broadcast services on a synchronized Single Frequency Network (SFN) with appropriate cyclic prefix design. This allows broadcast signals from different cells to combine over the air which significantly increases the received signal power and supportable data rates for broadcast services [8; 12; 13].

Cyclic prefix in OFDM is used to mitigate Inter Symbol Interference (ISI) effects, caused by multipath propagation, where several replicas of transmitted signal are received at the receiver with different delays. To mitigate ISI effect a guard period is added at the beginning of each OFDM symbol. Guard period is obtained by adding a copy of end of the symbol in the beginning of symbol which is called Cyclic Prefix (CP). CP length should be greater than the longest multipath delay component recieved.

For LTE downlink subcarrier spacing Δf is 15 kHz and CP length is 5.16 μs as shown in Figure 4.1. 15 kHz subcarrier spacing is sufficiently large enough to allow for high mobility and to avoid the need for closed-loop frequency adjustments. In LTE for large suburban and rural cells to ensure that delay spread is contained within the CP an extended length CP of 17 μs is used at the expense of more overhead from CP. When normal CP is used a 0.5 ms. slot consists of 7 OFDM symbols and 6 OFDM symbols are used if extended CP is used. Carrier spacing 7.5 kHz is dedicated for Multimedia Broadcast Multicast Services (MBMS) service only with 3 symbols in each slot. [3; 8]

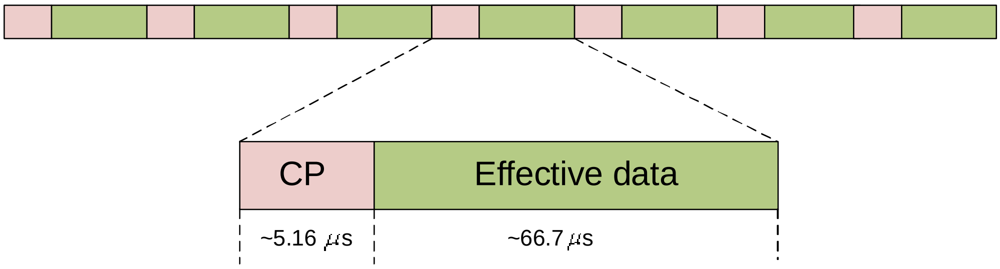

Figure 4.1. *Normal cyclic prefix ~6.67 % overhead [8].*

4.1.2. OFDMA

In OFDMA subcarriers are assigned to different users at the same time, so that multiple users can receive data simultaneously. To reduce the overhead and for the sake of simplicity contagious subcarriers are assigned to users in the form of groups. OFDMA enables the benefit of multiuser diversity for OFDM transmission. System spectral efficiency can be increased by assigning subcarriers on the basis of user channel feedback which makes system adaptive to its channel conditions. In OFDM subcarrier division to the users is only in time domain while in OFDMA subcarrier division to users is both in time and frequency domain and they can share the bandwidth as well which is called OFDMA time frequency multiplexing as shown in Figure 4.2. Each user is represented with different color and has been assigned different data symbol with different modulation and coding rate. OFDMA allows non continuous spectrum allocation to users e.g. user 6 is assigned resources in non continuous spectrum as can be seen from the figure. [3; 8]

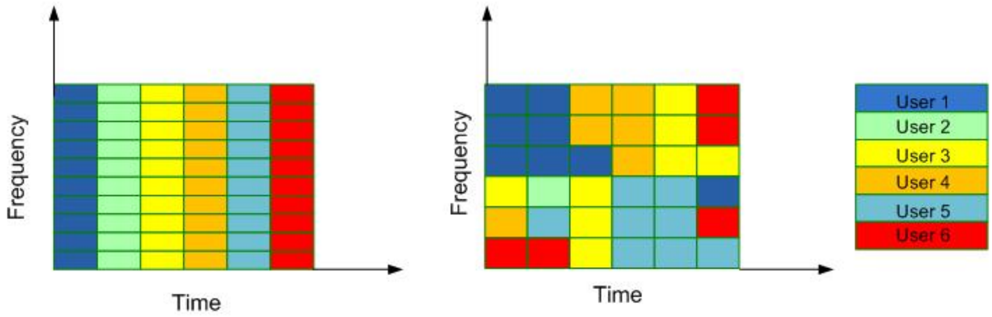

Figure 4.2. *OFDM and OFDMA subcarrier division [8].*

4.1.3. SC-FDMA

SC-FDMA has similarities with OFDM. It also divides spectrum bandwidth into multiple subcarriers maintaining orthogonality between subcarriers in frequency selective channel. However unlike OFDM, where data symbols directly modulate each subcarrier independently, in SC-FDMA signal modulated onto a given subcarrier is a linear combination of all data symbols transmitted at the same time instant as shown in Figure 4.3. Thus all transmitted subcarriers of SC-FDMA signal carry a component of each modulated data symbol [8]. This is how SC-FDMA enjoys benefits of OFDM keeping PAPR significantly low. For LTE uplink localized SC-FDMA is used where modulated symbols are assigned to adjacent subcarriers, which gives multi user scheduling gain in frequency domain.

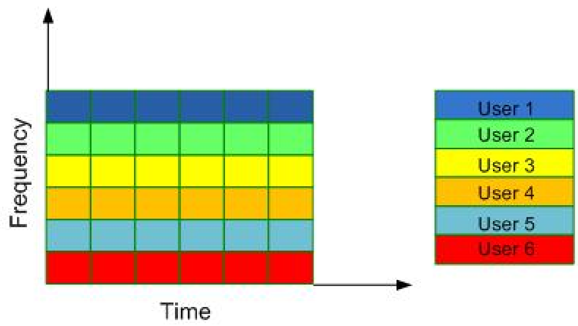

Figure 4.3. *SC-FDMA subcarrier division.*

4.2. Multiple antenna technology

Multiple antenna techniques known as Multiple Input Multiple Output (MIMO) were already used in Release 7 of HSDPA but LTE is the first global mobile communication system, which is designed with MIMO technology as a key component. MIMO helps to to increase capacity. Through the application of multiplexing and diversity techniques, MIMO technology exploits the spatial components of independent and identical wireless channels to provide capacity gain and increased link robustness [14]. The concept of parallel simultaneous radio channels in MIMO which can be described as transmission rank, also introduces challenges from radio propagation and its modeling point of view [15]. In LTE rank is used to indicate number of simultaneous parallel data streams transmitted. In LTE for 2 × 2 MIMO rank value is 2, where 2 simultaneous parallel data streams are transmitted using 2 antennas at eNB.

For LTE, transmission modes are defined for both uplink and downlink directions. There are 7 transmission modes to support Physical Downlink Shared Channel transmission for LTE downlink given in [8; 16].

Transmission Mode 1 Transmission from a single eNB antenna port.
Transmission Mode 2 Transmit diversity.
Transmission Mode 3 Open-loop spatial multiplexing.
Transmission Mode 4 Closed-loop spatial multiplexing.
Transmission Mode 5 Multi-user MIMO.
Transmission Mode 6 Closed-loop rank-1 pre-coding.
Transmission Mode 7 Transmission using user equipment specific reference signals.

Transmission Mode (TM) 1 uses **single antenna** to transmit single codeword without any pre-coding. Pre-coding is used to increase channel capacity using available channel state information. Pre-coding is used in TM 2 which uses **Transmit Diversity**. In LTE transmit diversity is defined for 2 and 4 transmit antennas and one data stream which is referred in LTE to one code word since for one transport block cyclic redundancy check is used per data stream. Transmit diversity is supported by means of Alamouti based linear dispersion codes. The coding operation is performed over space and frequency so the output block from the pre-coder (adopting code book based pre-coding technique) is confined to consecutive data resource elements in a single OFDM symbol. Space Frequency Block Codes are used for 2 transmit antennas at eNB. [8; 17]
Beam forming technique is used for directional transmission/reception using sensor arrays. In contrast to beam forming, transmit diversity does not improve the average SINR but reduces the variations in the SINR experienced by the receiver. It provides low spatial correlation at transmitter [18].
TM 3 uses **Open Loop Spatial Multiplexing**. User equipment indicates only the rank of channel instead of pre-coding matrix. If the rank used for Physical Downlink Shared Channel (PDSCH) transmission is greater than one (more than one layer is transmitted) then Cyclic Delay Diversity (CDD) is used. CDD transmits same set of OFDM symbols on same set of OFDM subcarriers from multiple antennas with different delay on each antenna. In the measurements conducted for this thesis only this TM 3 open loop spatial multiplexing mode is used. TM 4 uses **Closed Loop Spatial Multiplexing**. In this scheme, user equipment feeds back the channel information and desired pre-coding to eNB for the application of beam forming operations. [8]

TM 5 uses **Multi User-MIMO**. Several user equipments communicate with a common eNB using same frequency and time domain. In MU-MIMO full channel state information at the transmitter is required.
Number of user equipments are always less than or equal to transmit antennas at eNB.

The eNB transmits simultaneously to selected user equipments. Their streams are separated by multiple antenna pre-coding based on channel knowledge at eNB. To cancel the inter user interference total normalized transmit power constraint must be applied. However in worst conditioned channel high transmit power is required so it is not optimal. [8]
In one approach multiple antennas are simply treated as multiple virtual user equipments, allowing multiple antenna terminals to transmit/receive multiple streams, and at same time sharing channel with other user equipments.
In second approach additional user equipment antennas are used to strengthen the link between user equipment and eNB. Multiple antennas at user equipment are combined in Maximum Ratio Combining fashion in downlink. In uplink space time coding is used for same purpose. Antenna selection can be another way of extracting more diversity out of channel. [8]
TM 6 **Closed Loop Rank-1 Pre-coding**. This mode is similar to transmission mode 5, but without spatial multiplexing property and rank is always 1. It is simply a beam forming technique with single codeword transmitted over a single layer.
TM 7 **Transmission using user equipment specific Reference signals**. In this mode there is no pre-coding related feedback from user equipment. eNB deduces this information from DOA (direction of arrival) estimation in uplink. User equipment specific reference signal is transmitted in a way such that its time-frequency location does not overlap with the cell-specific reference signal, which is called calibration of eNB RF paths. [8]

In LTE beamforming is applied only to PDSCH not to control channels, which means cell range is limited by the range of control channels but PDSCH range can be extended by applying beamforming to PDSCH [8]. Significant array gains are achieved through beamforming which improves throughputs on the cell edge but not closer to the cell center [18].

4.3. Physical layer Structure

In this section LTE physical layer structure has been discussed. First physical layer channels and LTE resource block astructure is discussed shortly following with LTE cell specific reference signals.

4.3.1. Physical layer channels

In LTE, shared channels in downlink and uplink are optimized for packet oriented bursty traffic characteristics. Same physical channels are used to transmit higher layer information including user data and control messages. There are fewer channels defined by 3GPP in [19], and no more dedicated channels in LTE as compared to HSDRA release 6.

Physical Downlink Shared Channel (PDSCH) supports high data rates for user data and multimedia transmissions. The PDSCH modulation modes are QPSK, 16QAM and 64QAM. Spatial multiplexing is also used in the PDSCH.
Physical Downlink Control Channel (PDCCH) conveys user equipment specific control information. For PDCCH, robustness rather than maximum data rate is major concern. QPSK is the only available modulation format. The PDCCH is mapped onto resource elements in up to the first three OFDM symbols in the first slot of a sub frame. It contains System Information Blocks (SIBs).
Physical Control Format Indicator Channel (PCFICH) informs the user equipment about the number of OFDM symbols used for the PDCCHs. It is transmitted in the first OFDM symbol of the subframe.
Physical HARQ Indicator Channel (PHICH) carries Hybrid Automatic Repeat Request (HARQ) Acknowledgement (ACK), Negative Acknowledgement (NACK) in response to uplink transmissions, which indicates whether eNB has received the transmission on PUSCH correctly.
Physical Broadcast Channel (PBCH) carries system information of user equipments requiring access to the network. It contains Master Information Block (MIB) which includes information about system bandwidth and system frame number.
Physical Uplink Shared Channel (PUSCH) is uplink counterpart of the PDSCH. It transmits user data from user equipment to the eNB. This channel also transmits uplink control information such as channel quality, scheduling requests and ACK/NACK responses for downlink packets. Resources for the PUSCH are allocated on a sub-frame basis by the uplink scheduler. Subcarriers are allocated in multiples of 12 Resource Blocks (RBs) and may be hopped from subframe to sub-frame. The PUSCH may employ QPSK, 16QAM or 64QAM modulation.
Physical Uplink Control Channel (PUCCH) If there is no information to be transferred by user equipment on the PUSCH, then the control information is sent via the

PUCCH. So, PUCCH is never transferred simultaneously with the PUSCH from the same user equipment. PUCCH conveys control information including channel quality indication (CQI), ACK/NACK, HARQ and uplink scheduling requests.
Physical Random Access Channel (PRACH) is used for random access functions and contains random access preamble. LTE user equipments use PRACH for initial network access.
For detailed study about LTE channels and their functions, SIBs and MIB references [8; 19; 20] can be consulted.

4.3.2. LTE resource structure

LTE uses OFDMA in the downlink. OFDMA has good multiplexing characteristics. In LTE a user is assigned a specific number of subcarriers for a predetermined time which is called a Resource Block. Allocation of RBs is handled by a scheduling algorithm at eNB. A resource block is defined in both frequency and time dimensions for LTE. The largest unit in time is a radio frame of 10 ms, which is further divided in 10 sub frames. Each subframe has 2 time slots one slot of 0.5 ms as shown in Figure 4.4.
Frame Structure Type 1 is used for Frequency Division Duplex (FDD) in paired spectrum. [19; 20]

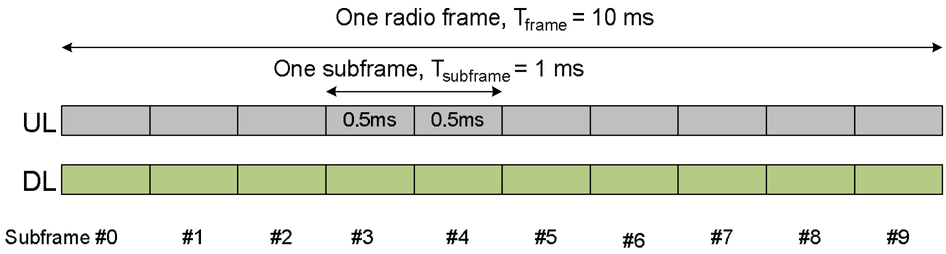

Figure 4.4. *Frame Structure Type 1 for LTE FDD.*

Each time slot comprises of 7 OFDM symbols in case of normal CP and 6 in case of extended CP configured in the cell. In frequency dimension 12 subcarriers (total bandwidth 180 kHz) form a single unit defined as a RB. Smallest unit is a Resource Element (RE) which consists of one subcarrier for the duration of one OFDM symbol. A RB has 84 REs for a normal or short CP and 72 for extended or long CP, configured in the cell. Some REs are used for handling synchronization signals, reference signals, control signal and critical broadcast system information. The rest of REs are used for data transmissions. Figure 4.5, shows basic time frequency resource structure for LTE. [8]

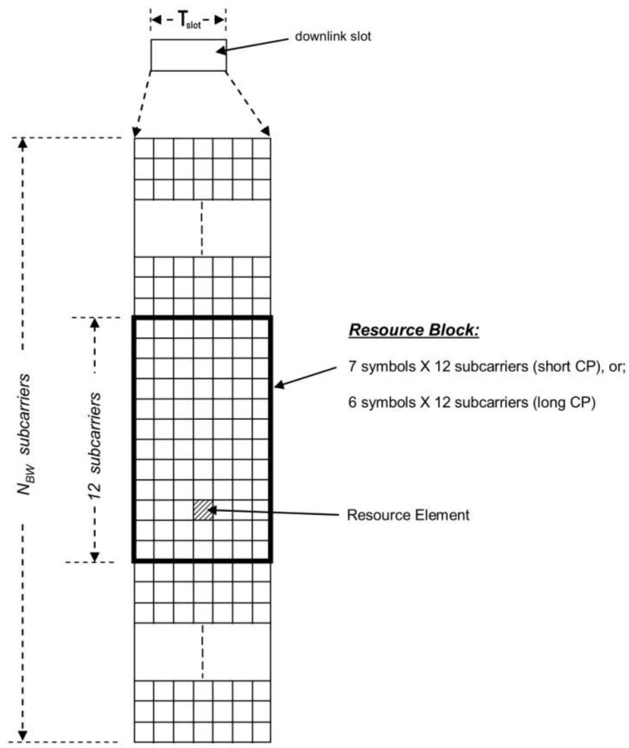

Figure 4.5. *Basic time frequency resource structure for LTE [21].*

Number of resource blocks and their available bandwidth information is provided in Table 4.6 [21]. Subcarrier bandwidth and resource block bandwidth is same for all system bandwidths. Number of resource blocks increase with higher system bandwidth. For 10 MHz system bandwidth 50 resource blocks and for 20 MHz system bandwidth 100 resource blocks are available.

Table 4.6. *Available Downlink Bandwidth and Resource Blocks [21].*

System Band-width (MHz)	1.4	3	5	10	15	20
Subcarrier bandwidth (KHz)	15					
Resource Block (RB) bandwidth (KHz)	180					
Number of available RBs	6	*15*	*25*	*50*	75	*100*

4.3.3. Cell specific reference signals

Cell specific Reference Signals (RS) also known as common RSs and they are available to all user equipments in a cell. These RSs identify a cell. A cell specific frequency shift is also applied to these RSs to avoid possible collisions with RSs of 6 adjacent cells, which allows RS boost in LTE. LTE downlink supports MIMO and transmitted RS corresponding to a given antenna port defines antenna port from user equipment point of view. It enables user equipment to estimate channel for that antenna port, regardless whether it represents single radio channel from one physical antenna or a composite channel from multiplicity of physical antenna elements together comprising antenna port [8].

4.4. Feed back information in LTE

Feed backs are used in LTE to exchange channel quality information from user equipment to eNB. This feed back information helps system with adaptation and eNB for changing modulations and coding rates according to reported channel quality. There are 3 types of feed backs which are used for downlink channel quality feedback reports. Channel Quality Indicator (CQI), Pre-coding Matrix Indicators (PMI) and Rank Indicators (RI).

CQI values are reported by user equipment, which correspond to the highest modulation and coding schemes that it can decode with a transport block error rate probability not exceeding than 10%. [8]

If user equipment knows the pre-coding matrices and channel transfer function from different antenna ports it can indicate the index for of spatial multiplexing matrix **W** in **PMI** report. **W** is index in pre coding matrix which is sent to eNB that maximizes the aggregate number of data bits, which could be received across all layers. [8]

User equipment can also report to eNB via **RI** which is a channel rank transmission. It means number of layers which can be transmitted. A layer is a mapping of symbols onto the transmit antenna ports. [8]

However eNB is not bound to fulfill user equipment request for pre-coder. If eNB chooses another pre-coder it means that reported CQI is not valid. An eNB can also put codebook subset restriction which means user equipment can only evaluate and request from that restricted set of pre-coders. In LTE time domain channel dependent scheduling and Adaptive Modulation Coding (AMC) is supported. The modulation and channel coding rates are constant over the allocated frequency resource blocks for a given user. [8]

Table 4.7 below gives the information about CQI index values corresponding to different modulation schemes, code rates and efficiency defined by 3GPP in [22].

Table 4.7. *CQI index table [22].*

CQI index	modulation	code rate x 1024 (bps)	efficiency
0	out of range		
1	QPSK	78	0.1523
2	QPSK	120	0.2344
3	QPSK	193	0.3770
4	QPSK	308	0.6016
5	QPSK	449	0.8770
6	QPSK	602	1.1758
7	16QAM	378	1.4766
8	16QAM	490	1.9141
9	16QAM	616	2.4063
10	64QAM	466	2.7305
11	64QAM	567	3.3223
12	64QAM	666	3.9023
13	64QAM	772	4.5234
14	64QAM	873	5.1152
15	64QAM	948	5.5547

4.5. LTE MAC and physical layers protocol architecture

In Figure 4.8, LTE protocol architecture for Medium Access Control (MAC) and physical layers has been shown. This protocol architecture shows the flow of packet data in MAC and physical layers from eNB to user equipment in downlink direction. Data comes from Packet Data Convergence Protocol (PDCP) layer to Radio Link Control (RLC) layer with segmentation function. After RLC data comes to MAC layer with multiplexing and HARQ functions. After MAC layer on physical layer coding, modulation and antenna resource mapping is performed. Then eNB transmits data using air interface to user equipment where opposite functions are performed in reverse. Here only a few functions have been described which are most relevant to this thesis study.

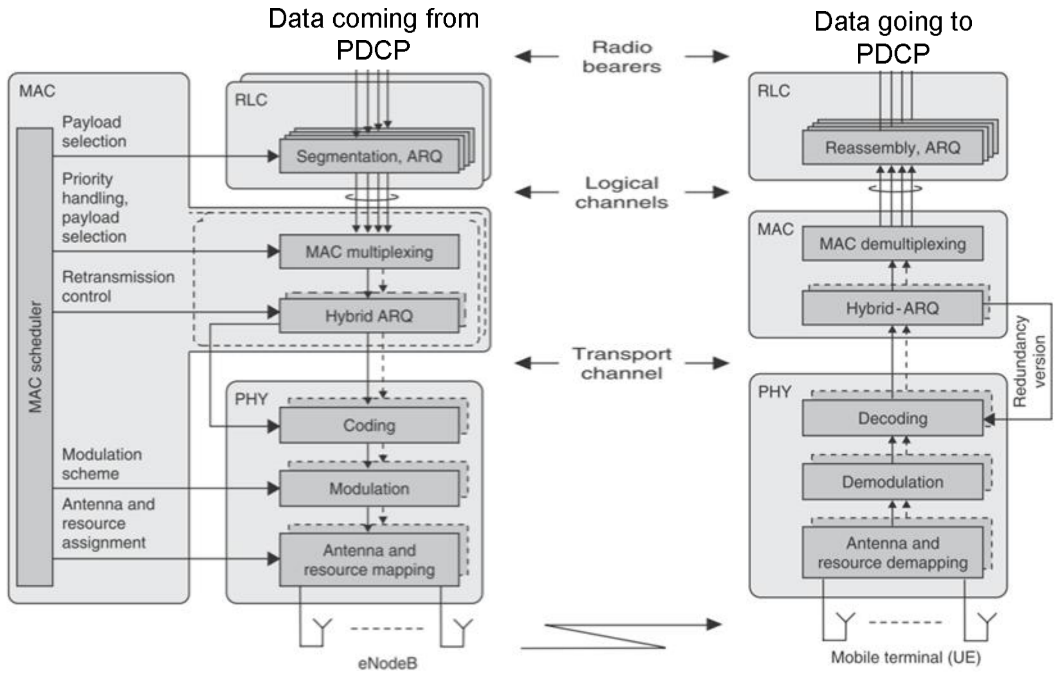

Figure 4.8. *LTE downlink MAC and physical layer protocol architecture [23].*

4.5.1. Hybrid Automatic Repeat Request (HARQ)

Hybrid Automatic Repeat Request (HARQ) is combination of forward error correction scheme and automatic repeat request. It is used in MAC layer for detecting errors in transmission and correcting them by using retransmissions. HARQ's Round Trip Time (RTT) and Dropped Packet Delay Bound (DPDB) time affect the delay sensitive services like VoIP and real time streaming. In LTE, for VoIP there is a delay bound of 50 ms which limits uplink HARQ RTT to 8 ms meaning that up to 6 transmissions per VoIP packet are possible. HARQ requires ACK/NACK to be sent back to inform transmitter of success or failure of packet reception. [8]

Block error rate is a measure of unsuccessful data transfer referred as:

$$\text{BLER (\%)} = \frac{\text{Number of NACKs received}}{\text{Total number of blocks transmitted}} \times 100, \tag{4.1}$$

CQI values are reported by user equipment, which correspond to the highest Modulation and Coding Schemes (MCS) that it can decode with a transport block error rate probability not exceeding than 10%. Maximum three MAC layer retransmissions were observed during LTE measurements.

4.5.2. Power control

Uplink power control is necessary for any mobile communication system for optimizing uplink system capacity by controlling transmitted energy per bit to achieve required QoS, to minimize interference to other users in the system and to prolong battery life for user equipment. For this purpose power control scheme needs should be considered and being adaptive to radio propagation channel characteristics such as path loss, shadowing, fast fading, intra cell and inter cell interference from other users. [8]
In LTE power control scheme provides support for more than one mode of operations. Different power control strategies can be used depending on the deployment scenarios, system loading, scheduling strategy and operator performance. LTE employs a combination of open loop and closed loop power control. It achieves desired data rates with less feedback overhead and fast adaptation of modulation and coding scheme using uplink scheduling grants for varying transmitted bandwidth. In LTE inter cell interference is more critical than intra cell interference because LTE uplink is orthogonal by design. Optimum power control and inter cell interference coordination enables frequency reuse factor 1. In Wide band Code Division Multiple Access (WCDMA) UMTS for increasing uplink data rate spreading factor is reduced and transmission power is increased but in LTE uplink data rate can be increased by varying transmitted bandwidth, modulation and coding scheme, while keeping transmitted power per unit bandwidth constant for a given MCS. LTE selects suitable Power Spectral Density (PSD) by open loop method for an average MCS for particular path loss and shadowing conditions. To achieve better control, dynamic Transmit Power Control (TPC) offsets are used by means of MCS dependent offsets, closed loop corrections using explicit Transmission Control Protocol (TCP) commands. Bandwidth adaptation and changing MCS is used to set different BLER points for different HARQ processes. This is how variable degree of freedom is achieved for LTE uplink power control: [3; 8]

Power per Resource Block = Basic Open Loop Operating Point + Dynamic Offset. (4.2)

Basic open loop operating point is comprised of a common power level for all user equipments in the cell and a path loss compensation factor. Dynamic offset depends on modulation and coding scheme and explicit transmit poer control commands. To find out LTE's user equipment total transmit power in a sub frame, another factor of bandwidth (amount of allocated RBs) should be added to the formula given in equation (4.2).

User equipment Transmit Power = Basic Open Loop Operating Point + Dynamic Offset + Bandwidth Factor (4.3)

The overall power control formula allows user equipment's transmit power to be controlled with 1 dB accuracy within a range set by performance requirements for user equipment, typically from -50 dBm to +23 dBm. [8]

4.6. Timing advance

In LTE timing control mechanism is used by eNB to maintain the orthogonality in the uplink among user equipments at different distances. This is achieved through timing advance values which are sent by eNB to user equipment through medium access control packet data unit. The time alignment timer with the delay durations of 500 ms, 750 ms, 1280 ms up to infinity, is provided by radio resource control layer. The timer is restarted every time user equipment receives timing advance value. If it does not receive any timing advance value during the delay duration user equipment stops uplink transmissions to avoid interference with other users in uplink. Timing advance integer values range from 0 to 1282 [26]. Timing advance values are received in the multiples of $16 \times T_s$ symbol duration = 0.52 μs. Distance of user equipment from eNB can be calculated through timing advance values using speed of light 300 $m/\mu s$. [24; 25]

Distance of single timing advance step = (300 $m/\mu s$ × 0.52 μs) / 2 = 78 m.

Distance 'd' between eNB and user equipment as a function of timing advance value 'z' can be calculated as:

$$d = (z + 1) \times 78. \quad (4.4)$$

4.7. LTE downlink peak data rate calculation

LTE downlink data rates can be calculated using system bandwidth, overheads, modulation, effective coding rate, multiple antenna scheme used and block error rate. Besides these factors LTE user equipment category also limits achievable downlink data rates. In this section these parameters will be also discussed which limit the LTE downlink data rates.

4.7.1. Overheads in LTE downlink

In LTE there are 3 types of overheads which are used in the calculation of LTE peak data rates.

- Normal cyclic prefixes overhead in 0.5 ms slot is approximately 33 μs 6.6 %. [26]
- Downlink common reference signals overhead is 9.5 % for 2 transmit antennas. [26]
- The LTE control signal carries the L1 and L2 control information in 1, 2, or 3 first OFDM symbols in a subframe. PDCCH overhead is 11.9 % when number if symbols N = 2, PDCCH overhead is 19 % for worst case when number of symbols N = 3. [26]

- SCH and BCH both individually have 6 physical resource blocks in 4 OFDM symbols in every 10 ms radio frame with total overhead 0.7 %+ 0.7 % = 1.4 %

So total overhead in LTE downlink for 20 MHz system bandwidth is 36.5 % = 0.365 when PDCCH overhead is 19 % in worst case with N = 3 and 29.4% = 0.294 when PDCCH overhead is 11.9 % with N = 2.

4.7.2. Effective coding rate in LTE downlink

LTE data rates are directly affected by use of antenna scheme and different coding rates. QPSK, 16 QAM and 64 QAM are used in LTE. Different coding rates are available which give a choice between higher payload and better redundancy. A tradeoff between higher throughput and redundancy is available. Lower redundancy gives higher throughput but data is more immune to channel impairments, while higher redundancy gives robustness against channel impairments. Some available coding rates are 1/2, 3/4, 1/1.
The effective coding gain of a coded modulation scheme is measured by the reduction in required bit error rate or SNR to achieve a certain target error probability relative to uncoded scheme [27]. If effective coding rate is higher than 0.876 then user equipment may skip decoding a transport block in HARQ transmission [28].

4.7.3. Modulation and multiple antenna schemes

The choice of modulation schemes affects on achievable downlink data rates. The higher the modulation higher data rates are achieved because there are more bits available per symbol. Number of bits per symbol is increased 2 times for 2 x 2 MIMO as compared to 1 x 1 antenna configuration. [3] Number of bits per symbol is given in the Table 5.8, for modulation schemes used in LTE for single antenna configuration and 2 x 2 MIMO. [3]
Theoretical downlink peak data rate for 2 x 2 MIMO with 64QAM in LTE can be calculated now using Equation (4.5).

Downlink Peak data rate = (1 – overhead) × (effective turbo coding rate) × (number of bits per symbol) × (system bandwidth) (4.5)
= (1 – 0.294) × (0.876) × (12 bits per symbol) × (20 MHz) = 148.43 Mbps.

In Table 4.9 LTE downlink peak data rates have been given for 20 MHz bandwidth and 100 resource blocks. Different modulation schemes and coding rates are used in calculation for single stream and 2 × 2 MIMO using effective turbo coding scheme and PDCCH overhead 11.9 % when number of symbols N = 2.

Table 4.9. *LTE Downlink peak data rates for 20 MHz system bandwidth and 100 resource blocks [3].*

	Coding rate	Bits/symbol	MIMO usage	Data rates
QPSK	1/2	1	Single stream	12.37
16QAM	1/2	2	Single stream	24.74
16QAM	3/4	3	Single stream	37.11
64QAM	3/4	4.5	Single stream	55.66
64QAM	1/1	6	Single stream	74.21
64QAM	3/4	9	2 × 2 MIMO	111.32
64QAM	1/1	12	2 × 2 MIMO	148.43

4.8. LTE downlink channel capacity

Theoretical peak data rates are difficult to achieve in practical situations because of channel impairments noise and interference from own and other cells. Shannon channel capacity for single antenna in bit rate can be derived through conventional Shannon formula given in Equation (4.) which is a function of bandwidth and signal to noise ratio (SNR) [3].

$$\text{Bit rate [Mbps]} = \text{Bandwidth [MHz]} \times \log_2(1 + \text{SNR}). \qquad (4.6)$$

For LTE a modified Shannon formula (4.7) is defined in [29] to calculate channel capacity taking channel impairments in account.

$$\text{Bit rate [Mbps]} = \text{BW\_eff} \times \text{Bandwidth [MHz]} \times \log_2(1 + \text{SNR/SNR\_eff}). \; (4.7)$$

BW_eff is a parameter for adjusting overheads effect to bandwidth efficiency. Bandwidth efficiency is reduced due to many issues discussed and given in Table 4.10, in [29]. SNR_eff is a parameter for adjusting SNR efficiency. A correction factor can be multiplied with BW_eff. Due to requirements to adjacent channel leakage ratio and practical filter implementation, the BW occupancy is reduced to 0.9. The overhead of the cyclic prefix is approximately 6.6% and the overhead of pilot assisted channel estimation is approximately 6 % for single antenna transmission and 11% for dual antenna transmission ideal channel estimation is used. Pilot overhead is not included in the link performance BW efficiency but only in system BW level efficiency. This issue also impacts the SNR_eff, as shown in Table 4.10 the extracted link level bandwidth efficiency is about 83%. [29]

When fiting Equation (4.7) to the Shannon performance curve in Additive White Gaussian Noise (AWGN) channel conditions, we extract the best value for SNR_eff using the setting for BW_eff of 0.83 from Table 4.10 and the fiting parameters are indicated in parentheses as (BW_eff, SNR_eff). The results are presented in Figure 4.11. We can observe that LTE is performing less than 1.6~2 dB off from the Shannon capacity bound. There is nevertheless a minor discrepancy in both ends of the G-factor dynamic range. This is because the SNR_eff is not constant but changes with the G-factor. Where G-factor distribution is defined as the average own cell power to the other-cell power plus noise ratio. With OFDMA in a wide system bandwidth this corresponds to the average wideband signal to interference plus noise power ratio (SINR). [29]

Table 4.10. *Link and system bandwidth efficiency with a 20 MHz system bandwidth [29].*

Impairments	Link: BW_eff	System_ BW_eff
BW efficiency	0.9	0.9
Cyclic prefix	0.93.4 = 0.93 app.	0.93.4 = 0.93 app.
Pilot overhead	1	0.94, **0.89**
Dedicated and Common control channels	N/A	0.715
Total	0.83 app.	0.57, **0.53 app.**

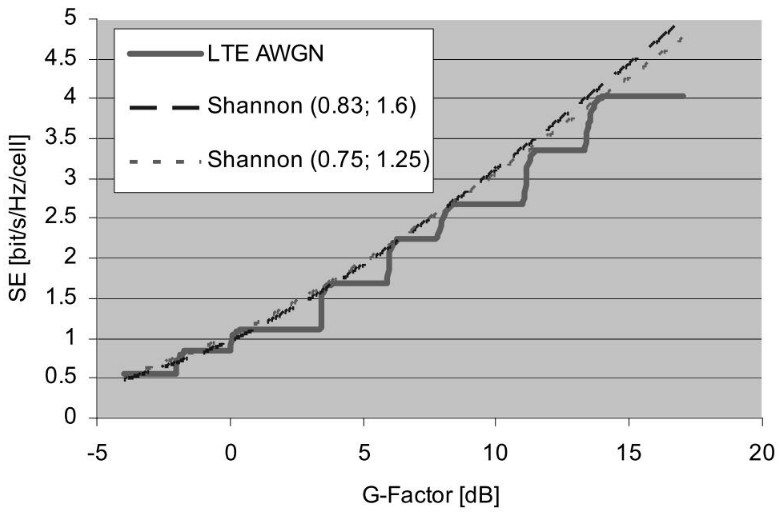

Figure 4.11. *LTE spectral efficiency (SE) as a function of G-factor(dB) including curves for best Shannon fit. The steps are due to the limited number of modulation and coding schemes in the simulation [29].*

In Table 4.10 dual antenna transmission overheads are given in red bold fonts. Because in our measurements in this thesis only TM 3 open loop spatial multiplexing 2 × 2

MIMO has been used so these results and Figure 4.11 cannot be used for comparison purposes. Because overheads used in [29] are for single antenna transmission scheme. Shannon limit for 2 × 2 MIMO is calculated using ideal Shannon capacity formula multiplying the result with 2 for transmission rank 2 as described in Equation (4.8). The result is shown in Figure 4.12 with red line.

$$C_{\max} = 2B\log_2(1+SNR) \tag{4.8}$$

For 20 MHz system bandwidth with 2 × 2 MIMO physical layer limit has been calculated for 29.4 % overhead which are theoretically more accurate for dual antenna transmissions in LTE on physical layer as shown with black line in Figure 4.12. Green line in Figure 4.12 corresponds to 2.1 % MAC layer overhead and retransmissions with MAC BLER rate 10%. Average MAC overhead 2.1 % is calculated from data obtained in Pyynikintori measurement round. Maximum value for MAC BLER 10% is defined for LTE high data rates. These limits will be used in this thesis later for comparison with practical measurement results. We can see downlink throughput saturates after a certain SNR value it is because of limitations of use of higher order modulation and coding scheme in LTE.

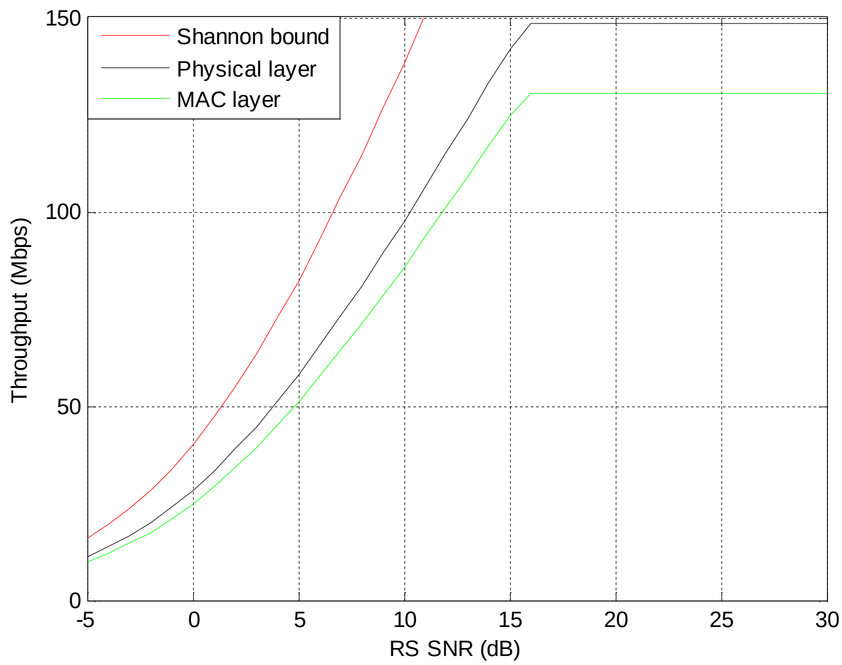

Figure 4.12. *LTE downlink throughput limits vs. RS SNR for* 2 × 2 MIMO.

4.9. LTE link budget

Link budget is prepared for calculating path losses in coverage planning. Total path loss includes all the losses between base station and mobile station. From total path loss maximum cell range is defined by using a suitable path loss model e.g. Okumura Hata model. The cell range gives the number of base station sites required to cover the target geographical area. The link budget calculation can also be used to compare the relative coverage of the different systems. The relative link budget indicates how well the new LTE radio system will perform when it is deployed on the existing base station sites that are designed for GSM and WCDMA. [3] The parameters for LTE downlink budget have been introduced in [3]. Here only LTE downlink budget is given in Table 4.13.

$$N_t = KTB = (1.3807\times10^{-23} JK^{-1})\times(270K)\times(18\times10^{6} Hz). = 6.7102\times10^{-14} J/s \qquad (4.9)$$

In Equation 4.9 N_t is thermal noise calculated in watts but used in dBm -101.7, K is boltzman constant, T is thermal noise and B is bandwidth. Thermal noise value is calculated using Equation (4.9) for 100 resource blocks with band width 180 kHz × 100 = 18 MHz.

Table 4.13. *Downlink Link budget for 20 MHz LTE system bandwidth.*

Downlink		**LTE**
System bandwidth		20 MHz
Resource blocks		100
Transmitter-eNB		
Tx Power (dBm**)**	**a**	46
Tx antenna gain (dBi)	**b**	18
Cable loss (dB)	**c**	2
EIRP (dBm)	**d = a + b - c**	62
Receiver-user equipment(UE)		
UE Noise figure (dB)	**e**	7
Thermal Noise (dBm)	**f**	-101.7
Receiver Noise floor (dBm)	**g = e+f**	-94.7
SINR (dB)	**h**	-9
Receiver sensitivity (dBm)	**i = g+h**	-103.7
Interference margin (dB)	**j**	4
Control channel overhead (dB)	**k**	1.2
RX antenna gain (dBi)	**l**	0
Body loss (dB)	**m**	0
Maximum Path loss (dB)		160.5

5. MEASUREMENT CAMPAIGNS AND RESULTS

In this chapter first description of measurement equipment, tools and softwares is given which were used during measurement campaigns and post processing of data to obtain results for this thesis. Measurement campaigns are introduced and discussed. Then results and analysis with different key performance indicators and parameters are discussed.

5.1. Measurement equipment and post processing tools

Test equipment and software tools used during the measurement campaigns are given below.

- One category 3 mobile: Hawei E398
- Garmin GPS device
- Laptop
- Nemo Outdoor v.6.

The softwares and tools used for post processing and analysis of data and results are given below.

- Nemo Analyze v.5
- Matlab
- Microsoft Excel

Nemo Analyze v.5 was used to extract required data in Excel files. Then Matlab was used for post processing of data in Excel files.

5.2. Introduction of measurement campaigns

There were three different environments chosen for measurement campaigns one was with high antenna on top of Pyynikintori Tampere hill which was macro/rural type environment with highways on measurement route. Second was suburban site in a small city Nokia. Third was with roof top antenna on a building in Tampere city center in a pure urban environment. This thesis study and scenario is based on single user measurements and performance analysis. Single user test equipment was used during measurements despite the fact of presence of other users in the network which was unknown but expected. System bandwidth was 20 MHz with maximum 100 resource blocks allocation for a single user and frequency band was 2600 MHz. Different key performance indica tor parameters were used for post processing and analysis of the results. These parameters are RS SNR, RSRP, MAC downlink throughput, timing advance and CQI. All the measurements were taken during weekend on 14th and 15th of January 2012.

5.2.1. Key performance indicators

During analysis for this thesis we have used following key performance indicators.

- RSRP
- RS SNR
- RSRQ
- MAC DL throughput
- Timing advance
- CQI

RSRP, RS SNR and RSRQ are physical layer measurement parameters while MAC downlink throughput, timing advance and CQI are other performance indicators.

RSRP is reference signal received power which indicates serving cell signal strength. This measurement is used to rank different LTE cells for handover and cell re-selection. RSRP is defined for a specific cell as linear average over power contributions of resource elements which carry cell specific reference signal within the considered measurement frequency bandwidth. Reference signals transmitted on first antenna port are used to measure RSRP but reference signals on 2nd antenna port can also be used if user equipment can determine them. RSRP is measured in dBm. [8]

RS SNR is reference signal's signal to noise ratio. It is used in link adaptation procedure. RS SNR is measured in dB. Required SINR is the main performance indicator for LTE. Cell edge is defined according to the Required Signal to Interference and Noise Ratio (SINR) for a given cell throughput. Required SINR depends on Modulation and Coding Schemes (MCS) and propagation channel model. Higher the MCS used, higher the required SINR and vice versa. [30]

$$SINR = \frac{P_r}{i_{other} + N_s} \tag{4.7}$$

$$SINR_{req.} \geq \frac{1}{i_{other} + NP_L} \tag{4.8}$$

Where P_r is average received power, $SINR_{req.}$ is required SINR, i_{other} is other to own cell interference, N_s is thermal noise and P_L is own path loss component.

RSRQ based results includes E-UTRA RSSI, which is the total received wideband power on a given frequency. Thus it includes the noise from the whole universe on the particular frequency, whether that is from interfering cells or any other noise source. [3]

$$RSRQ = N\frac{RSRP}{RSSI} \tag{4.9}$$

N is number of resource blocks allocated.

RSRQ was measured but was not analyzed in this thesis because of its total received wideband power on a given frequency.

MAC DL Throughput is the throughput received in downlink at MAC layer level. It does not include overheads from physical layer that's why it has been used instead of physical layer throughput. MAC DL throughput is measured in Mbps.

Timing advance is an integer value sent by eNB to user equipment. This value is used in timing control mechanism to avoid interference among user equipments. It indicates the distance between eNB and user equipment. Timing advance has been discussed in detail in section 5.8.

CQI is a feedback value between 0 to 15 which is reported by user equipment indicating eNB about the conditions and potential of channel. CQI values have been given earlier in Table 5.5.

5.2.2. Description of measurement routes

For this thesis there were three measurement campaigns conducted in three different locations and environments using Elisa Network for LTE. Description of these three measurement campaign (MC) with type of environment have been discussed below.

- Pyynikintori MC
- Nokia MC
- Nalkala MC

Pyynikintori measurement campaign was conducted with a longer route in Tampere, Finland, as compared to other two measurement routes which was also including high way. The eNB is located on top of Pyynikintori hill. These characteristics make this environment macro/rural type. In Pyynikintori MC only 2 Physical Cell Identities (PCI) 60 and 62 were measured. PCI is a physical cell identity of LTE serving cell. Approximate eNB location in measurement route is shown in Figure 5.1, where PCI 60 is with dark red legend and PCI 62 is with parrot green legend.

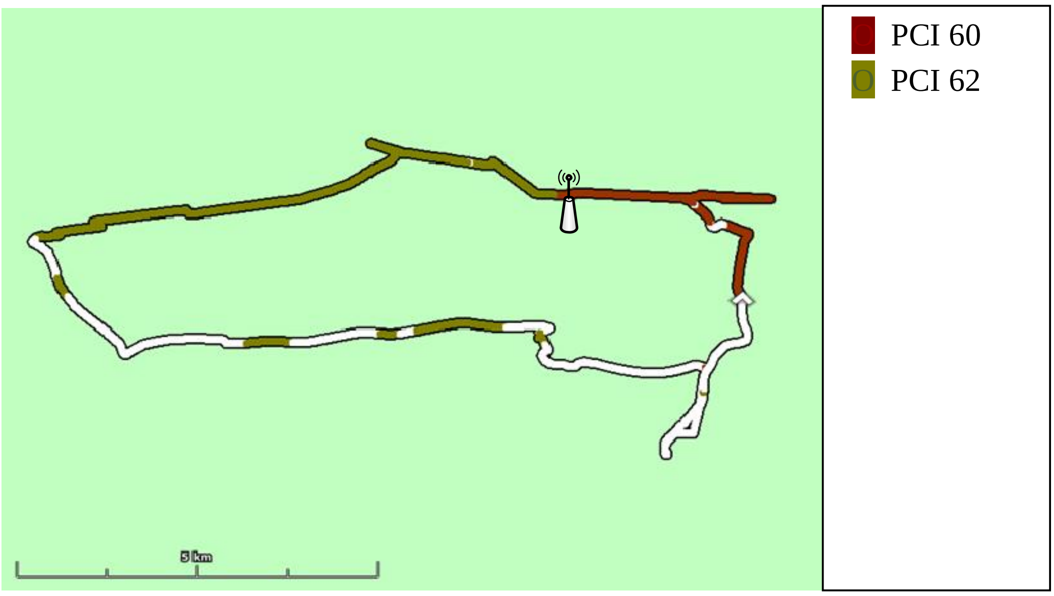

***Figure 5.1**. PCI 60 and 62 in Pyynikintori MC*

Nokia measurement campaign was conducted in Nokia city in Finland with suburban type of environment. During measurements 6 PCIs were observed but PCIs 72 and 77 are used in our analysis. Approximate eNB location is shown in Figure 5.2, where PCI 72 is with dark red legend and PCI 77 is with parrot green legend. PCI 77 was configured for 10 MHz system bandwidth so for comparison and analysis purpose MAC downlink throughput samples from PCI 77 are multiplied with 2 so that they can be compared with samples and results obtained from other PCIs with system bandwidth 20 MHz.

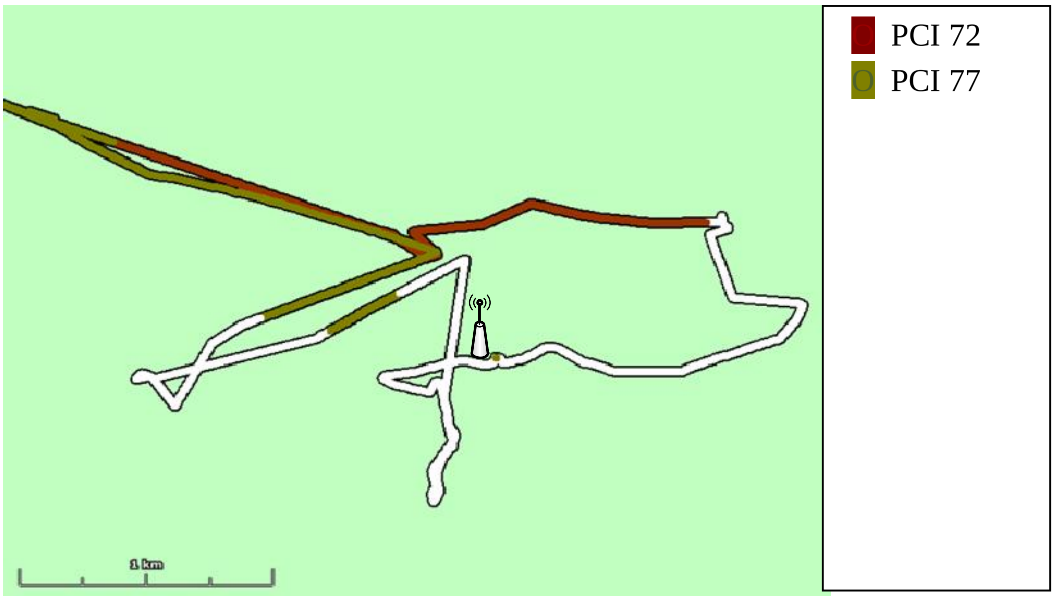

***Figure 5.2.** PCI 72 and 77 in Nokia MC.*

Nalkala measurement campaign was conducted in city center of Tampere Finland in pure urban environment. PCI 66, 67 and 68 were measured and used in analysis. Approximate eNB location is shown in Figure 5.3, where PCI 66 is with dark red legend, PCI 67 is with parrot green legend and PCI 68 is with blue legend.

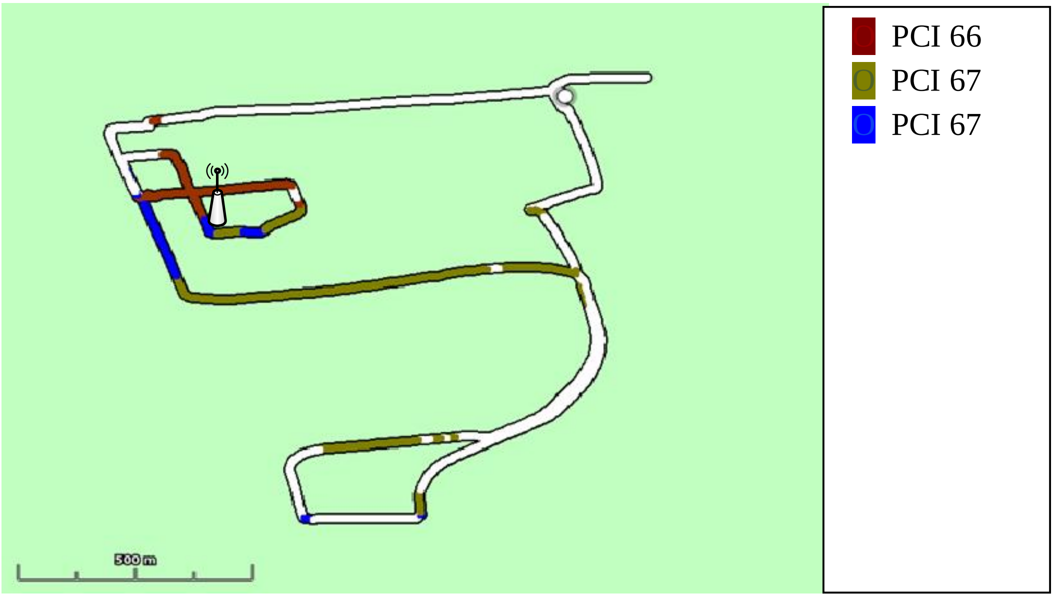

Figure 5.3. *PCI 66, 67 and 68 in Nalkala MC.*

For this thesis LTE measurements were done on 2600 MHz frequency band with 20 MHz system bandwidth. In the uplink 2500 to 2570 MHz and in downlink 2620 to 2690 MHz which is 7th index from potential operating bands for LTE which are mentioned in [17].

An overview of measurement routes is given with Cumulative Distribution Functions (CDF) of different key performance indicators and parameters discussed in Section 5.2.1. CDF gives the idea of samples probability distribution area.
In Figure 5.4, CDF plots of timing advance values from three different measurement routes are shown. These plots give an idea of distance of user equipment from eNB during each route with amount of percentage samples received during downlink measurements. For example, we received high timing advance values from Pyynikintori route which means Pyynikintori route was with longer distances between user equipment and eNB.

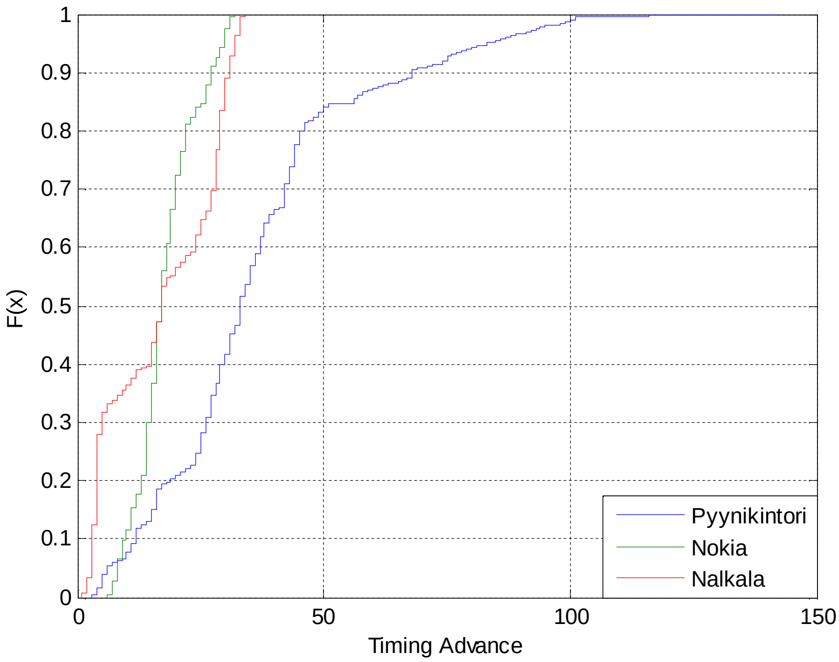

Figure 5.4. *CDF for timing advance of all MCs.*

In Figure 5.5, CDF plots of RSRP from three different measurement routes are shown. These plots show us path losses during each route with amount of percentage samples received during downlink measurements. For example, we received low RSRP values from Pyynikintori and Nokia measurement routes and high RSRP values from Nalkala measurement route.

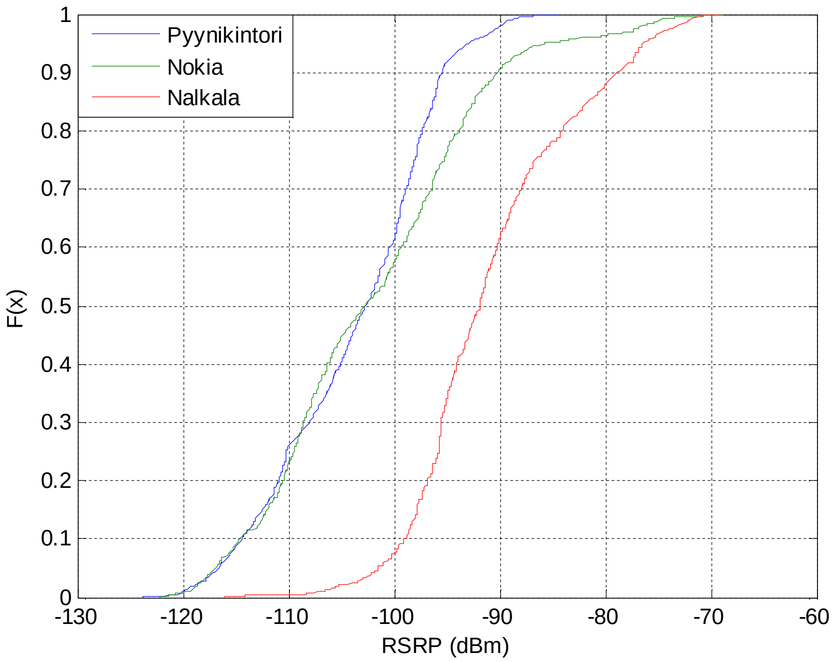

Figure 5.5. *CDF for RSRP of all MCs.*

In Figure 5.6, CDF plots of RS SNR from three different measurement routes are shown. These plots show us RS SNR values during each route with amount of percentage samples received during downlink measurements. For example, high deviation in RS SNR values can be noticed from Pyynikintori and Nokia routes. We have received negative RS SNR values from Nokia route as well.

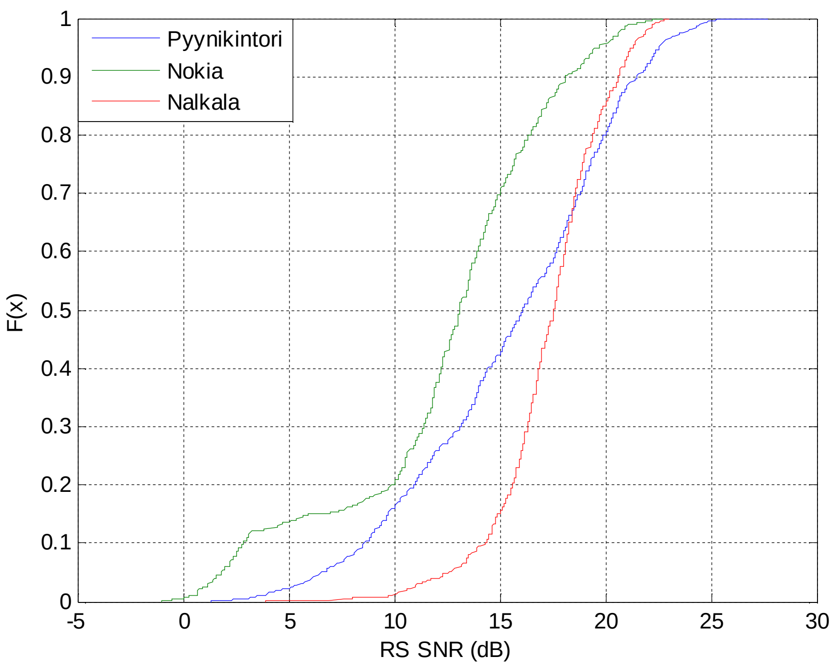

Figure 5.6 *CDF for RS SNR of all MCs.*

In Figure 5.7, CDF plots of CQI values reported by user equipment in three different measurement routes are shown. These plots show us CQI values during each route with amount of percentage samples received during downlink measurements. For example, higher percentage of high CQI values from 10 to 14 is reported by user equipment during Nalkala route. CQI values are feedback from user equipment to eNB how good channel conditions user equipment is having.

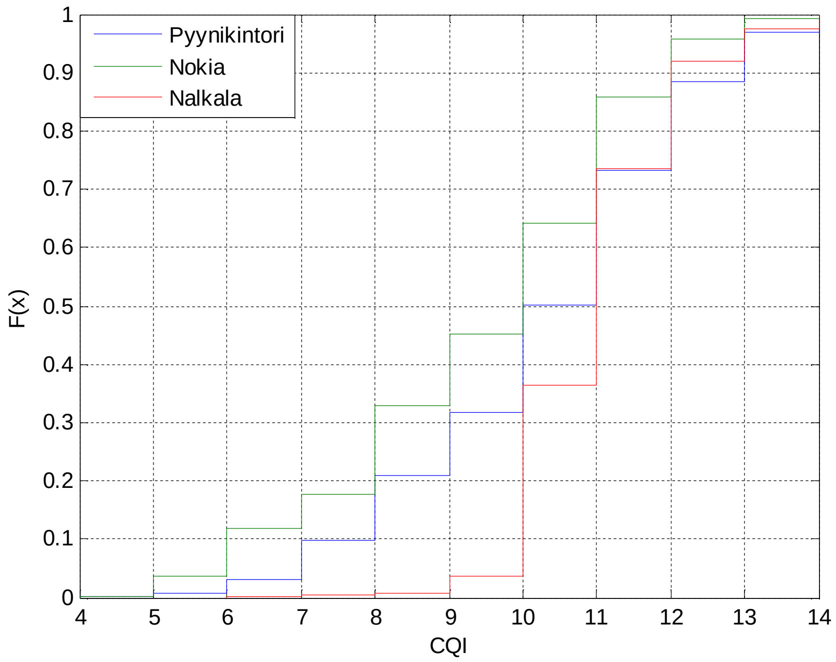

Figure 5.7. *CDF for CQI of all MCs.*

In Figure 5.8, CDF plots of received MAC downlink throughput in three different measurement routes are shown. These plots show us amount of percentage MAC downlink throughput samples received during each route. For example 50 % MAC downlink throughput samples are received in Pyynikintori route below ~48 Mbps, in Nokia below ~54 Mbps, in Nalkala below ~37 Mbps.

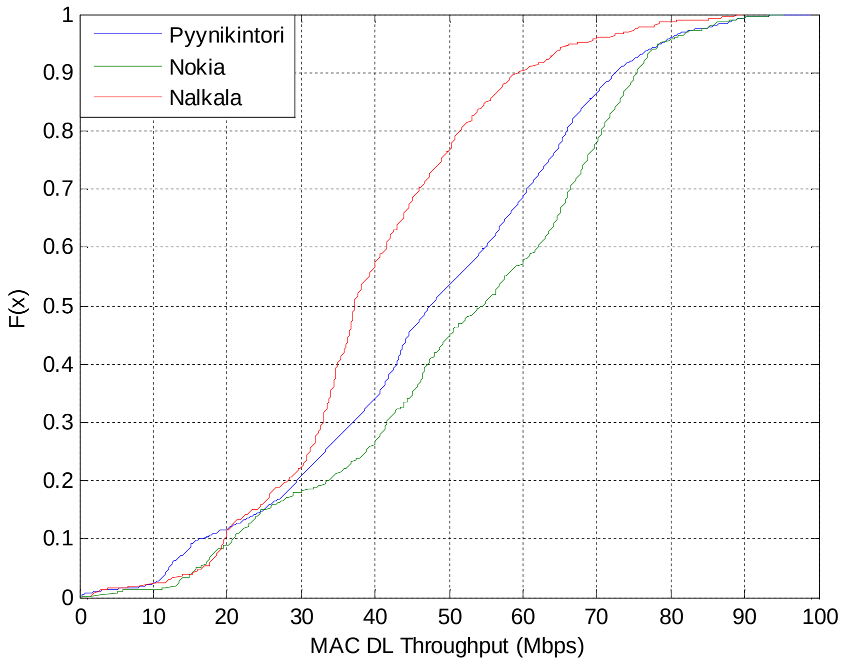

Figure 5.8. *CDF for MAC downlink throughput of all MCs.*

5.3. LTE performance analysis

In this section results will be presented and analyzed which give an idea about LTE performance in general and in different type of environments. These results are listed below.

- Impact of high speed on LTE downlink
- Practical throughputs vs. theoretical limits
- Timing advance based results and comparison (for the timing advance range 0 to 20)
- RSRP based results and comparison (for the range -100 to -90 dBm)
- CQI vs. MAC downlink throughput results
- CQI vs. RS SNR results

These results will be discussed and a possibility of their reliability will be also assessed with the quality of outcome results in the next chapter in conclusion discussion.

5.3.1. Impact of high speed on LTE downlink

It is observed from the results from Pyynikintori measurement campaign that LTE gives high data rates even at the speed more than 90 km/h as can be seen from Figure 5.9, which shows samples from PCI 60 and PCI 62. We have received MAC downlink throughput samples more than 90 Mbps at speed higher than 90 km/h.

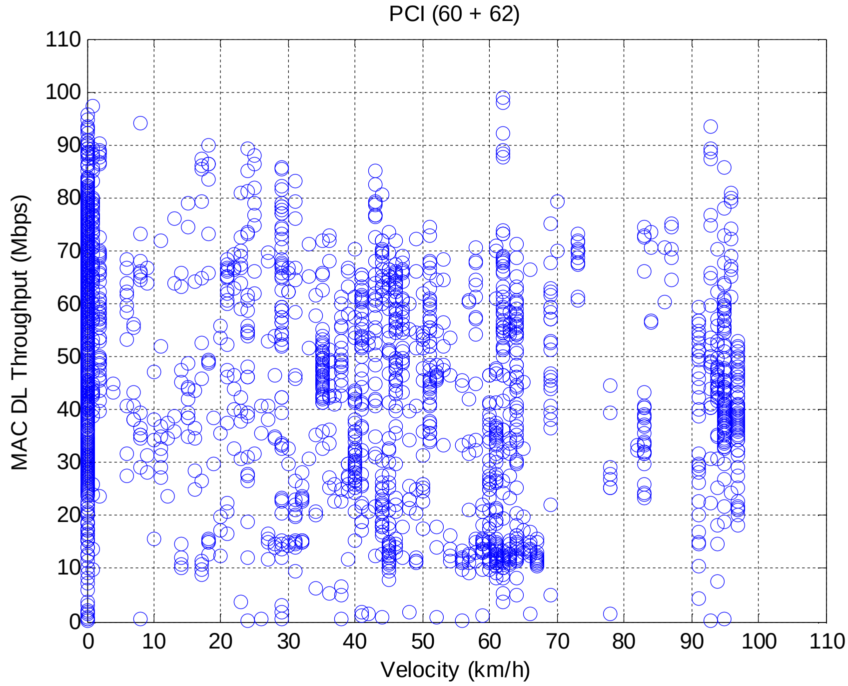

Figure 5.9. *MAC downlink throughput vs. velocity results from Pyynikintori MC.*

5.3.2. Practical throughputs vs. theoretical limits

In Figures 5.10 a), b) and c), practical MAC downlink throughputs are shown in comparison with theoretical limit lines from three different environments and measurement campaigns. Shannon ideal limit for 2 × 2 MIMO is shown with red line, Physical layer limit with black and MAC layer limit with green. These figures give an idea about the gap between LTE theoretical throughputs and practical achieved MAC downlink throughputs in different type of environments and antenna locations. It can be seen from the results that high antenna position in Pyynikintori measurement campaign and suburban site and antenna location in Nokia, give better performance and throughputs as compared to urban site and antenna location on top of a building from Nalkala measurement campaign. From Pyynikintori measurement campaign we have received samples with higher deviation. In Nokia measurement campaign we have received few samples at very low RS SNR even some at negative values. It can be seen that gap between practical throughput vs. theoretical throughput limits increases with increase of RS SNR values from very low negative RS SNR to higher RS SNR values.

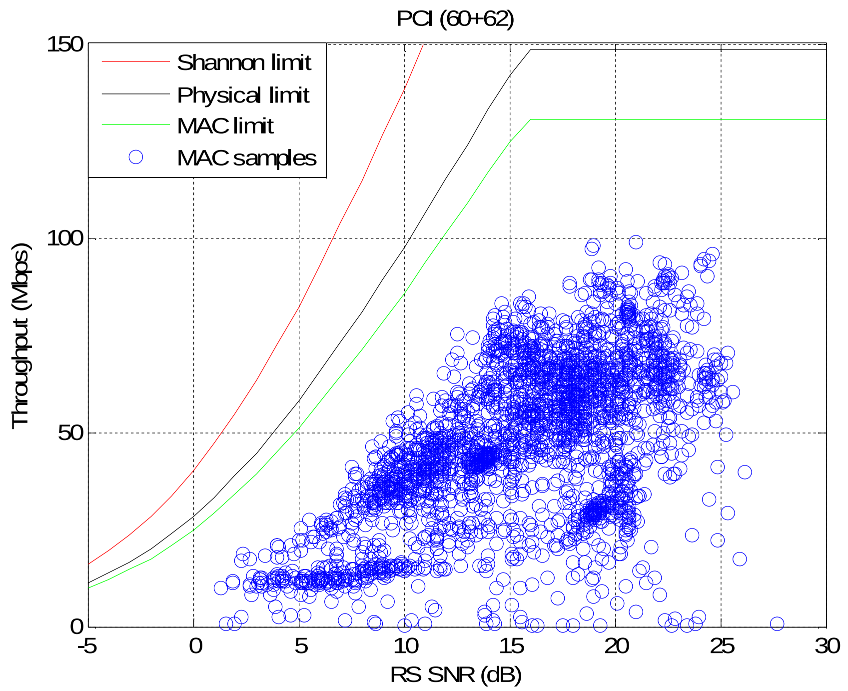

Figure 5.10. *a) Samples from Pyynikintori MC vs. theoretical Shannon limits.*

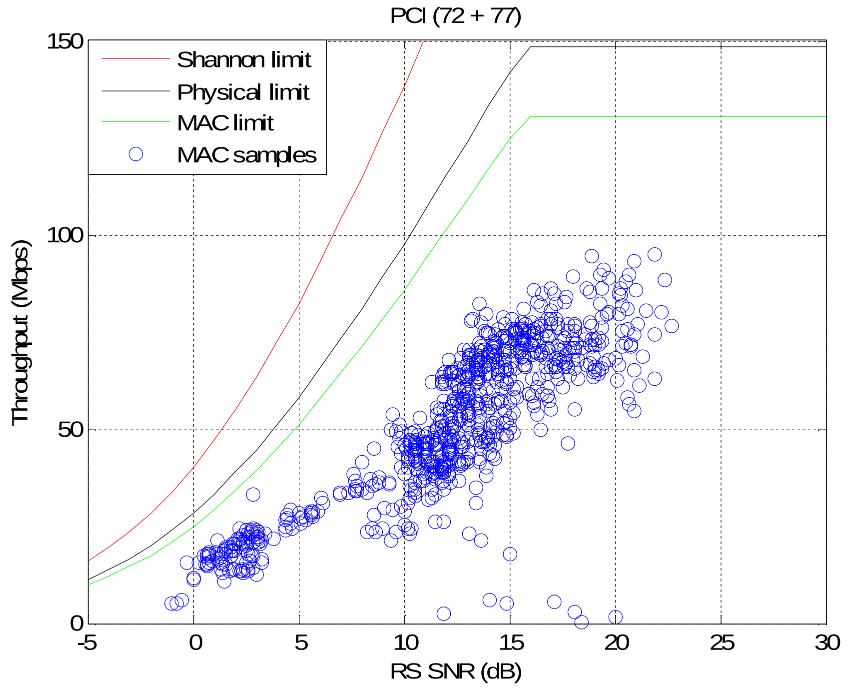

Figure 5.10. *b) Samples from Nokia MC vs. theoretical Shannon limits.*

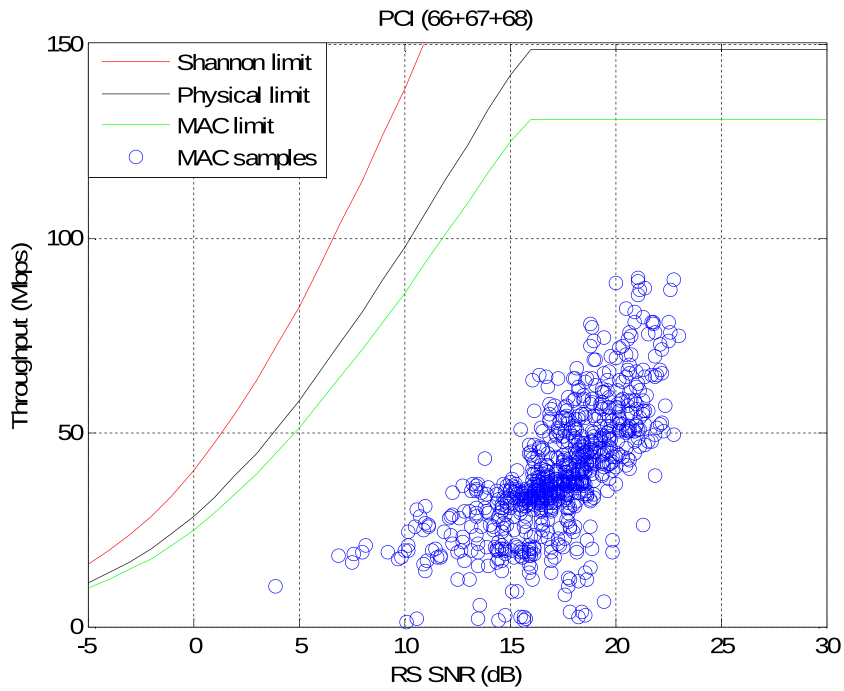

Figure 5.10. *c) Samples Nalkala MC vs. theoretical Shannon limits.*

With user equipment limitations LTE provides a few high data rate samples quiet close up to ~100 Mbps in MAC layer mostly with an approximate average gap of ~20 Mbps to Shannon MAC layer limit in Pyynikintori and Nokia measurement campaigns. But there is 2 times higher gap between theoretical MAC layer's limit and received MAC downlink throughput samples in Nalkala urban measurement campaign as compared to Pyynikintori macro/rural and Nokia suburban. This difference can be seen very easily from the Figure 5.10 d) which gives a combined results overview from all three different measurement campaigns with different legends.

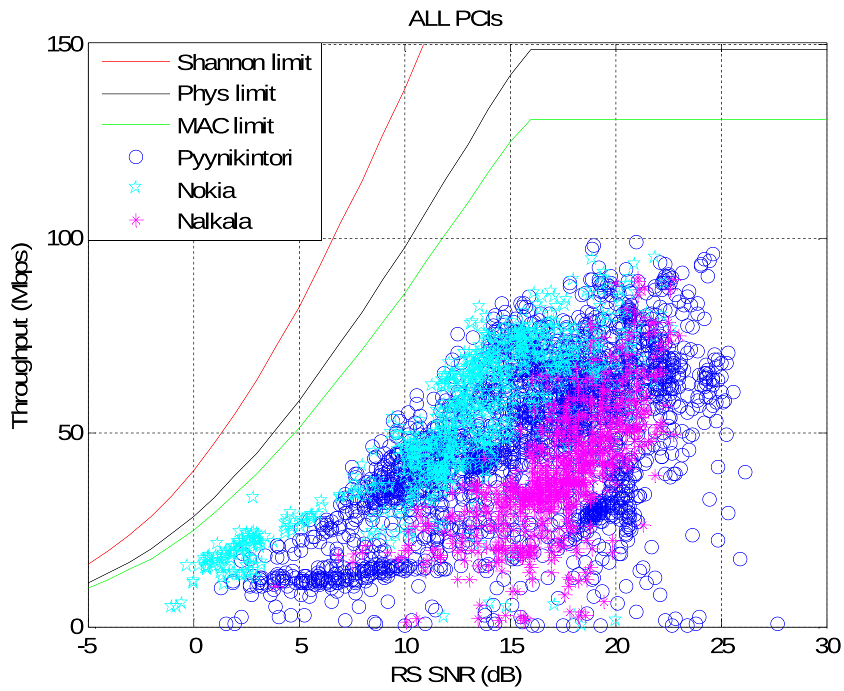

Figure 5.10. d) *Overview of all MCs vs. theoretical Shannon limits.*

5.3.3. Timing advance based results and comparison

In Figures 5.11 a), b) and c), timing advanced based results are shown from three different environments and measurement campaigns. These results are for timing advance range 0 to 20. The range of timing advance 0 to 20 is chosen for comparison for the reason of having good amount of samples from all three different measurement campaigns which are enough for comparison.

It can be seen that Nalkala measurement results give lower MAC downlink throughputs with higher RS SNR values and range as compared to Nokia and Pyynikintori measurement results. These results again show that suburban Nokia cells and high antenna positioned cells in Pyynikintori give better performance as compared to urban roof top antennas and cells in Nalkala. The results obtained from Nokia sub urban measurement campaign are providing high throughputs like Pyynikintori measurement campaign but the difference is RS SNR range. From Pyynikintori measurement campaign we have received samples with higher deviation.

Figure 5.11 d) gives a combined results overview from all three different measurement campaigns with different legends for timing advance range 0 to 20.

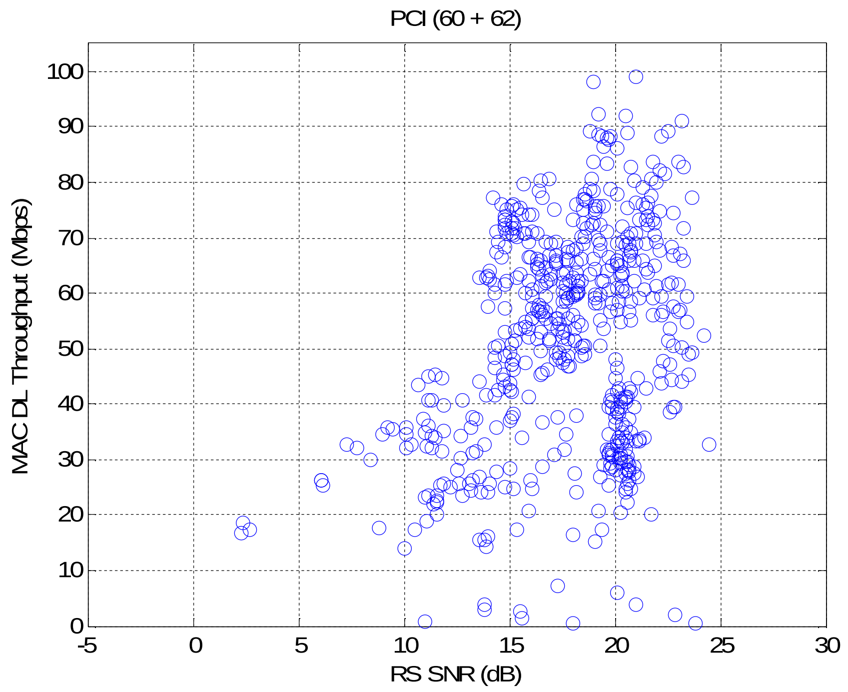

Figure 5.11. *a) Timing advance based results for range 0 to 20, Pyynikintori MC.*

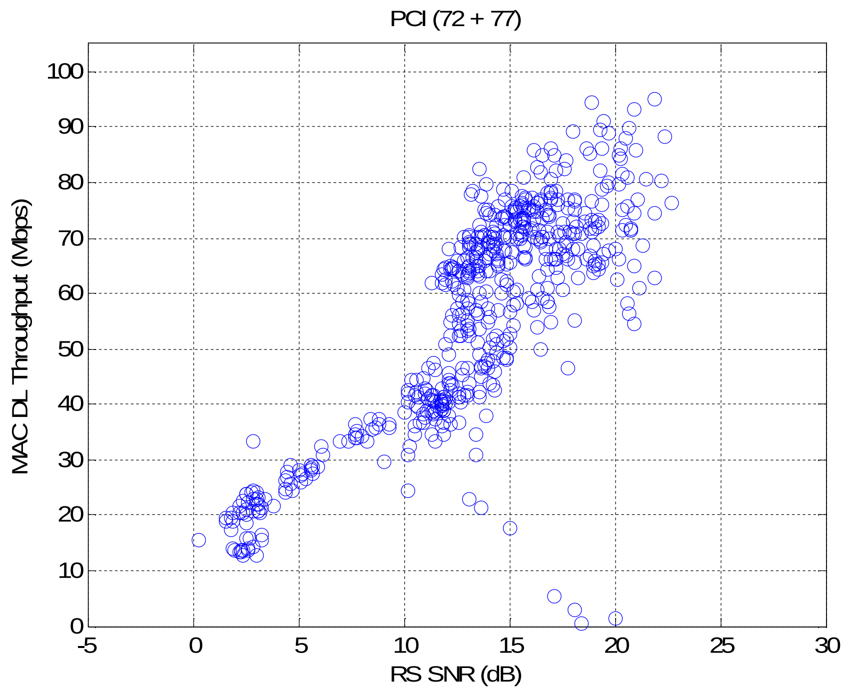

Figure 5.11. *b) Timing advance based results for range 0 to 20, Nokia MC.*

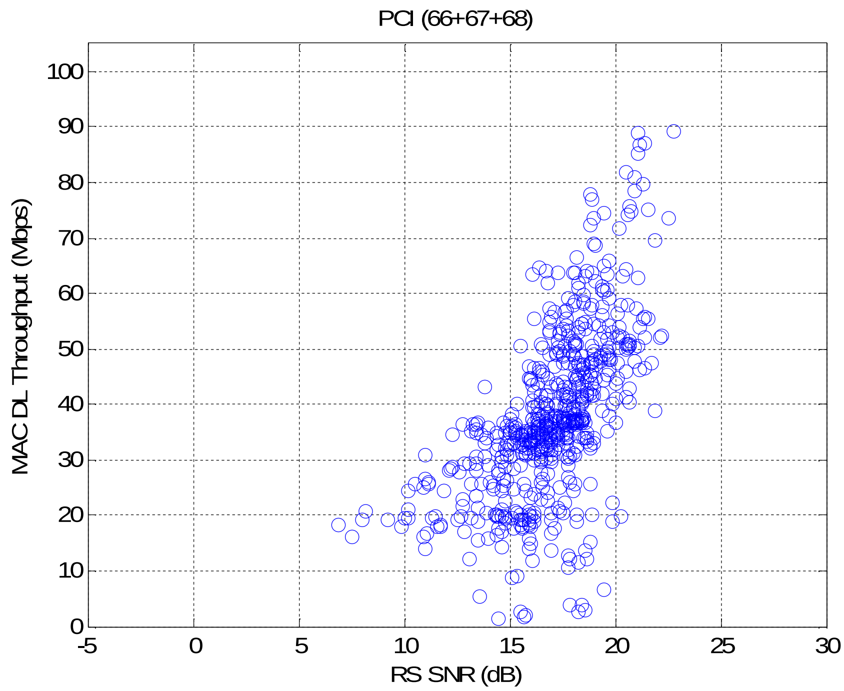

Figure 5.11. *c) Timing advance based results for range 0 to 20, Nalkala MC.*

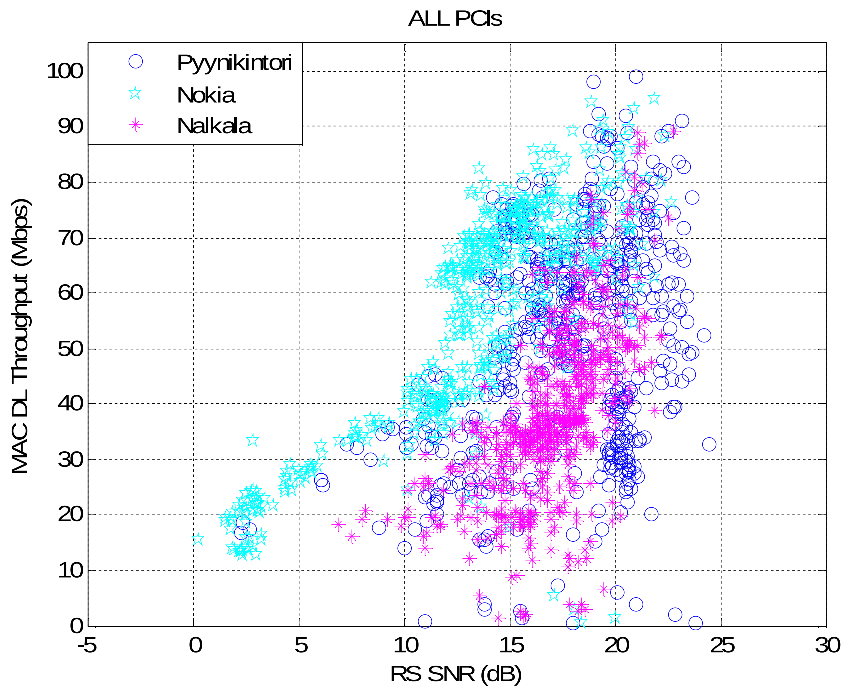

Figure 5.11. *d) Timing advance based results for range 0 to 20, overview of all MCs.*

In Appendix A, measurement results from three different environments for other timing advance ranges are given. These results are not analyzyed because of maturity of samples in all three environments was not enough for comparison.

5.3.4. RSRP based results and comparison

In Figures 5.12 a), b) and c), RSRP based results for the range -100 to -90 dBm are shown from three different environments and measurement campaigns. The range of RSRP -100 to -90 is chosen for comparison for the reason of having good amount of samples from all three different measurement campaigns which are enough for comparison.

From Pyynikintori measurement campaign results we have better MAC downlink throughput samples but with higher deviation as compared to Nokia and Nalkala measurement campaigns results. Nalkala the urban measurement campaign results give lowest MAC downlink throughput with good RS SNR values and range as compared to high antenna macro/rural Pyynikintori and Nokia suburban environments. From Nokia suburban measurement campaign MAC downlink throughput results are clearly better than Nalkala measurement results.

Figure 5.12 d) gives a combined results overview from all three different measurement campaigns with different legends for RSRP range -100 to -90 dBm.

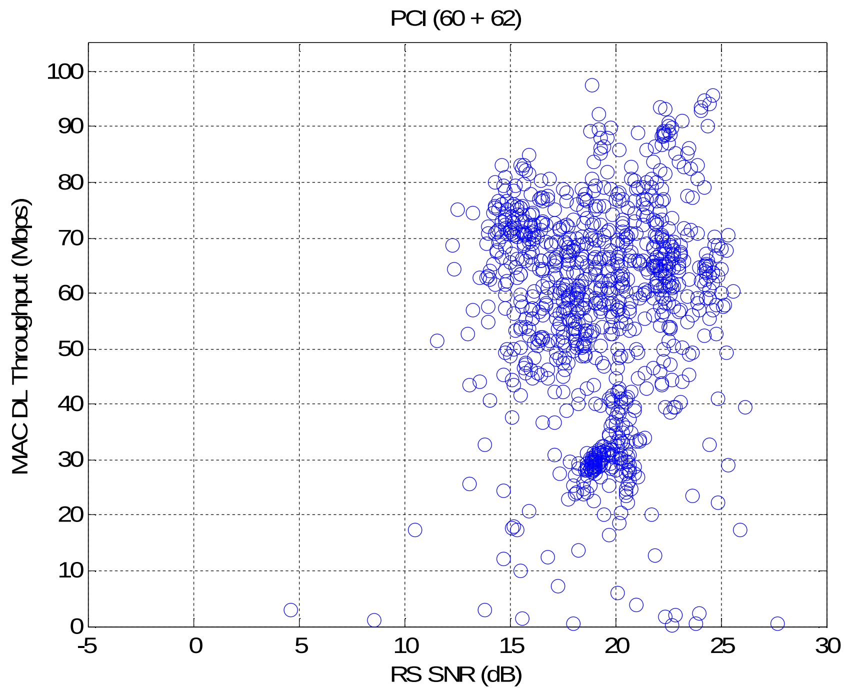

***Figure 5.12** a) RSRP based results for the range -100 to -90 dBm, Pyynikintori MC.*

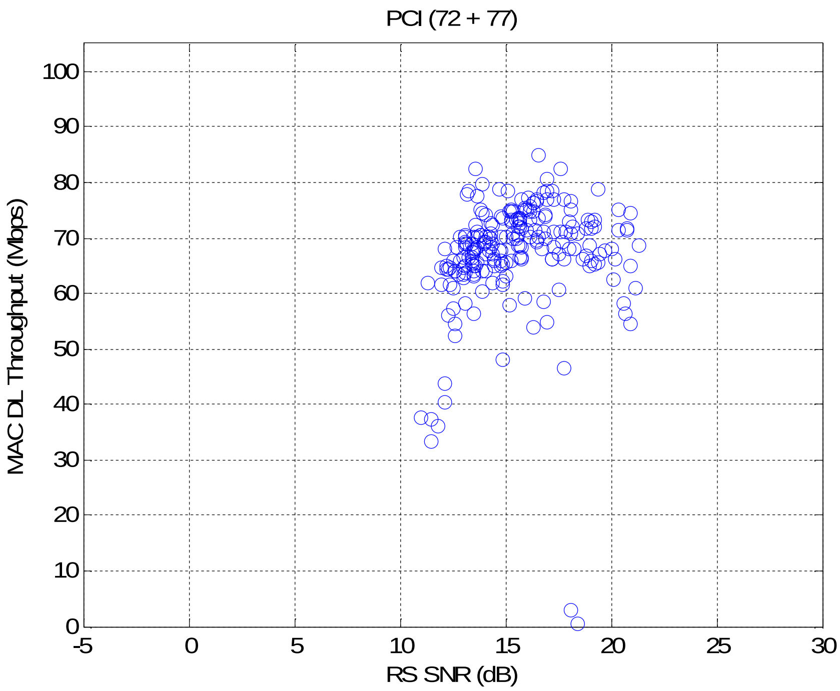

Figure 5.12 *b) RSRP based results for the range -100 to -90 dBm, Nokia MC.*

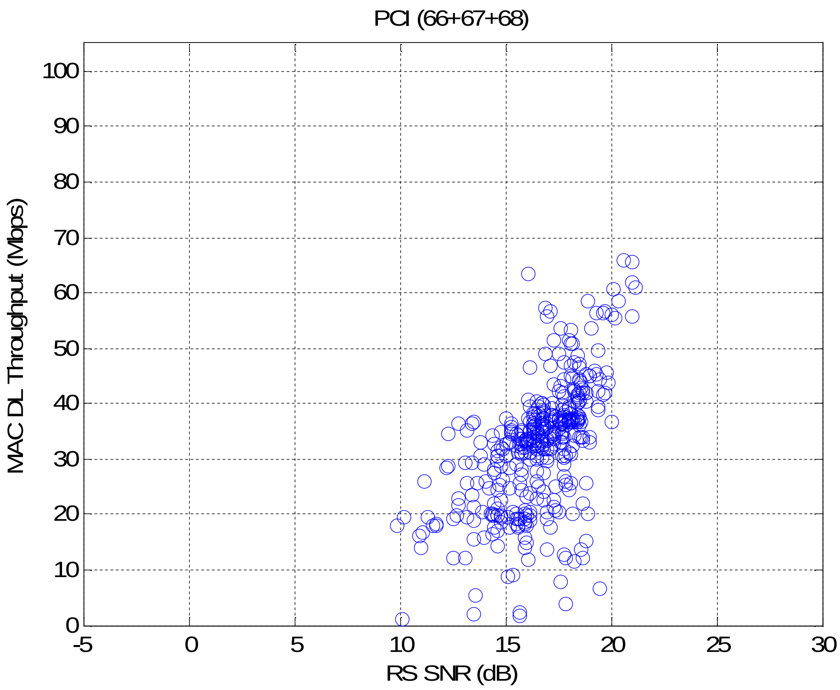

Figure 5.12 *c) RSRP based results for the range -100 to -90 dBm, Nalkala MC.*

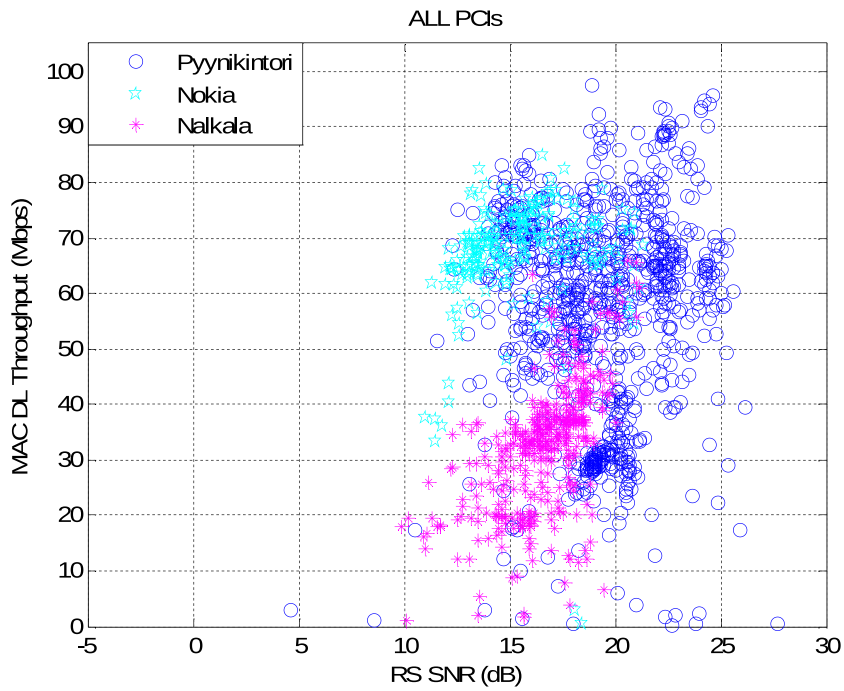

Figure 5.12 *d) RSRP based results for the range -100 to -90 dBm, overview of all MCs.*

In Appendix B, measurement results from three different environments for other RSRP ranges are given. These results are not analyzyed because of maturity of samples in all three environments was not enough for comparison.

5.3.5. CQI vs. MAC downlink throughput results

In Figures 5.13 a), b) and c), CQI vs MAC downlink throughput results are shown from three different environments and measurement campaigns. From these results we can understand the behavior of MAC downlink throughput in different environments as compared to CQI values reported by user equipment in LTE.
From CQI vs. MAC downlink throughput results for Pyynikintori measurement campaign and after comparing these to the results from Nokia and Nalkala we can observe deviation in Pyynikintori measurement campaign as compared to Nokia and Nalkala measurement campaigns. There is huge deviation in MAC downlink throughput results from 0 to ~80 Mbps approximately for a single CQI value for example 10 in Pyynikintori measurement campaign. In Nokia measurement campaign results this deviation is from 0 to ~80 Mbps approximately and from Nalkala measurement campaign results is from 0 to ~60 Mbps approximately for CQI value 10. Similar behavior is seen for other CQI values. From these results it is observed that deviation in received MAC downlink throughput samples increases from micro/urban to macro/rural environments with increase in CQI values. It is observed from results that from macro/rural to urban environment use of higher CQI values also increases as compared to lower values of CQI.

Figure 5.13 d) gives a combined results overview from all three different measurement campaigns with different legends for CQI vs. MAC downlink throughput.

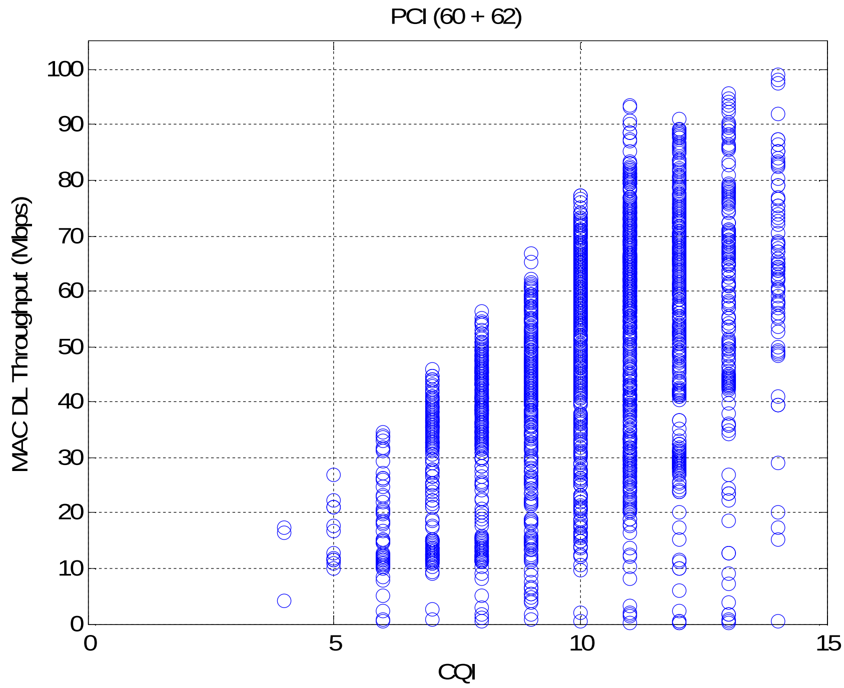

***Figure 5.13** a) CQI vs. MAC downlink throughput, Pyynikintori MC.*

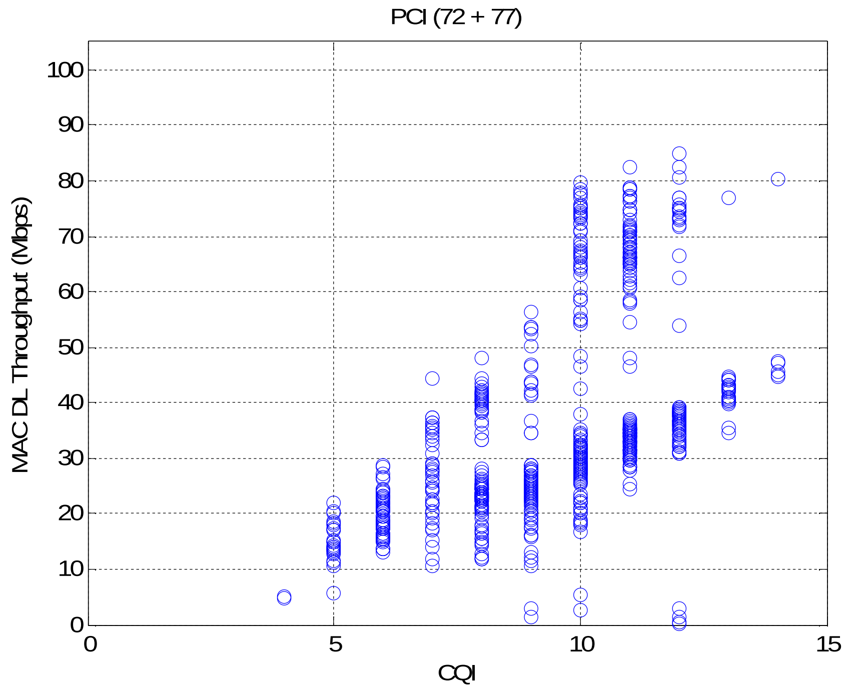

***Figure 5.13** b) CQI vs. MAC downlink throughput, Nokia MC.*

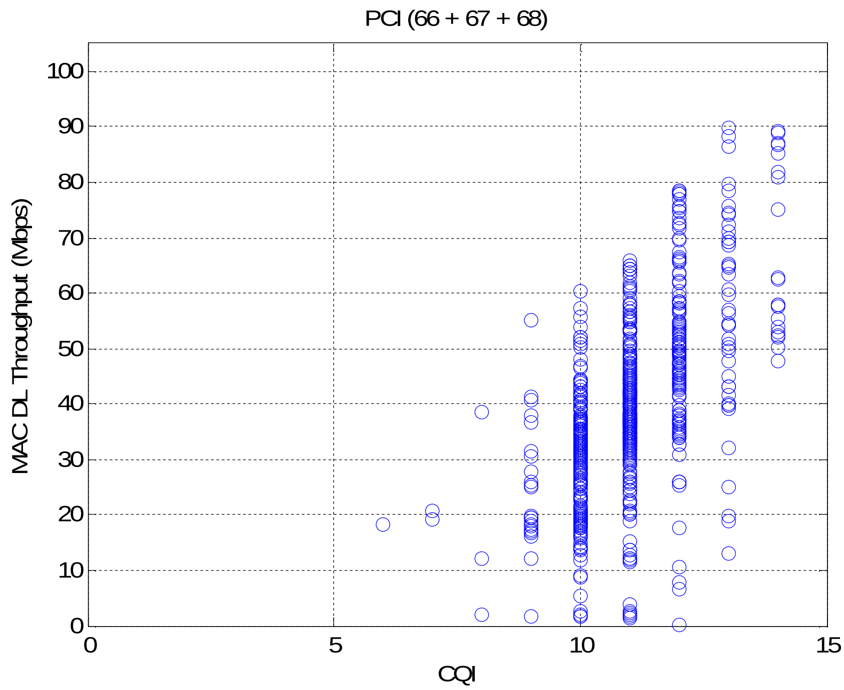

Figure 5.13 c) CQI vs. MAC downlink throughput, Nalkala MC.

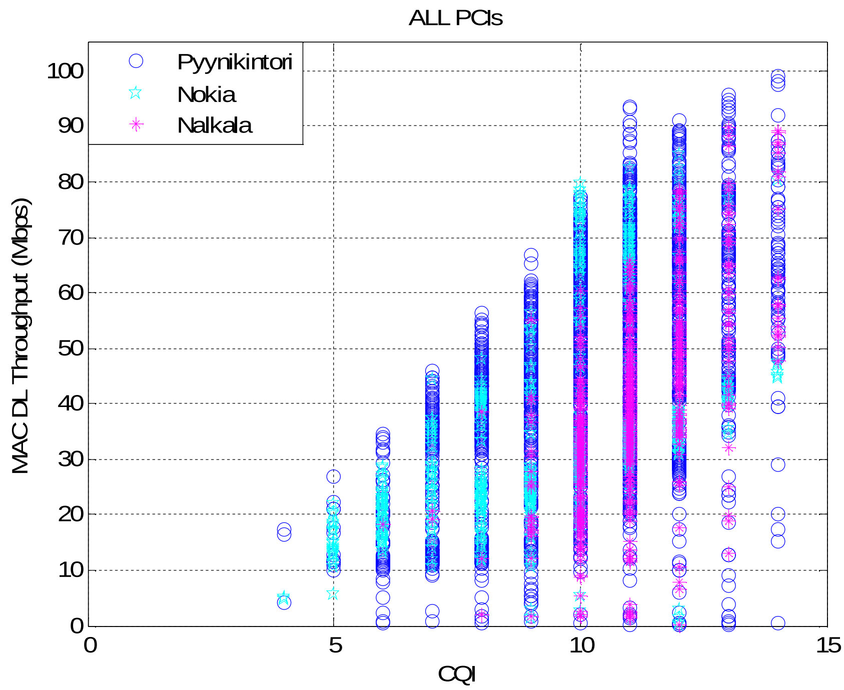

Figure 5.13 d) CQI vs. MAC downlink throughput, overview of all MCs.

5.3.6. CQI vs. RS SNR results and comparison

As we know that CQI value is reported by user equipment to eNB for indicating channel conditions it is having at that moment which is used by eNB to allocate higher modulation and coding scheme using adaptive schemes. Therefore there is a strong relationship between CQI value and RS SNR values. In this section we will observe and try to understand how CQI value and RS SNR behave in different environments in a relationship to each other.

In Figures 5.14 a), b) and c), CQI vs. RS SNR results are shown from three different environments and measurement campaigns. It can be seen that CQI reported value increases with increase in RS SNR but for single RS SNR value for example 20 dB 5 different CQI values from 10 to 14 are reported by user equipment and vice versa. This indicates there might be more vendor/operator specific parameters used for calculating and reporting a CQI value other than RS SNR value. From 20 dB and above RS SNR values CQI reported values are from 10 to 15.

Figure 5.14 d) gives a combined results overview from all three different measurement campaigns with different legends for CQI vs. RS SNR.

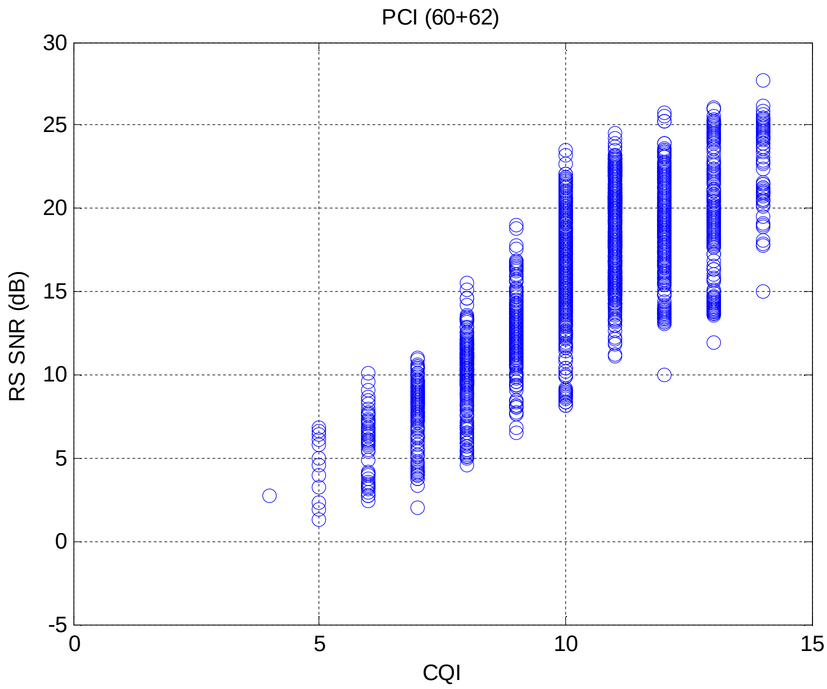

Figure 5.14 *a) CQI vs. RS SNR, Pyynikintori MC.*

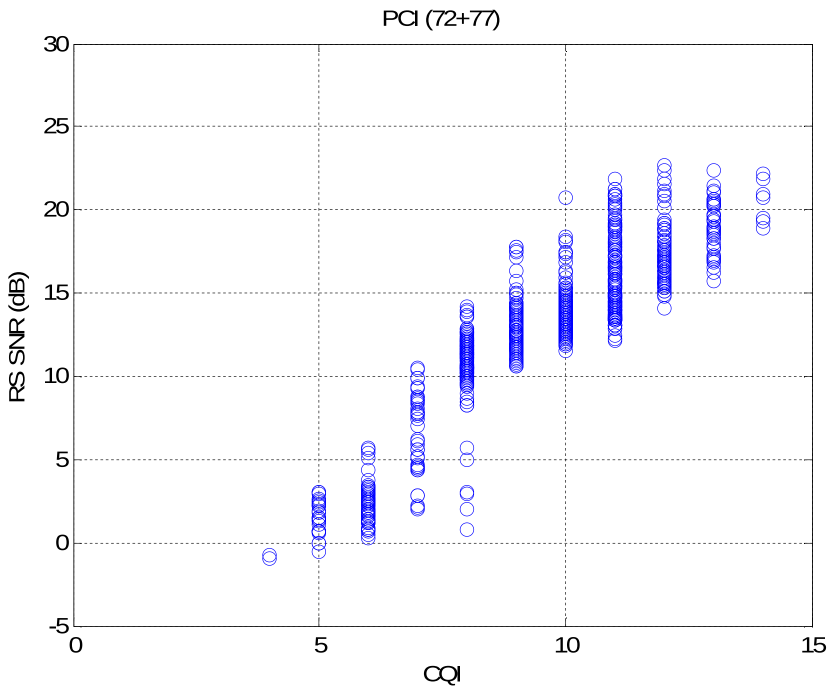

Figure 5.14 *b) CQI vs. RS SNR, Nokia MC.*

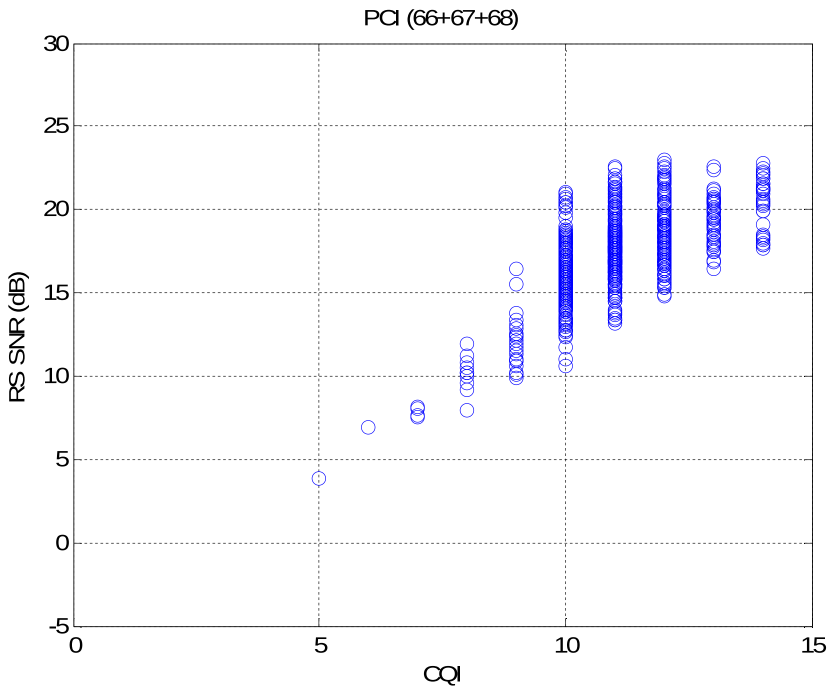

Figure 5.14 *c) CQI vs. RS SNR, Nalkala MC.*

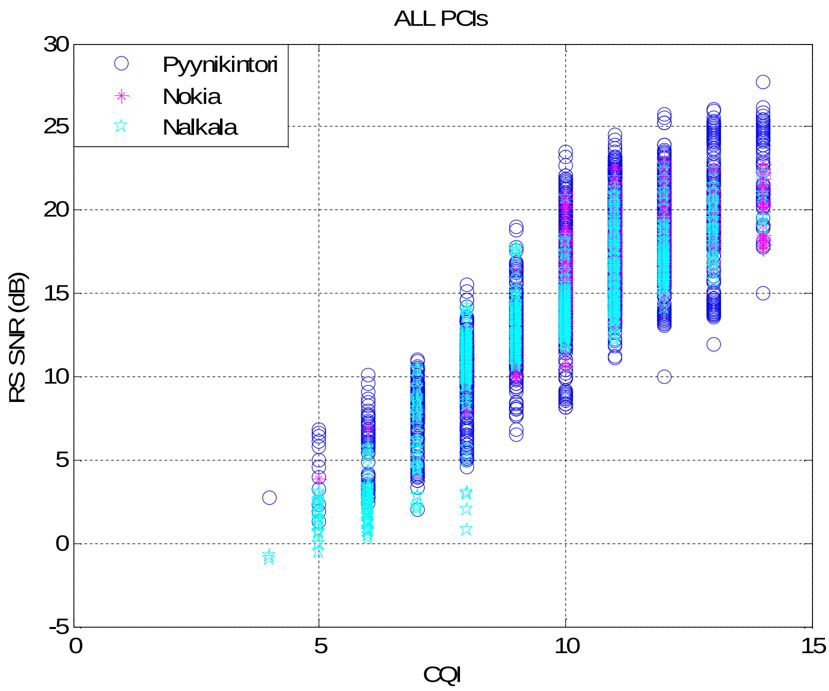

Figure 5.14. *d) CQI vs. RS SNR, overview of all MCs.*

5.4. Impact of environment on propagation

In this section the results of RSRP vs. RS SNR are discussed which give an idea and help to understand impact of different environments on propagation in LTE.

In Figures 5.15 a), b) and c), RSRP vs. RS SNR results from three different environments and measurement campaigns are shown. It can be seen from results cells with high antenna in Pyynikintori measurement campaign give better RS SNR even at lower RSRP as compared to other measurement campaign results. For example at -120 dBm Pyynikintori results for RS SNR are better than Nokia RS SNR results. We have received samples from Nokia suburban site at negative RS SNR values. From Pyynikintori cells samples were received at lower RSRP but with better RS SNR which indicates that cells with high antenna in Pyynikintori are suffering from less noise and inter cell interference as compared to suburban Nokia and urban Nalkala environments.

High RSRP values are received from Nokia and Nalkala routes as compared to Pyynikintori measurement route. Pyynikintori gives lowest RSRP values with a better range of RS SNR values e.g. between -100 to -90 dBm RSRP range gives better range of RS SNR but with larger deviation as compared to Nokia and Nalkala sites.

Overall on average in all measurements with 10 dB path loss RS SNR decreases ~4.4 dB. In rural and suburban it is almost same ~5 dB decrease in RS SNR with 10 dB path loss but in urban it is lowest ~3.3 dB. Figure 5.15 d) gives a combined results overview from all three different measurement campaigns with different legends for RSRP vs. RS SNR.

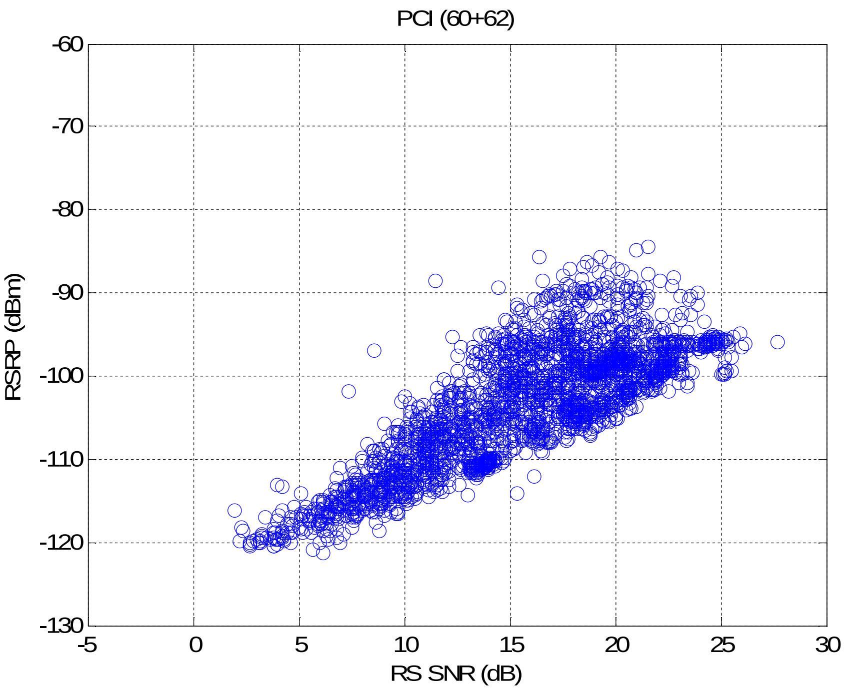

Figure 5.15. *a) Pyynikintori MC*

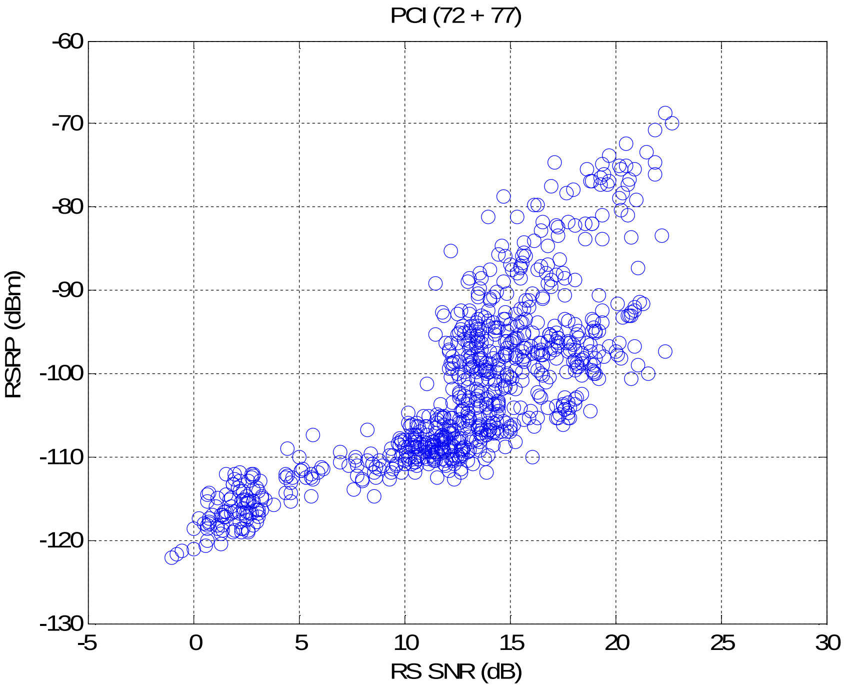

Figure 5.15. *b) Nokia MC*

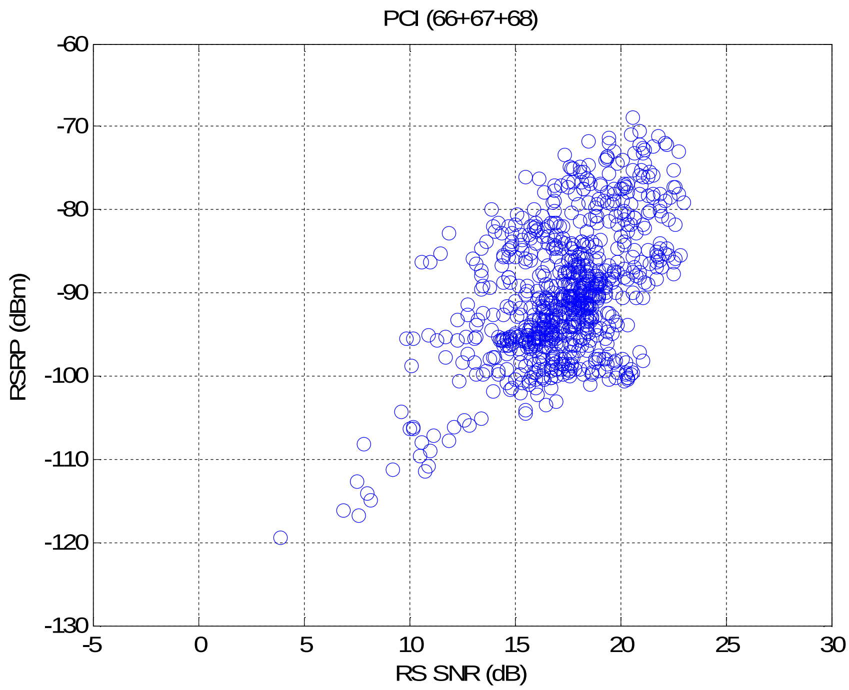

Figure 5.15. *c) Nalkala MC*

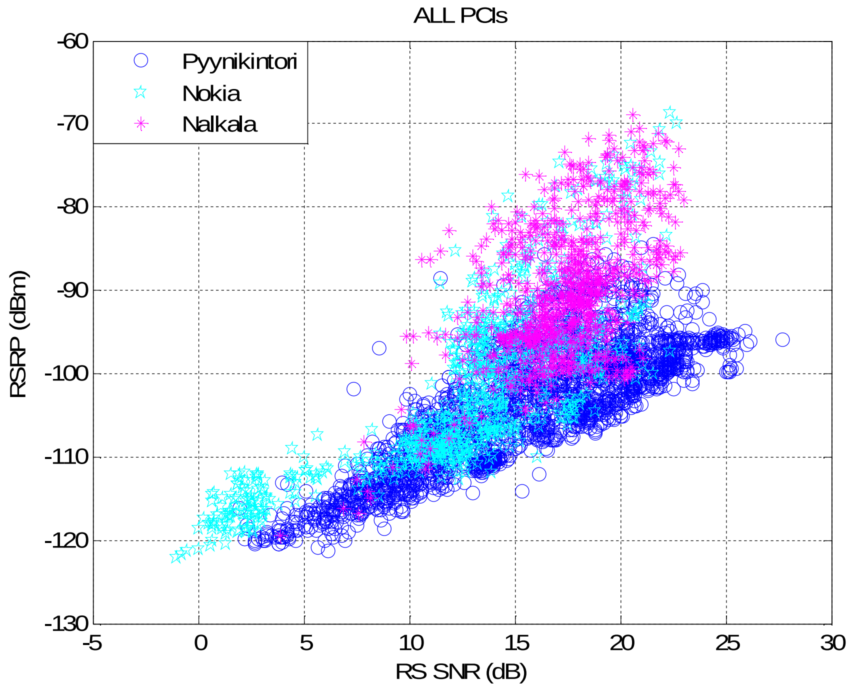

Figure 5.15. *d) All MCs*

Results from Pyynikintori in Appendix A and B explain the behavior of LTE network in a macro/rural environment over long distances between user equipment and eNB but these can be used in comparison with environments because routes for suburban and urban measurement campaigns were not so long and equal in length and dimensions.

These results explain the behavior of LTE network in three different outdoor environments including macro/urban, suburban and urban. These results can be beneficial as a pre-study for LTE planning and deployment phases in different outdoor environments.These results and performance analysis are provided using single test equipment used in measurements although there might be other users present in practical LTE network but they were unknown. Moreover there was no access to vendor/operator specific parameters and performance thresholds, which also limits with access to network and analysis. There was no parameter tuning option available and exact key performance indicator parameters which vendor/operator was using were unknown.

There is always a possibility of error in measurement results but quality and reliability of these results depends on Nemo tools output which is a commercial product and is being used in field by many companies for measurements. These results which have been used for analysis, no significant error was observed during post-processing and analysis. Quality and reliability of these results is good.

6. CONCLUSION AND DISCUSSION

The scope of this thesis was to give measurements based results, analysis and conclusion for LTE performance in different type of outdoor environments. Three different environments were chosen for this reason for measurement campaigns including macro/rural and urban in Tampere and suburban in Nokia Finland. This thesis study and scenario is based on single user measurements and performance analysis in different outdoor environments. Single user test equipment was used during measurements. Different key performance indicator parameters including RS SNR, RSRP, MAC downlink throughput, timing advance and CQI were used for post processing and analysis of the results.

From measurement results it is observed that high antenna position in Pyynikintori macro/rural environment provides high data rates at high speeds. Above 90 Mbps MAC downlink throughput samples were received at speeds higher than 90 km/h on highway. It supports the claim for one of LTE's goals that LTE should provide high data rates and optimized performance at high speeds. The gap between practical throughputs vs. theoretical throughput limits increases with increase in RS SNR values from very low negative RS SNR to higher RS SNR values. It is observed this gap is almost same in macro/rural and suburban environments but it is two times higher in pure urban environment. From timing advance range 0 to 20 based results and analysis it is observed that urban environment performs worst as compared to macro/rural and suburban environments. But there is huge deviation observed in MAC downlink throughput samples received in macro/rural environment as compared to suburban and urban environments. Almost similar results are observed for RSRP range -100 to -90 dBm. It is observed that deviation in received samples increases from micro/urban to macro/rural environments with increase in CQI values. From macro/rural to urban environment use of higher CQI values also increases as compared to lower values of CQI. For a single RS SNR four to five different CQI values are reported by user equipment and vice versa. From CQI based results it is observed that we cannot explain deviation in MAC downlink throughput vs. RS SNR just using RS SNR and CQI. Although there is a strong relationship between RS SNR and CQI reported value but there should be more vendor/operator specific parameters used for reporting a CQI value which were unknown. High RSRP values are received from urban and suburban environments as compared to macro/rural environment. In macro/rural environment better RS SNR values are received with lower RSRP values as compared to urban environment.

Overall conclusion to above discussion can be made that it is observed from measurement results that LTE downlink performs better with high antenna position in macro/urban environment and on highways as compared to roof top antenna in urban environment. But with high antenna there is huge deviation in LTE MAC downlink throughput samples in macro/rural type environment as compared to suburban and urban environments. In suburban environment with average antenna height LTE downlink was performing better than urban environment with even lower RS SNR range. There was less deviation in MAC downlink throughput samples from urban and suburban environment as compared to macro/rural environment. Overall results from urban environment show worst performance as compared to macro/rural and suburban environments.

When I chose this thesis study based on measurements I could not find any appreciable literature or study for LTE performance based on field measurement results. For the future research there is a huge potential for LTE downlink performance analysis with multi user scenario with more than one test equipments. In future with more than one test equipments inter cell interference and scheduling mechanisms can be studied as well for performance analysis of LTE downlink in practical situations with measurements. Access to the network and information of operator’s key performance parameters and performance thresholds can be very beneficial and recommended.

Bibliography

[1] Dictionary.com LLC IAC Corporation,"Performance". http://dictionary.reference.com/browse/perform (accessed September, 2011).

[2] Theodore S. Rappaport, "Wireless Communications", Second Edition, Prentice-Hall, 2002.

[3] Harri Holma and Antti Toskala, "LTE for UMTS OFDMA and SC-FDMA based radio access", John Wiley and Sons Ltd, 2009.

[4] BP Tiwari, "Enabling reuse 1 in 4G Networks". www.beyond4g.org. http://www.beyond4g.org/wp-content/uploads/2010/07/Enabling-reuse-1-in-4G-Networksv0.1.pdf (accessed January, 2012).

[5] S.R. Saunders, "Antennas and Propagation for Wireless Communication Systems", John Wiley and Sons Ltd, 1999.

[6] J. Lempiäinen, M. Manninen. "UMTS Radio Network Planning, Optimization and QoS Management for practical engineering tasks", Kluwer Academic Publishers, 2003.

[7] 3GPP, "About 3GPP". http://www.3gpp.org/About-3GPP (accessed September, 2011).

[8] Sesia, S., Toufik, I. & Baker, M. "The UMTS Long Term Evolution from Theory to Practice", John Wiley and Sons, 2009.

[9] ARIB TR-T12-25.913 V9.0.0, "Requirements for Evolved UTRA (E-UTRA) and Evolved UTRAN (E-UTRAN)".

[10] 3GPP TS 36.306 v8.2.0, "User Equipment (UE) radio access capabilities", August 2008.

[11] Alcatel-Lucent "The LTE Network Architecture", Strategic White Paper 2009.

[12] Motorola,"Long Term Evolution (LTE): Overview of LTE Air Interface", Technical White Paper, 2007.

[13] Mahmoud, H. Yucek, T. Arslan, H. "OFDM for Cognitive Radio: Merits and Challenges", Wireless Communications, IEEE April 2009.

[14] Christoph Spiegel, Jens Berkmann, Zijian Bai,"MIMO schemes in UTRA LTE, A comparison“, IEEE vehicular Technology Conference, 2008.

[15] Forenza, A., McKay, M.R., Pandharipande, A., Heath, R.W., Collings, I.B, “Adaptive MIMO transmission for exploiting the capacity of spatially correlated channels”.

[16] Andreas Mitschele-Thiel, Jens Mückenheim, “3G Long term Evolution (LTE) and Sytem Architecture Evolution (SAE)”, December 2009. http://www.scribd.com/doc/53627716/29/Multiple-Antenna-Techniques-Supported- in-LTE (accessed October, 2011).

[17] Application note, Agilent “3GPP Long Term Evolution: System overview”, Product Development and Test Challenges, Agilent Technologies, Inc, 2008, 2009.

[18] 4G Americas, “MIMO transmission schemes for LTE and HSPA networks”, June-2009.

[19] 3GPP TS 36.211 V9.0.0 2009-12, “Evolved Universal Terrestrial Radio Access (E-UTRA) physical channels and modulation”.

[20] 3GPP TS 36.104 V8.7.0 2009-09, “Evolved Universal Terrestrial Radio Access (E-UTRA) Base Station (BS) radio transmission and reception”, (Release 8).

[21] Jim Zyren, Dr. Wes McCoy, “Overview of 3GPP Long Term Evolution physical Layer”, A White Paper by technical editor Freescale Semiconductor products.

[22] 3GPP TS 36.213 V8.8.0 2009-09, “Evolved Universal Terrestrial Radio Access (E-UTRA) physical layer procedures”.

[23] Dahlman, E., Parkvall, S., Sköld, J. & Beming, P. “3G Evolution: HSPA and LTE for mobile broadband”, Academic Press, First edition 2007.

[24] Christina Gessner, “Long Term Evolution: A concise introduction to LTE and its measurement requirements”. Rohde & Schwarz; 1 edition (4 Jan 2011).

[25] Ralf Kreher, Karsten Gaenger, “LTE signaling: troubleshooting and optimization”, John Wiley and Sons Ltd, 2011.

[26] White Paper, “NGMN radio access performance evaluation methodology”, NGMN Alliance, January 2008.

[27] GD Forney Jr., Gottfried Ungerboeck, ”Modulation and Coding for Linear Gaussian Channels”, IEEE 1998.

[28] Cui, D. “LTE peak rates analysis”, IEEE 2009.

[29] P. Mogensen et al. “LTE capacity compared to the Shannon bound”, IEEE Proc. Vehicular Technology Conference, pp. 699–703, April 2007.

[30] Abdul Basit, Syed, “Dimensioning of LTE network description of models and tool, coverage and capacity estimation of 3GPP Long Term Evolution radio interface”. Master’s thesis, Helsinki University of Technology February 2009.

Appendix A.

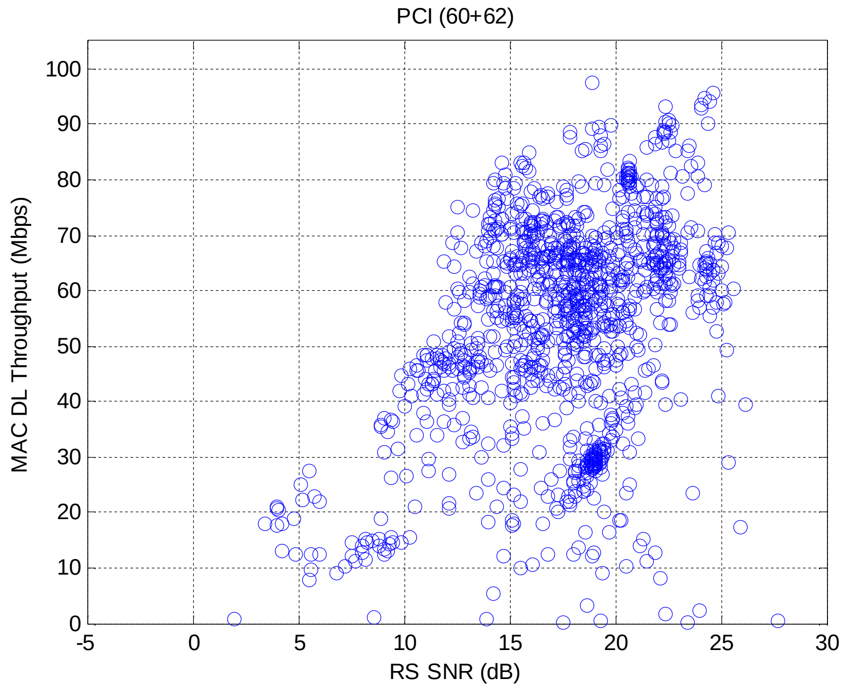

Figure A1. a) *Timing advance based results for range 21 to 40, Pyynikintori MC.*

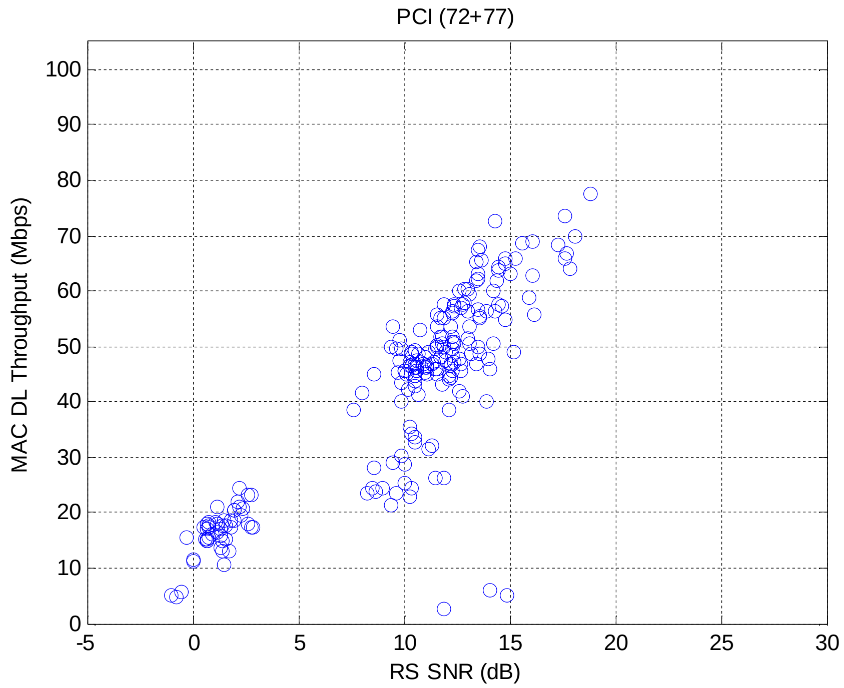

Figure A1. b) *Timing advance based results for range 21 to 40, Nokia MC.*

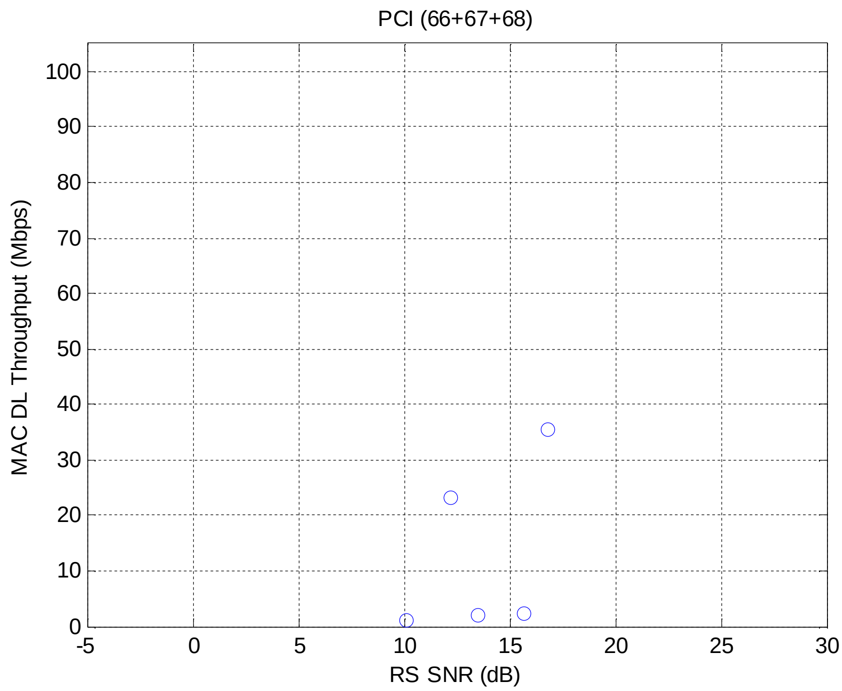

Figure A1. c) *Timing advance based results for range 21 to 40, Nalkala MC.*

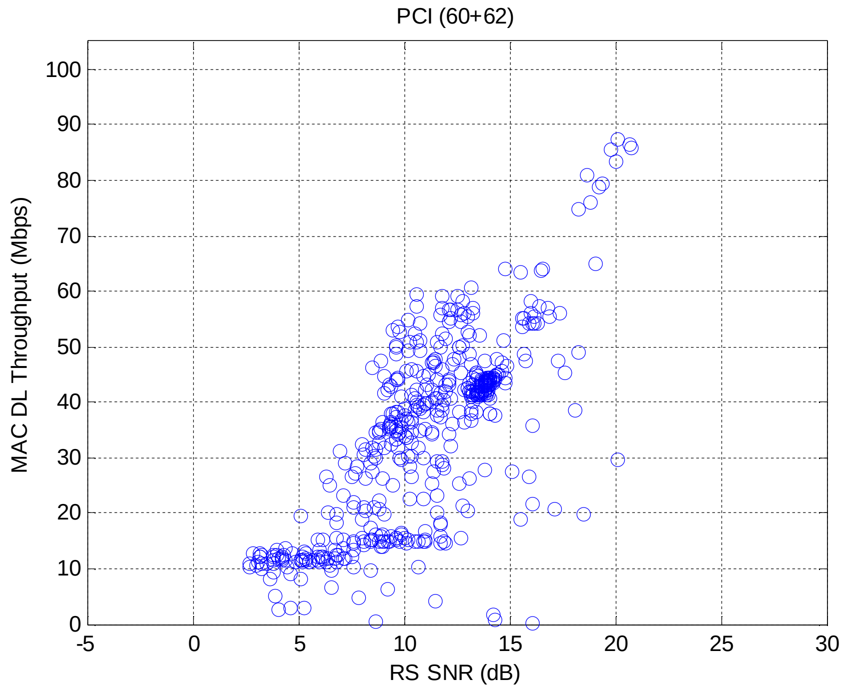

Figure A2. *Timing advance based results for range 41 to 60, Pyynikintori MC.*

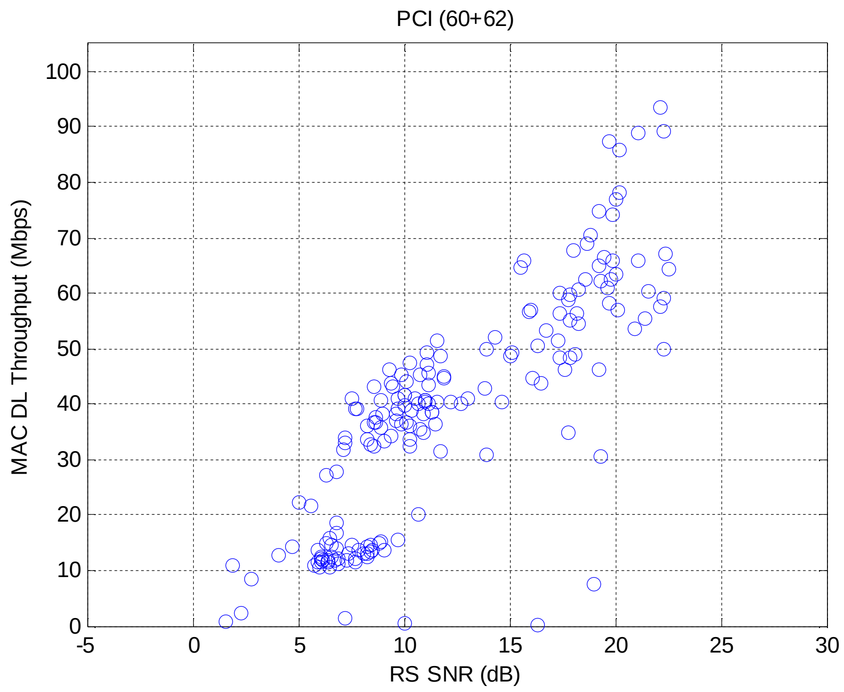

Figure A3. *Timing advance based results for range 61 to 80, Pyynikintori MC.*

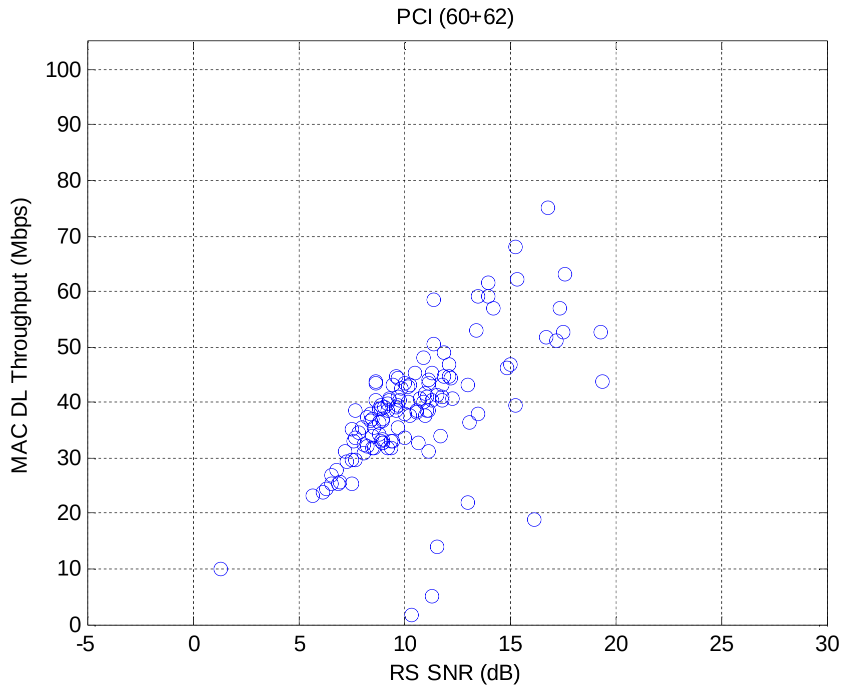

Figure A4. *Timing advance based results for range 81 to 100, Pyynikintori MC.*

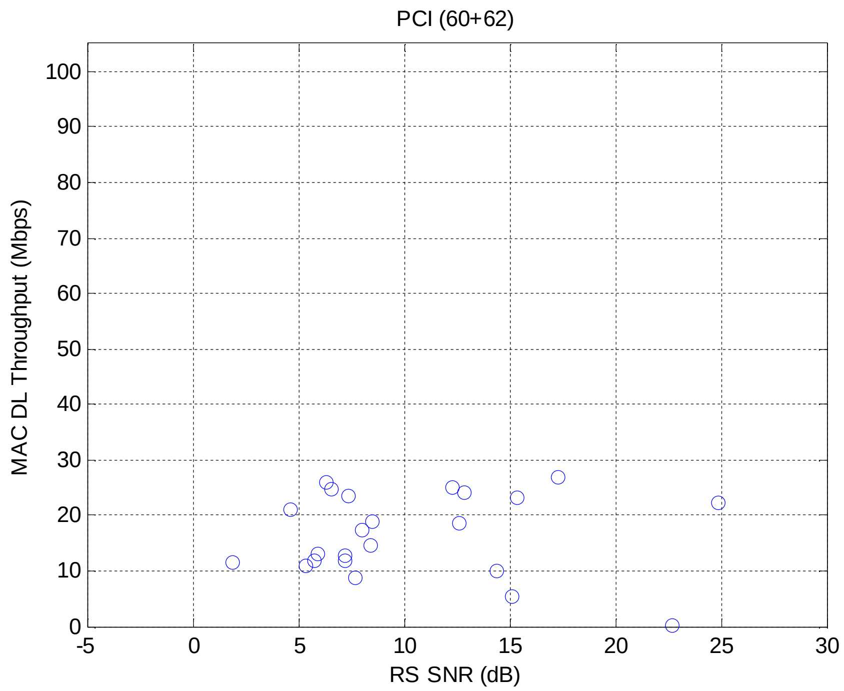

Figure A5. *Timing advance based results for range 101 to 120, Pyynikintori MC.*

Appendix B.

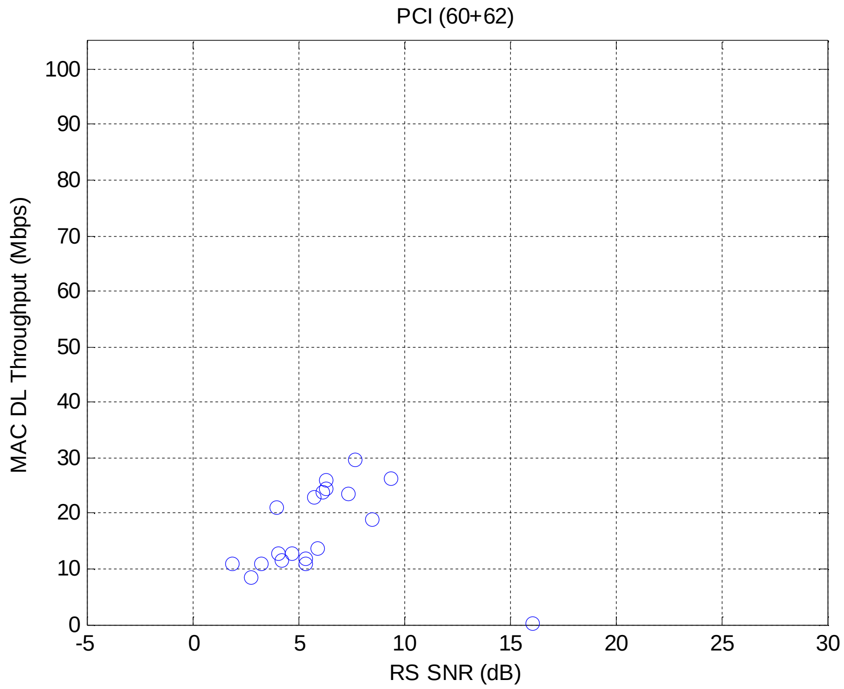

Figure B1. *a) RSRP based results for the range -130 to -120 dBm, Pyynikintori MC.*

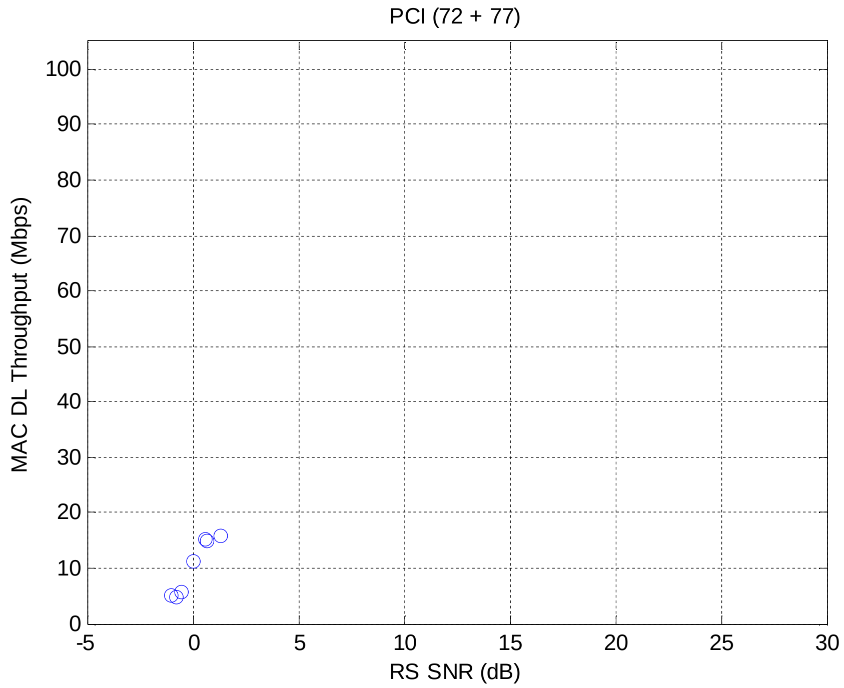

Figure B1. *b) RSRP based results for the range -130 to -120 dBm, Nokia MC.*

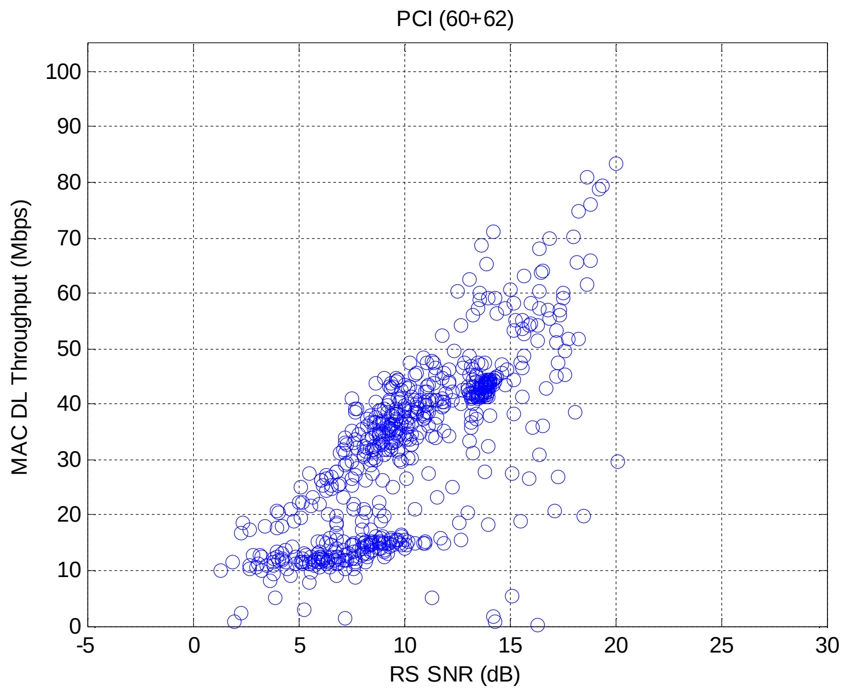

Figure B2. *a) RSRP based results for the range -120 to -110 dBm, Pyynikintori MC.*

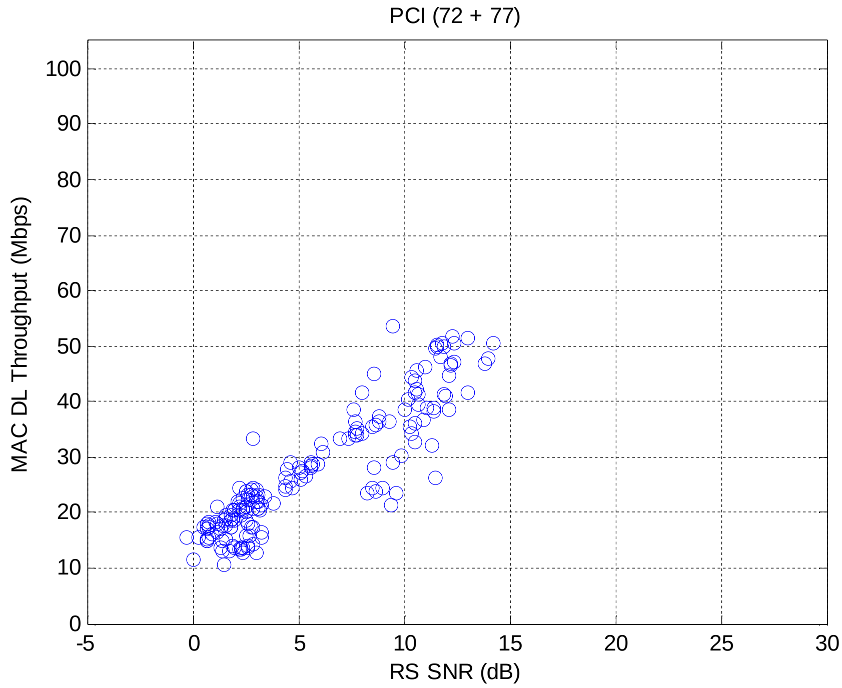

Figure B2. *b) RSRP based results for the range -120 to -110 dBm, Nokia MC.*

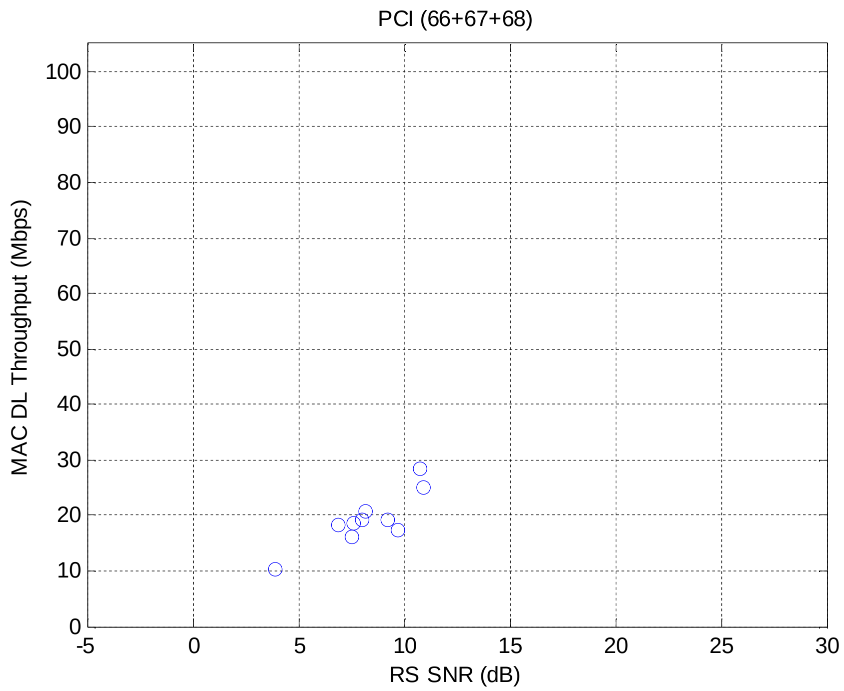

Figure B2. *c) RSRP based results for the range -120 to -110 dBm, Nalkala MC.*

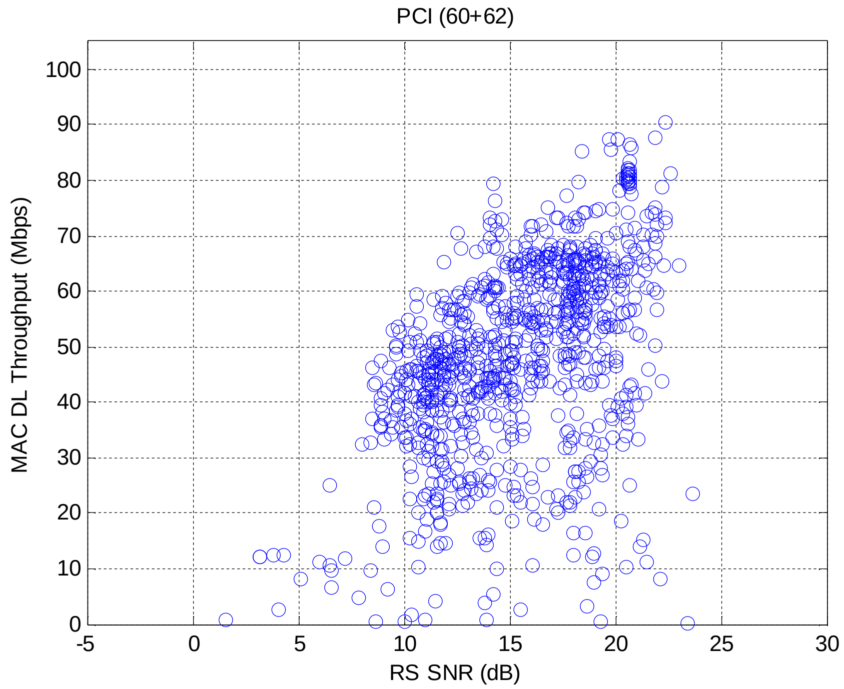

Figure B3. *a) RSRP based results for the range -110 to -100 dBm, Pyynikintori MC.*

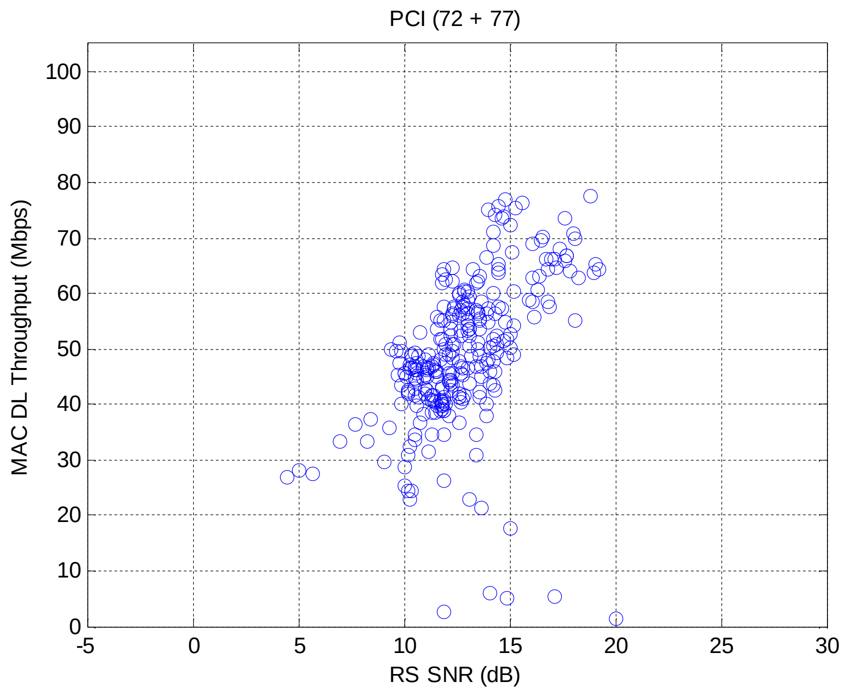

Figure B3. *b) RSRP based results for the range -110 to -100 dBm, Nokia MC.*

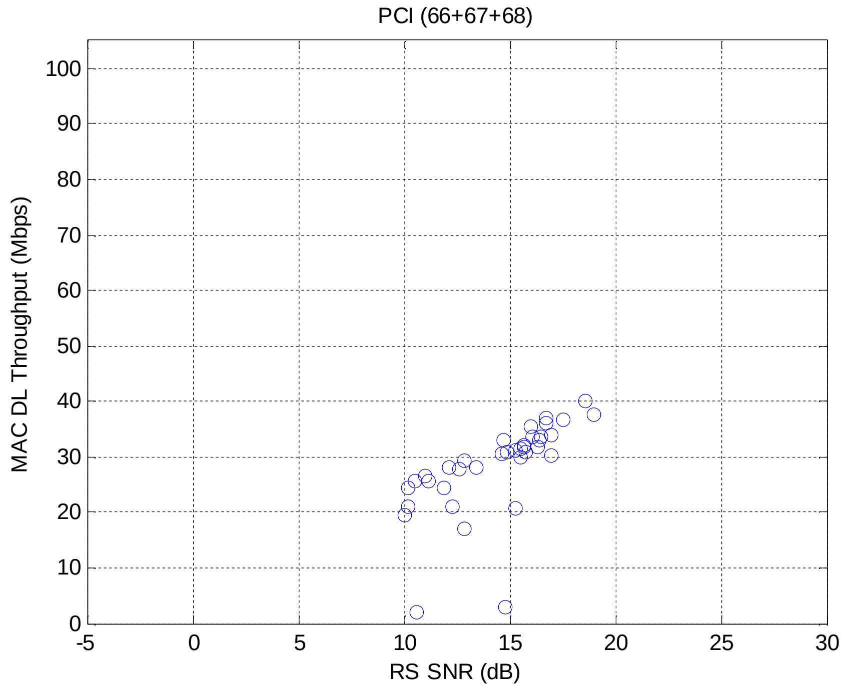

Figure B3. *c) RSRP based results for the range -110 to -100 dBm, Nalkala MC.*

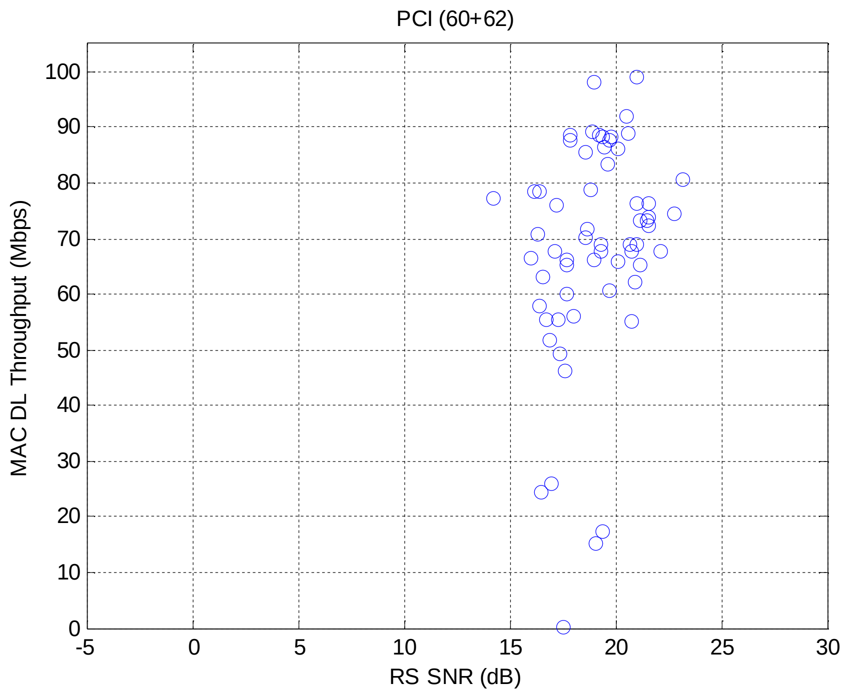

Figure B4. *a) RSRP based results for the range -90 to -80 dBm, Pyynikintori MC.*

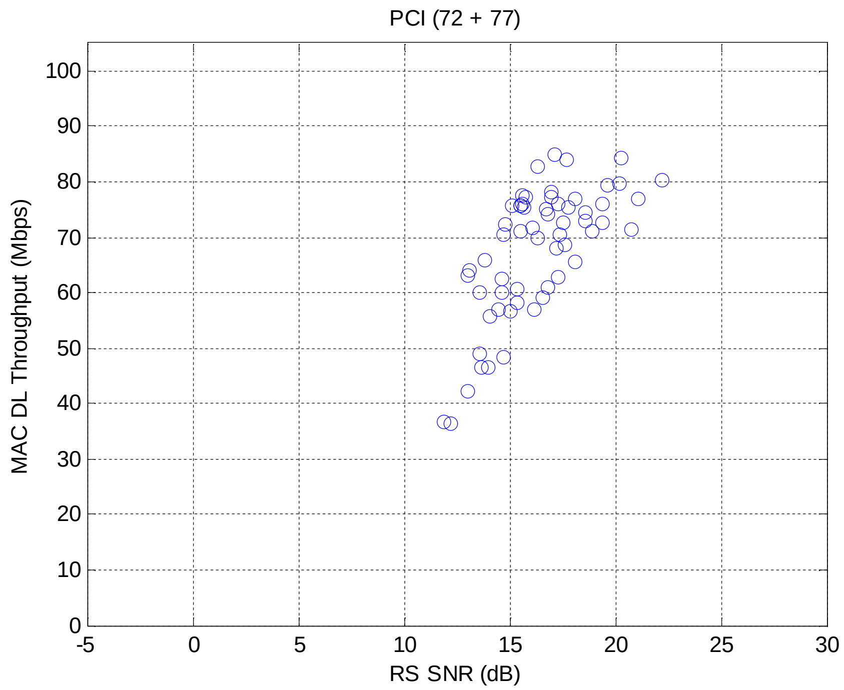

Figure B4. *b) RSRP based results for the range -90 to -80 dBm, Nokia MC.*

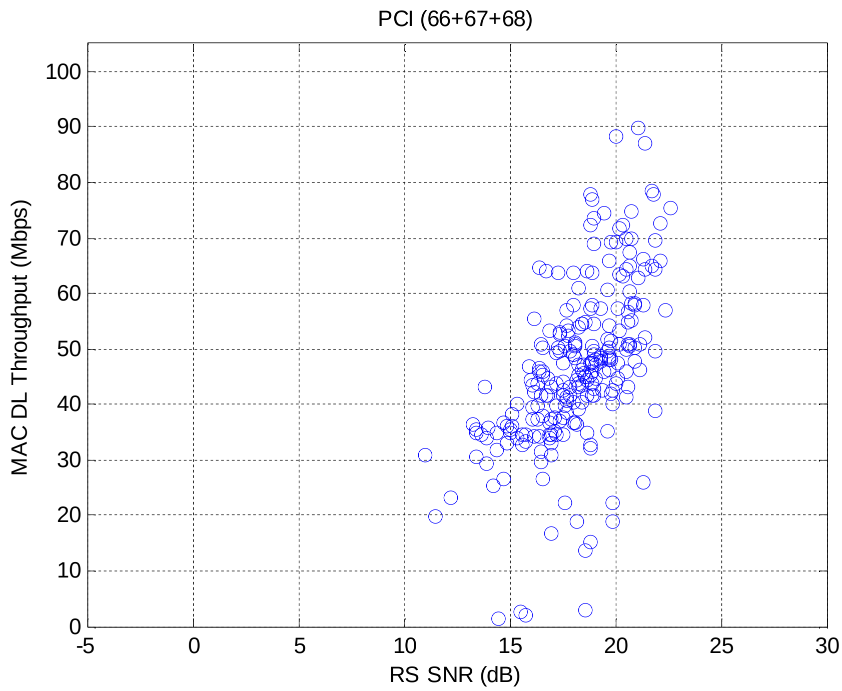

Figure B4. *c) RSRP based results for the range -90 to -80 dBm, Nalkala MC.*

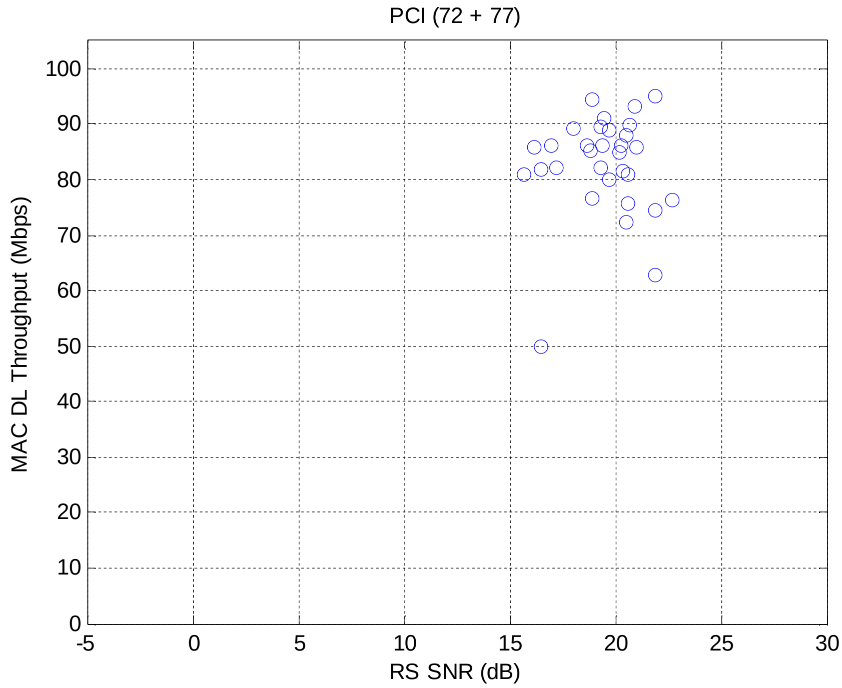

Figure B5. *a) RSRP based results for the range -80 to -70 dBm, Nokia MC.*

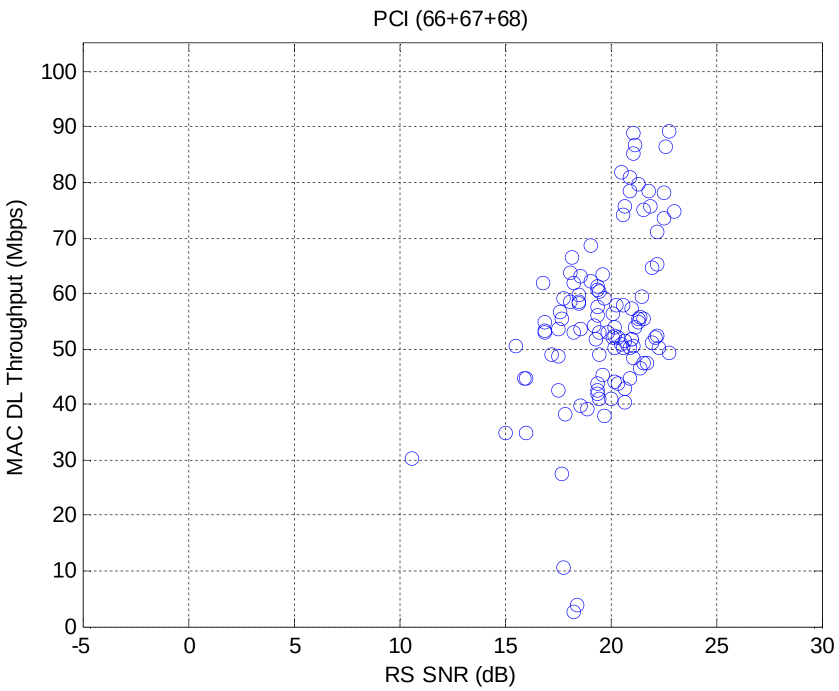

Figure B5. *b) RSRP based results for the range -80 to -70 dBm, Nalkala MC.*