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Measuring Performance of Mobile Broadband Networks under Mobility

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Abstract

Mobile Broadband (MBB) traffic is increasing rapidly, and is estimated to keep growing in future due to the availability of high speed 3G/4G networks and the popularity of mobile devices. People are accessing Internet irrespective of their locations and time thus introducing mobility in the access paradigm and making MBB as a future of the Internet. The expansion of MBB traffic necessitates the detail study of the characteristics of MBB networks with regards to network performance and reliability. It is observed that the literature towards the study of MBB performance mostly concern static scenarios. Therefore, in this thesis, effects of mobility on MBB performance are studied, and the QoS performance of Norwegian MBB networks under mobility are compared to provide a realistic view of the QoS characteristics experienced by the end-users. For this, performance metrics such as delay, packet loss, connectivity are measured for four operational MBB networks under mobility simultaneously using NorNet Edge (NNE), the dedicated testbed for experimentation and measurements in MBB networks. Measurements in different speed are examined to see how speed affects MBB performance. Radio conditions such as Local Area Code (LAC), Cell Identification (CellID) are also investigated to establish relation between the measured performance and physical locations as well as cell attachment and handover behaviors. Mode and Submode are also observed to see 2G/3G networks coverage and packet distribution in HSPA+, HSDPA, HSUPA, WCDMA and EDGE networks. The results of this thesis show that MBB performance is affected (degraded) by mobility, but degree varies with respect to performance metrics. It was found that MBB operators under mobility perform differently even though the underlying technology is same.

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Chapter 1

Introduction

1.1 Motivation

Mobile broadband (MBB) networks form a crucial part of our daily life along with the development of small & multi-purpose mobile devices such as tablets & smart phones and the availability of high capacity 3G & 4G/LTE Internet services. MBB traffic has grown rapidly and is being estimated to grow by 66% annually until 2017 [2]. Although, Wi-Fi has much higher capacity than 3G, Wi-Fi in mobile nodes is challenging due to coverage area of access points (APs), and the connection-quality is a function of the speed under mobility [4]. People are browsing web, sending emails, making VOIP calls in mobile devices irrespective of where they are and what they are doing, due to the ubiquities availability of MBB networks so that Internet access paradigm is changing from static to mobile, and making MBB as a future of the Internet.

Data networks should be available where and when one needed. If users are not satisfied with the connectivity & QoS performance of the MBB networks they have subscribed to, it is natural that they change the Internet service even if it costs more to new service. Therefore, it is important to provide reliable MBB services with good performance.

Objective MBB performance information is required by many stakeholders. Operators can use those information to identify the problems in their networks. Tech business firms can make use of the network performance information not only to develop robust products and services but also to accommodate future trend and requirements. Application designers will get guidelines to develop efficient applications considering the underlying characteristics and behaviors of networks. End users can get information about the performance and reliability of subscribed services and choose the operators that suit them the best.

Although MBB is the major shareholder of future Internet, there are still issues related to performance of MBB specifically under mobility. In order provide realistic performance information to many stakeholders and assuring quality of services to the subscribers of MBB networks, detail study is needed about the performance, stability and reliability under mobility. In literature, most of the research activities on the performance and reliability of MBB networks focus on static cases. This thesis focuses on mobility and studies MBB performance of four 3G UMTS service providers of Norway. This study is carried out in dedicated NorNet Edge (NNE) testbed [1].

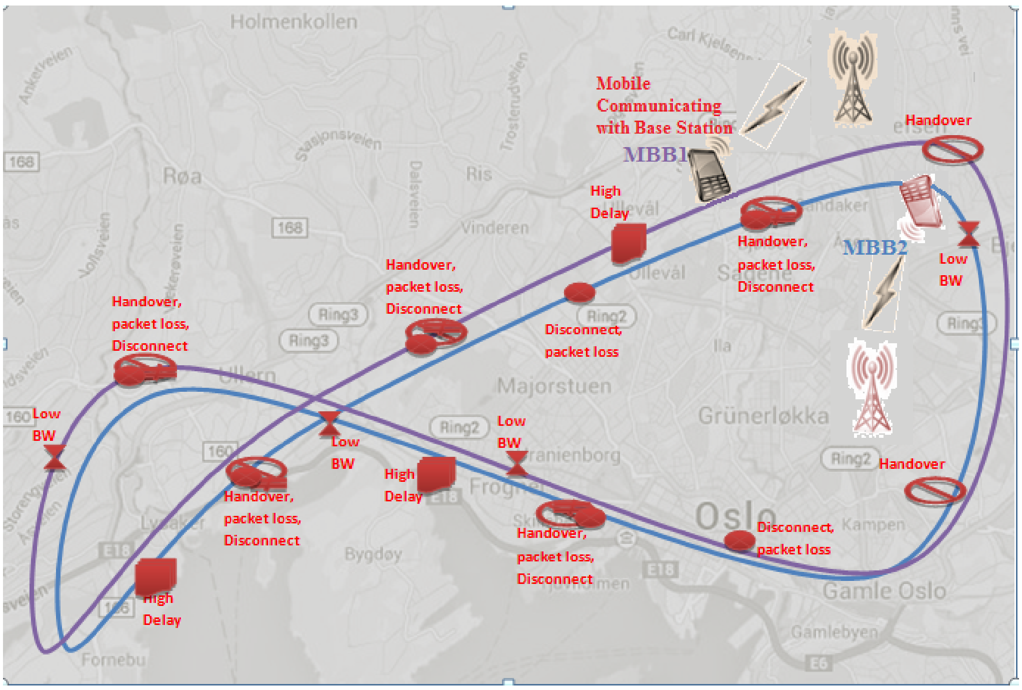


Figure 1.1: MBB events/problems in Mobility

Fig 1.1 shows probable scenario of different MBB networks characteristics/performance under mobility. Different operators have different base stations (BSs) and they are placed geographically different locations affecting signal strength and quality on subscriber's node. Mobile node under mobility may suffer disconnection, packet loss, handover, high delay, low bandwidth, low signal etc. in different places. One MBB network may be good in one area while other MBB in other areas. One network provider may have high delay while other may have high packet loss in particular location. Operators may have different performance in different speed. One Operator might be good in city area, but other in country side. It is worth to know which MBB is better in which performance metrics and where.

In this thesis, performance of four Norwegian MBB operational networks under mobility are measured simultaneously. Measurements are conducted in different locations and time to observe the spatial and temporal variance. The measured performance and behaviors under mobility are compared with regards to different metrics and radio conditions. The study provides mobility performance for multiple operational MBB operators.

1.2 Problem Statement

To measure the effects of mobility on the performance of Mobile Broadband (MBB) networks using NorNet Edge node equipped with GPS and modems. The research tried to answer:

1. "How do MBB networks perform under mobility?" i.e.
    - How does mobility affect QoS characteristics of MBB networks? Is loss, delay and connectivity in mobile scenario different than static?
    - How does handover affect loss, delay and connectivity? Do all handovers cause packet loss, high delay and connection failure? How frequently handover takes place in different networks?
    - Does speed of mobile node affect the performance i.e how MBB performance is affected while node is moving in different speeds i.e. from walking to traveling through bus and train?
    - Which factor affects connection failures, delay and loss more among node's speed, mode/submode change, handover etc.?
    - do the rural networks behave differently than city networks with regard to performance?
2. Do different MBB networks under mobility perform same or differently? If they perform differently, which is good and in which performance parameter? Which is above averages in all performance metrics?

1.3 Measurement Parameters

To measure the quality as experienced by end users, a systematic approach of end to end measurement is necessary. This way of measurement reveals more information compared to monitoring within network. The focus of the research is to measure the QoS characteristics of 3G MBB networks like connectivity, delay, packet loss, and hand off performance. They are measured in static and mobile scenario to study the effects of mobility and to compare QoS characteristics between the operators.

Systematic measurement can be performed with several possible approaches involving different parties:

- Drive tests by the operators to find performance as well as coverage
- Performance tests by end users
- Independent tests on dedicated testbed or measurement infrastructure

From above approaches, third one is chosen in this thesis with dedicated measurement NNE testbed [1]. The measurements are carried out in different parts of Oslo while traveling in public buses, trains and private cars in normal, peak and off-peak hours, week days and weekend, moving with slow and high speed; so that both predictable and less-predictable traffic patterns can be collected with spatial and temporal variance on performance. The summary of the MBB parameters measured in this project work are presented below.

Connectivity
Connectivity is measured as consecutive number of packets received without loss. It is observed that do packets are received continuously throughout the operation or not? MBB connectivity performance is related with frequency of connection disruption. If connectivity is lost, then there might be issues like link down, handover, congestion etc.

Latency
Latency is sum of several kind of delay occurred while processing and transmitting network packets. In 3G MBB networks, the latency highly depends on the type of access networks, protocol, packet loss and MBB providers' specific configuration. In this thesis, uplink latencies, downlink

latencies and overall latencies (RTTs) are evaluated for different traffic patterns and geographical locations. Variation of delay characteristics for different scenarios are also observed.

Packet Loss

Packet loss in 3G MBB networks may occurs due to the congestions, transmission errors over the air interfaces, handover in mobility and insufficient buffers at end points. Packet loss is important QoS requirements of MBB networks. It indicates how reliable the networks are by number of packet loss during communication/transmission. Packet loss also affects latency and available bandwidth. Packets can be lost in uplink or in downlink. In this project, uplink loss is measured as the difference between packets sent by node and received by server where as downlink loss is calculated by the difference of packets sent from server and received by node.

MBB radio conditions

Apart from above mentioned three performance metrics, MBB radio conditions are also measured for all operators simultaneously. MBB mode, submode, LAC and Cell are also measured to study handover behavior, network coverage and characteristics associated with them.

MBB mode and submode

MBB modes like GSM or WCDMA are measured to know 2G or 3G or 4G network coverage. Additionally, submodes like GPRS, EDGE, HSDPA, HSPA, HSPA+ etc are also measured to find the which variant of 2G or 3G is in use in different part of coverage area. The detail of mode and sub mode are discussed in section 2.1.2.

Local Area Code (LAC) and CellID

LAC and CellID give the unique identification of cell that is communicating with mobile. LAC and CellID are changing frequently while mobile changes base stations (Node Bs) and cell coverage area. It is significantly important to measure those cell changes to know point of attachment mobile has in different areas. The details of LAC and CellID are discussed in section 2.1.3.

Receiver Signal Strength Indicator (RSSI)

RSSI is the strength of perceived radio signal that may vary in different location and coverage area for different MBB networks. It is important to measure RSSI in mobility to know whether signal quality of MBB operators is within satisfactory level or not. The details of RSSI is discussed in section 2.1.4.

1.4 Thesis Structure

The whole thesis is structured into six chapters. Chapter 2 describes the literature and background related to problem domain of this research. Chapter 3 explains methodology and approach for measurements, results and analysis. Chapter 4 presents results and analysis of the measured performance parameters. Chapter 5 includes discussion and future work followed by Conclusion on chapter 6. Appendices and Bibliography are presented afterward.

Chapter 2

Background and Literature

2.1 Mobile Broadband (MBB)

Mobile Broadband (MBB) is high speed Internet broadband service designated to broadcast signals to mobile phones, tablets, laptops and other digital devices in significantly larger geographic coverage utilizing wireless technologies [6]. MBB is extending its market share of Internet both in developed and developing countries [25] meeting the consumer needs with improved mobility and extended coverage making content available virtually anywhere and anytime [6]. It is surprisingly taking market share of fixed broadband rising strategic concern to broadband operators [26].

MBB technologies evolved till date are classified in different generations among them 2G and 3G are widely used. 4G is also started to implement but not ubiquitous currently. 5G is in design stage, hopefully will come in future. MBB evolution is presented in figure 2.1 [28].

Global System for Mobile (GSM), General Packet Radio Service (GPRS) and Enhanced Data Rate for GSM Evolution (EDGE) are well known second generation (2G) technologies. GSM is a Time Division Multiple Access (TDMA) based technology that initially used 25 MHz frequency spectrum in 900 MHz band but now also works on 1800 MHz (in US, 850 MHz and 1900 MHz are more prominent) [27]. GPRS and EDGE are some evolutions on GSM to enhance data services as well as to improve Quality of Service (QoS) of 2G MBB networks. Apart from these, IS-95 is also 2G technology which uses Code

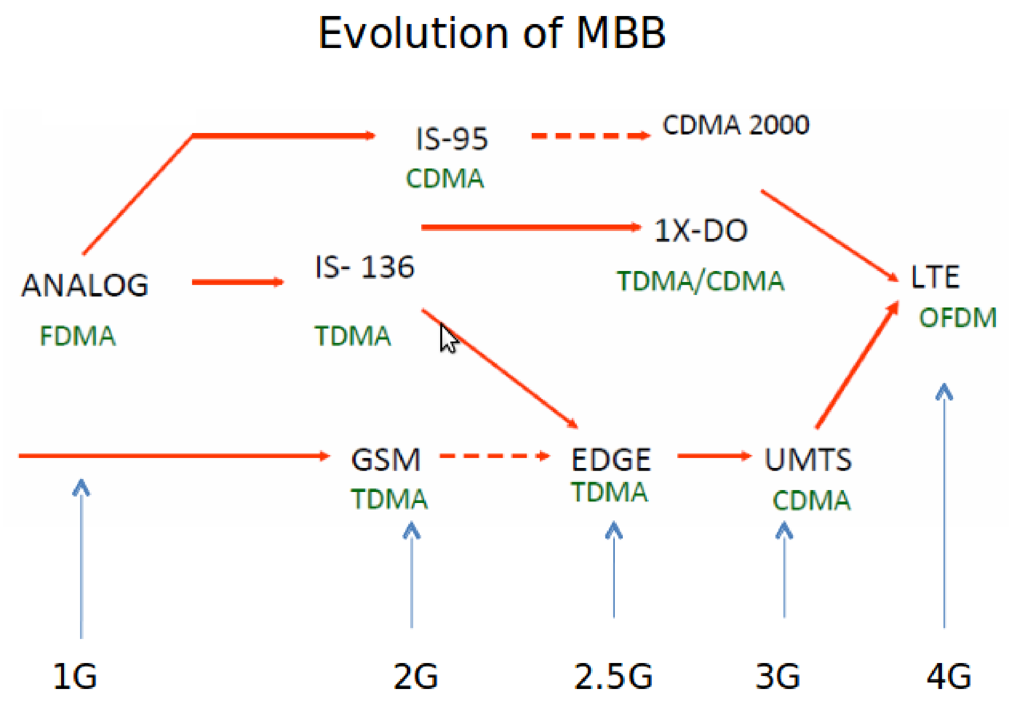


Figure 2.1: MBB Evolution

Division Multiple Access (CDMA).
Third Generation (3G) MBB networks are broadly classified as 3G UMTS (Universal Mobile Telecommunication Services) and 3G CDMA2000. The Third Generation Partnership Project (3GPP)[1] has defined air interface evolution for 3G UMTS technologies like WCDMA (Wide band Code Division Multiple Access), HSPA (High Speed Packet Access), HSPA+ (Evolution of HSPA) etc.[7] fulfilling the IMT-2000 (International Telecommunication Union-2000) specifications. Similarly, 3GPP2[2] standardized CDMA2000. CDMA2000 1xEV-DO (Evolution–Data Optimized) is later stage of the CDMA2000 family standards.

Advanced LTE (Long Term Evolution) and Mobile WiMAX (WiMAX 2) are the examples of Fourth Generation (4G) technologies which fully realized as Mobile broadband. HSPA+, LTE and WiMAX 1 are also considered as pre-4G technologies.

[1] http://www.3gpp.org
[2] http://www.3gpp2.org

Table 2.1 lists MBB technologies from 2G to 4G with their some features and associated bandwidth [29].

Generation	Standard	Bandwidth	Features
2G	TDMA, GSM, CDMA, IS-95, IS-136	14.4 Kbps	digital, voice and short text
2.5G	GPRS, EDGE	Up to 48 Kbps	packetized and digital, voice, data, email, web browsing
3G	IMT 2000, CDMA 2000 (Ev-DO), (EGPRS) EDGE, UMTS, FDMA, TD-SCDMA	144 Kbps to 2 Mbps	digital and broadband, voice, data, video, MMS
3.5G	HSDPA, HSUPA	3.56 Mbps to 14.4 Mbps	digital and broadband, voice, data, video and interconnectivity
4G	Wi-Fi, WiMAX, WI-BRO, LTE	10 Mbps to 1 Gbps	digital, broadband and IP Network, voice, data, video, interconnectivity, lower costs

Table 2.1: MBB generations with standards, speed and features

2.1.1 Third Generation (3G) UMTS and WCDMA

3G started at ITU (International Telecommunication Union) in 1980s, issued first recommendation on 1990s as FPLMTS (Future Public Land Mobile Telecommunication Systems) and later revised as IMT-2000 in 1997. Task Group 8/1 set the initial evaluation criteria for IMT-2000 with data rate for 3G circuit-switched and packet-switched services as listed below [30].

- up to 2 Mbps in indoor condition
- up to 144 Kbps in pedestrian condition
- up to 64 Kbps in vehicular condition

But today 3G systems are deployed beyond those initial benchmark data rates.

3G research in Europe was carried out by RACE (Research into advanced communication in Europe) and 3G was named as UMTS (Universal Mobile Telecommunication Services) in first phase. In second phase research, 3G UMTS is further developed as WCDMA (Wide band CDMA) and Wide band TDMA. At the same time, USA, Japan and Korea also started research work 3G WCDMA[30].

To standardize WCDMA and to harmonize parallel activities towards the 3G research, 3GPP has formed in late 1990s as partnership project of the standards bodies ETSI(Europe), ARIB(Japan), TTC(Japan), TTA(Korea), CCSA(China), ATIS(USA). Simultaneously, 3GPP2 was formed in 1999 to develop specifications for Another 3G technology, called cdma2000 which was developed from 2G CDMA-based standard IS-95 with same partners. Apart from developing specifications for WCDMA, specifications for GSM/EDGE and UTRA(Universal Terrestrial Radio Access) are also developed, maintained and approved in 3GPP in later stage. Specifications developed for WCDMA radio access Release 99 meets the IMT-2000 requirements defined by ITU. Two major addition of radio access features to WCDMA, Release 5 with HSDPA (High Speed Downlink Packet Access) and Release 6 with HSUPA (High Speed Uplink Packet Access) , together referred as HSPA, successor of WCDMA[30].

LTE is another evolution of 3G defined by 3GPP which can operate in new and more complex spectrum without backward compatibility with WCDMA where as HSPA needs to consider backward compatibility. Normally, HSPA doesn't include all the technologies that LTE uses and essentially in HSPA, installed base of equipment can be upgraded to accommodate new features while serving old terminals as well, cost-effective approach. But LTE is free from legacy terminals which is not restricted by older designs, and is purely optimized for IP transmission [30].

2.1.1.1 3G UMTS Networks

UMTS networks are designed for any type of service contrary to GSM, as GSM was originally designed for voice services. Initial UMTS network used 3GPP release 99 specifications for voice and data services.

The 3G UMTS system consists number of logical network elements with defined functionalities for each. Such functionalities are grouped into Radio Access Network (RAN, UMTS Terrestrial RAN- UTRAN) and Core Network (CN). UTRAN is responsible for Radio related functionality where as CN handles data connections to external networks as well as switching and routing calls. User Equipments (UEs) is third subsystem of UMTS which interfaces user with radio interface as depicted in Fig 2.2 [31].

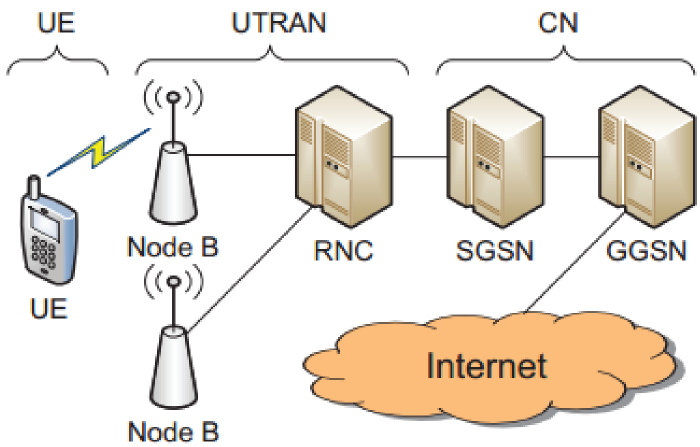


Figure 2.2: UMTS Architectureumts

UMTS standards defined open interfaces between logical network elements as shown in Fig. 2.4. The main such interfaces are shown below.
Cu interface: Electrical interface between ME and USIM
Uu Interface: WCDMA radio interface which is used by UE to access fixed part of the UMTS system and considered as most important UMTS interface.
Iu Interface: Interface that is used to connect UTRAN to CN
Iur Interface: This interface is responsible for soft handover between RNCs.
Iub Interface: This interface connect RNC and Node B

In UMTS, a common core network can support multiple radio-access networks like GSM, GPRS, EDGE, WCDMA, HSPA and their evolutions, providing flexibility to operators for different service to customers in their coverage area as shown in Fig 2.3 [34].

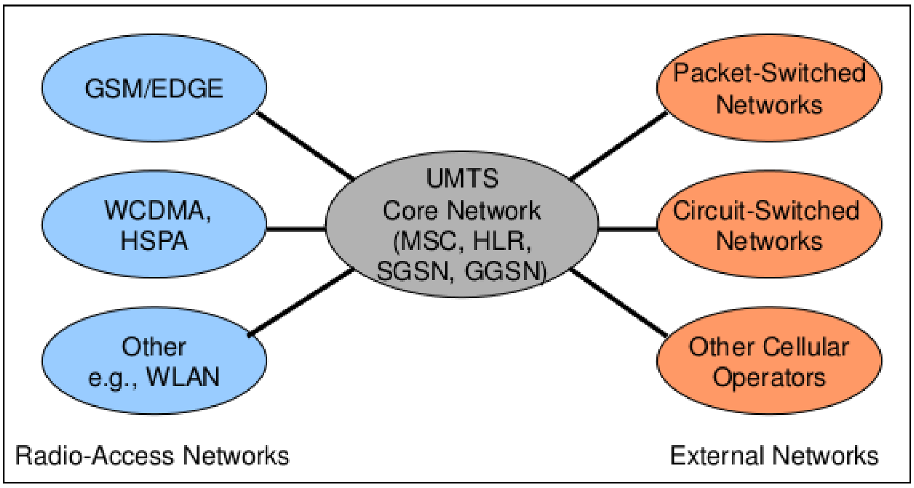


Figure 2.3: UMTS Multi Radio-Access Networks

2.1.1.1.1 UMTS service Applications

Some examples of UMTS services applications are:
Circuit-switched services: Adaptive Multi Rate (AMR) Video Telephony and voice service

Packet-switched services: Image and Multimedia (MMS, Real time video sharing), Push-to-Talk over Cellular (PoC), Voice over IP (VOIP), Multi player games etc.

MMS (Multimedia messaging): MMS is enhanced SMS (short message services) from user perspective [30]. The essential requirements for successful MMS are reliability and delivery time. It should be possible to send MMS at same time to voice call, so both mobile station and network are able to handle multiple radio access parallel.

Real time video/audio sharing: Video sharing can be one way video sharing/streaming or two way video sharing as per the requirements and available bandwidth. The performance requirements for real time video sharing are image quality and update rates, delay between taking picture and showing in other sides (e.g. less than 5sec) etc. The UMTS network should be able to deliver reasonably constant high data rate and concurrent voice connections in case of packet-switched voice services for low delay video sharing.

Apart from these, other UMTS services are: Browsing, Audio and Video streaming, Content Download, Multimedia Broadcast/Multicast services and Business connectivity.

2.1.1.1.2 UMTS Terrestrial Radio Access Network (UTRAN)

UTRAN is composed of one or more Radio Network subsystems (RNS) as sub-network within UTRAN. Each RNS consists of one Radio Network Controller (RNC) and one or more base stations (Node-Bs) as shown in fig 2.4 [30].

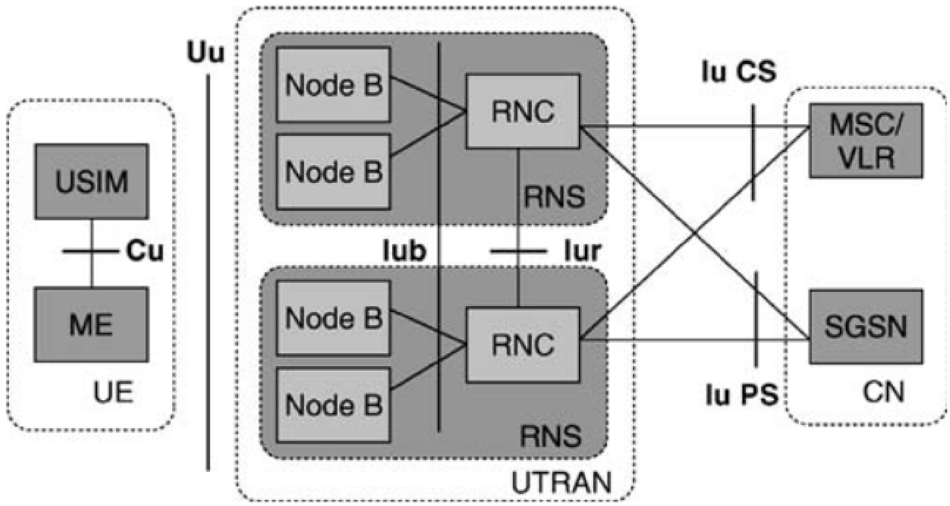


Figure 2.4: UTRAN architecture and interfaces to connect with UE and CN

RNC is responsible for owning and controlling of radio resources of UTRAN. RNC terminates the RRC protocol between mobile and UTRAN and also interfaces CN. RNC can be viewed as service access point for all services UTRAN provides to the CN, for e.g. management of connections to the UE. It controls base stations (Node Bs) whose main function is to perform air interface L1 processing (channel coding & interleaving, rate adaption etc.). Additionally, Node-B is also responsible for basic Radio Resource Management (RSM) like inner loop power control.

2.1.1.1.3 User Equipment (UE)

UE has two parts: Mobile Equipment (ME) and UMTS Subscriber Identity Module (USIM). ME is radio terminal used for radio communication. On the other hand, USIM is a smart card holding subscriber identity. It performs authentication using stored encryption and authentication keys as well as subscription information that is required by terminal.

2.1.1.1.4 Core Network (CN)

CN consists of Home Location Register (HLR), Mobile Service switching Center/Visitor Location Register (MSC/VLR), Gateway MSC (GMSC), Serving GPRS Support Node (SGSN) and Gateway GPRS Support Node (GGSN). HLR is a database which stores main copy of user's service profile and located in user's home system. MSC/VLR is switch cum database that serves UE. MSC switches the Circuit-switched (CS) transactions where as VLR keeps track the copy of visiting user's service profile. GMSC is the gateway for all incoming and outgoing CS connections. SGSN works same functions as MSC/VLR do but for packet-switched (PS) services. GGSN is gateway for all incoming and outgoing CS connections as GMSC do for CS domain.

2.1.1.1.5 UE's modes and Radio Resource Control (RRC) state

RNC enables UE to connect to CN and keeps track of UE's RRC states in idle or connected mode. In case of connected mode, each UE's is assigned RRC state and kept track by RNC in Node B. There are mainly three typical UE's RRC service states, which are: IDLE, Cell_DCH (Dedicated channel) and Cell_FACH (Forward Access Chanel), basically differs from what kind of physical channels a UE is using. IDLE is disconnected state where as Cell_DCH and Cell_FACH are connected state. Cell_DCH is for high bandwidth data transmission where as Cell_FACH for low bandwidth [9]. Cell_DCH, as name suggested, dedicated to single UE and limited per Node B. UE's modes and RRC states are depicted in Fig 2.5 [30].

IDLE: When UE is switched on, it will by default in IDLE mode. It then selects a PLMN (Public Land Mobile Network) to contact, searches suitable cell of

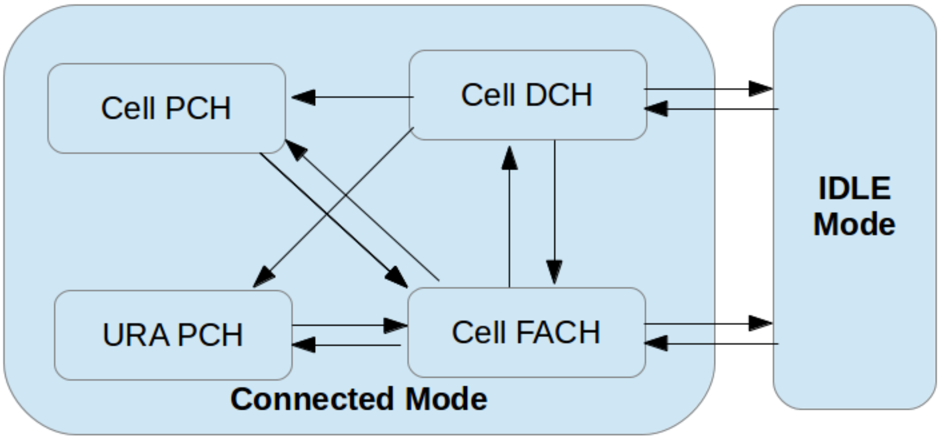


Figure 2.5: UE modes and RRC state of 3G UMTS

that PLMN to provide available services and tunes to its control channel. After this cell search procedure, UE is able to receive system information and cell broadcast message but stays in IDLE mode until it requests to establish RRC connection. In IDLE state, UE is identified as non-access identities such as IMSI (International Mobile Subscriber Identity), TMSI (Temporary Mobile Subscriber Identity), and P-TMSI (Packet Temporary Subscriber Identity) but UTRAN can only address all UEs in a cell as UTRAN has no information of individual IDLE mode UEs. After RRC connection failed or released, UE is returned back to IDLE mode from connected mode.

Cell_DCH: In Cell_DCH state, a physical channel is allocated for the UE. The UE is either known by active set level or its serving RNC on a cell. In this state, UE is able to perform measurements according to measurement control information received from RNC and sends measurement reports. In this state, UEs with some capabilities are able to see system information message in FACH channel.

Cell_FACH: There is no dedicated channel in Cell_FACH state but FACH and RACH channel are used to send both user plane data and signaling message. In Cell_FACH state, UE is capable to listen broadcast channel (BCH) to get system information. In this state, UE performs cell re-selections, followed by sending Cell Update message to RNC to inform RNC about UE location in cell level.

Apart from these important states, some additional states in connected mode are Cell_PCH and URA_PCH.

Cell_PCH (Cell Paging Channel): This state is only reachable through paging channel (PCH), though it is also considered as state on a cell level in SRNC. In this state, a UE also listens on BCH for system information. If a UE executes a cell reselection, it directs independently to Cell_FACH state to run cell update procedure, and if no other activities requested during cell update procedure, UE returns to Cell-PCH state.

URA_PCH (UTRAN Registration Area Paging Channel): URA_PCH doesn't execute Cell Update Procedure every time after cell reselection, otherwise similar to Cell_PCH. It runs Cell updates only if UTRAN registration area (URA) changes after cell reselection which is notified from BCH. URA update procedure is triggered if UE can't find its latest URA identification from list of URAs, as one cell can be associated with one or many URAs.

The RRC of 3G CDMA2000 is similar to 3G UMTS [30] and is tracked by PDSN (Packet Data Serving Node). 3G CDMA primarily consists three states: INACTIVE, ACTIVE and DORMANT [33] plus one additional CONTROL HOLD MODE, in some configuration to reduce delay between ACTIVE and DORMANT states. No data transfer takes place in DORMANT state and no signaling between base station and UE but registration for packet data service is maintained.

2.1.1.2 Radio Resource Management

Efficient utilization of radio air interfaces is handled by Radio Resource Management (RRM) algorithms for different functions such as power control, admission control, handover control, packet scheduling and load control. Power control is essential to maintain required quality of services and interface levels at minimum in the air interface. Handover control is associated with cellular systems under mobility of mobile node across cell boundaries. Packet scheduling, load control and admission control are responsible to maintain guaranteed QoS as well as to maximize system throughput in 3G networks [30].

2.1.1.2.1 Handover Control

Handover is mechanism which switches the user's connection from one cell to another with the requirements of minimizing service interruption and providing seamless handover. When user equipment (UE) moves towards area where signal strengths it receives from cell associated with it is marginally lower than neighbor cell or base station, then handover is triggered [19]. With the additions of applications like Skype, Facebook, MSN Messenger etc. handovers are expected to increase as such applications send periodic keep alive messages to the UE making active data transfers even the applications are not in active use [18]. The Main functions during handover procedure are: handover measurement and handover decision-execution [16]. Handover measurement deals with measuring service quality of serving cell with signal strength and discovering appropriate cell when handover is necessary.

Handover decision-execution evaluates if handover is necessary or not and if it is required, it coordinates multi-party handshaking among users and cells for transparent and smooth handover. In mobile-assisted network-controlled handover, mobile assists to make handover decision by measuring the signal quality of its neighbor cells and report the results to the network system followed by synchronization with neighbor cell and calculation of the signal quality of the cell such as Signal to interference plus noise ratio (SINR) [17].

3G permits that adjacent cells can operate in same frequency band which enables the mobile node to detect several such neighbor cells that is also refereed as intra-frequency cells [15]. The numbers of cells mobile can scan per measurement period is called mobile's measurement capability. Higher the measurement capability, higher will be the handover measurement and Handover [17].

Handover can be hard handover or soft handover. Soft handover implements make-before-break strategy i.e. mobile node communicates with several base stations or cells and make a new connection to a cell before breaking connection to old cell [20]. Where as in hard handover, mobile node changes cell trying to minimize interruption. Handover can be classified differently as horizontal handover and vertical handover. Handover between same type of network is considered as Horizontal handover where as handover between dissimilar access technologies is vertical handover [21].

In HSDPA, mobile node can be connected to only single serving cell or Node B which leads to hard handover procedure but the associated DCH itself can be soft handover and maintain DCH active set [22]. Handover procedure is initiated when a link in DCH active set is maintained in higher strength for certain period, also called time-to-trigger followed by measurement report sent from UE to Node B and then forwards to RNC. Then UE is consented by RNC to make handover by sending signaling radio bearer (SRB) message if admission control requirements are satisfied. In case of Intra Node B handover, there is minimal interruption of data flow by maintaining Node B buffers where as in inter Node B handover, Node B buffers are flushed. In HSUPA, mobile node can transmit to two or more cells simultaneously leading to soft handover procedure similar to WCDMA Rel'99 [23]. HSPA+ supports both soft and hard handover.

Different types of WCDMA handovers, their measurements and reason are summarized in table 2.2 [30].

Handover type	**Handover measurements**	**Handover measurement reporting from UE to RNC**	**Typical handover reason**
WCDMA intra-frequency	Measurements all the time with matched filter	Event-triggered reporting	normal mobility
WCDMA to GSM inter-system	Measurement started only when needed, compressed mode used	periodic during compressed mode	coverage
WCDMA inter-frequency	Measurement started only when needed, compressed mode used	periodic during compressed mode	load, service, coverage

Table 2.2: WCDMA handover types

2.1.1.2.2 Power Control

There should be mechanism to keep received power levels of mobile stations equal all times, otherwise single overpowered mobile station could block whole cell, also called near-far problem. To address this issue, fast closed loop power control can be used in WCDMA.

Fast closed loop power control

In GSM, only slow power control in 2Hz is used, where as fast power control in 1.5KHz can be used in both uplink and downlink of WCDMA. Slow power control addresses the path loss and shadowing issue but not fast fading, So fast power control is needed and more effective in slow speed mobile nodes. In uplink, received Signal-to-Interface Ratio (SIR) estimated by base station is compared with target SIR. If estimated SIR is too higher or smaller than target SIR, base station gives command to mobile station to decreases or increases its power. In downlink, a base station originates all the signals to all mobiles within one cell. In cell edge, some additional power is desirable due to other-cell interference. Enhancing weak signals caused by Rayleigh fading with additional power at low speed is also needed in downlink [30].

Outer loop power control

Target SIR set point in base station is adjusted by outer loop power control as per the needs of each radio link and constant quality requirements defined with bit error rate (BER) and block error rate (BLER). BLER depends on multipath profile and mobile node speed. If SIR is set with in high mobile speed and is worked in low speed, much of the connections' capacity is wasted and demanded to change target SIR in such worst case. Outer loop power control is normally implemented within RNC, typically after soft handover with the tagged uplink user data frame with CRC by base station during decoding procedure. When CRC indicates RNC about decreased transmission quality, RNC gives signal to base station to increase target SIR set point[30].

Outer loop power control is needed in case of WCDMA since there is fast power control in both uplink and downlink. In this case, uplink outer loop is located in RNC whereas downlink power control in mobile station.

2.1.1.2.3 Load Control/Congestion Control

RRM measures load of radio air interface and control not to be overloaded and maintains stable system. If appropriate admission control and packet scheduling algorithms are implemented, it is rare case that system can be overloaded and if overloaded by the way, load control functions quickly returns system back to the defined targeted load. Some such load control functions are [30]:

- Decrease the packet data traffic throughput
- Reduce uplink target set with fast power control
- Reduce downlink fast load control by denying power-up commands from UE
- Ignore/drop less important calls
- Reduce bit rates of UE working in real time
- Handover to another career/system

2.1.1.2.4 Admission Control

Admission control algorithm accepts or rejects admission request of mobile node into radio access networks. This important RRM function is implemented in RNC, where load information is collected from different cells. Admission of new UE into existing coverage area of a cell has to be done with controlled fashion so that it doesn't hinder service quality and planned values. Both uplink and downlink admission control procedure need to be evaluated before making decision to admit. If not, new bearer can produce excessive interference in the network. Such different admission control mechanisms are [30]:

Wideband power-based admission control: new mobile station is not allowed to admit by uplink admission control algorithm if total interference is greater than threshold interference, same as maximum uplink noise rise and the algorithm is also called inference-based admission control algorithm[30]. $I\_total\_old + I\_increased < I\_threshold$

Throughput-based admission control: New UE is admitted into radio access network if total uplink load is less than threshold uplink load and total download load is also less than threshold downlink load as shown below[30].
$Load\_up + Load\_Increased < Load\_threshold\_up$
$Load\_down + Load\_Increased < Load\_threshold\_down$

2.1.1.2.5 Packet Scheduling

Packet scheduling is crucial functions of RRM, which deals with non real time traffic (elastic traffic) and tries to maintain desired quality of service by allocating optimum bit rates of multiple connections and schedules packet data transmissions [38]. Elastic traffic is transmitted over common or shared channel in contrary to real time traffic that is transmitted in dedicated channel[39].

Elastic traffic shares same code in common packet channel (CPCH) in uplink and downlink shared channel (DSCH) in downlink along with admission control algorithm to maximize the number of flows while maintaining QoS. Packet scheduler manages the resources for elastic traffic users overs shared channels aiming to meet performance targets like fair time share, fair throughput and optimum throughput[30].

Fair Throughput (FT) packet scheduling
In FT packet scheduling, power left by other connections is fairly shared among bearer services for each scheduling period in terms of throughput i.e. all users get equal bit rates ideally . If available power is quite enough, all users get the maximum possible bit rates they are requested satisfying the Power allowed to share, given by [40]
$P\_allowed = P\_target - (P\_a + P\_i, GB + KP\_i, DTX) - - - - - -(I)$

where P_target is planned transmission power, P_a is power of all active connections, P_i,GB is guaranteed power for just admitted but not active connection and P_i,DTX is reserved power for discontinuous connections in IDLE or reading period. K is either 0 or 1 where 1 indicates IDLE or reading period.

Fair Resources (FR) packet scheduling
In FR packet scheduling, all users receive same amount of available power. Users don't get equal bit rates unlike FT as their bit rates depends on signal to interference ratio which means users near to base stations are likely to get more bit rates than users who are far from base stations (Node Bs)[40]. Similarly, power-allowed can be computed by equation (I).

Packet scheduling can also be studied in different components like user-specific packet scheduling and cell-specific packet scheduling. User-specific packet scheduling is responsible for the effective utilization of radio resource transport channels, control states and their bit rates as per traffic volume where as cell-specific part takes care the sharing of radio resources between users[40].

2.1.2 MBB Modes and Submodes

Popular mobile broadband connection mode for 2G networks is GSM and for 3G is WCDMA. GPRS and EDGE are mainly used submodes in GSM where as HSPA+, HSUPA, HSDPA, HSPA (HSDPA+HSUPA) and are main radio access connection submodes in WCDMA.

2.1.2.1 GSM, GPRS and EDGE

GSM is widely deployed TDMA based cellular technology which operate like spread-spectrum systems and provides voice as well as data service via GPRS/EDGE as depicted in Fig 2.6[34]. GPRS is the fundamental data service for GSM where as EDGE enhances GPRS data capability. GPRS with EDGE radio interface is called Enhanced GPRS (EGPRS). GPRS and EDGE both provide packet based IP connectivity solution and operate as wireless extension to the Internet with convenience to connect from anywhere. EDGE can give up to 200 kbps peak bandwidth where as GPRS can work only up to 40 Kbps.

The function of basic data elements are[34]:

- The base station controller receives/sends packets from/to the serving GPRS Support Node (SGSN), which authenticates and tracks the location

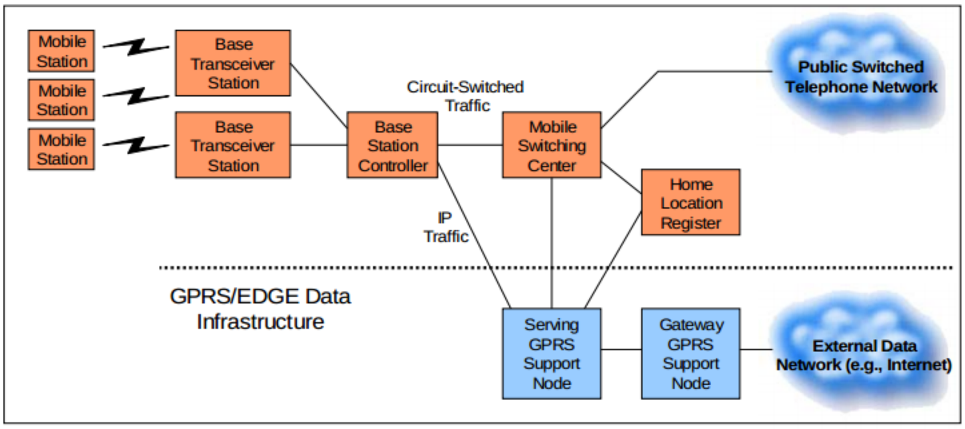


Figure 2.6: GSM/GPRS/EDGE Architecture

of mobile station and functions similar services for data that Mobile Switching Center (MSC) performs for voice.

- The SGGN receives/forwards user data from/to the Gateway GPRS Support Node (GGSN) as mobile IP router to external IP networks. Furthermore, GGSN is responsible for dynamic assignment of IP addresses to mobile stations for their data sessions.

- Home Location Register (HLR) keeps account information of users for both voice and data. This same data service architecture can be supported in both GSM as well as UMTS-HSPA networks, making upgrade simple.

GSM uses radio link of 200 KHz width, which is structured as eight time-slots of 577 microseconds repeating in every 4.6 msec [39]. Each cell can have multiple such radio channels. Each time-slots can have different tasks assigned by networks such as Broadcast Control Channel (BCCH), packet broadcast control channel (PBCCH),packet data channels and circuit-switched functions like voice calls as well as data calls. Dynamic adjustment of voice and data channels capacity reserving minimum resources for each service is the beauty of of GSM/EDGE which allows more data traffics when voice traffic is low and vice versa.

EDGE can be used in 850, 900, 1800 and 1900MHz spectrum bands. EDGE is fully backward compatible with older GSM, which leads that both GPRS and EDGE can operate simultaneously and applications developed for GPRS can be used with EDGE.

Evolved EDGE is further enhancement of EDGE capabilities in release 7 considering the widespread infrastructure of GSM networks and less costly as compared to upgrading to UMTS. Evolved EDGE is improved in data rates, system capacity, cable modem speed, latency and spectral efficiency[34]. Evolved EDGE offers improved service continuity between EDGE and HSPA so the users can move between these technologies without significant different experience.

2.1.2.2 WCDMA, HSDPA, HSUPA, HSPA, and HSPA+

Wideband Code Division Multiple Access (WCDMA) is Frequency Division Duplex (FDD) mode of UMTS, a popular mode than TD-CDMA (Time Division CDMA) that is Time Division Duplex (TDD) mode of UMTS. In FDD, different radio bands are used to transmit and receive; where as in TDD, both functions on same radio bands in different time-slots alternatively. WCDMA is direct sequence spread spectrum system, spectrally more efficient than GSM [30]. Wide band naturally able to translate the available spectrum into high data rates and flexibility to manage multiple traffics like voice, narrowband data as well as wideband data.
WCDMA created new horizon of advanced capabilities in UMTS such as [30]:

- high data rate beyond 10 Mbps in 3GPP release 5.
- Voice and data capability simultaneously
- compatibility with existing GSM/GPRS networks
- low RTT (delay) less than 200 ms
- Quality of service (QoS) for high efficiency of service delivery
- seamless mobility for packet data

3GPP defined HSDPA and HSUPA in Release 5 and Release 6 respectively. HSPA supports both HSDPA and HSUPA so HSDPA+HSUPA is refers HSPA [34]. HSPA+ is evolution of HSPA to maximize CDMA-based radio performance initiated in 3GPP Release 7 and continue till Release 11. HSUPA, HSDPA, HSPA and HSPA+ are enhancements and optimizations in CDMA based systems and studied as connection submode of WCDMA [30].

HSDPA improves downlink performance. It provides better network performance for packet-data service under loaded conditions, lower latency, greater range of applications with faster application performance and increased productivity. To achieve those features it implements techniques like higher order modulation, high-speed shared channels, short transmission time interval (TTI), fast scheduling, fast link adaption, variable coding and soft combining. On the basis of these features and techniques, HSDPA is able to provide new classes of applications and supports huge number of users access the network compared to WCDMA release 99. Table 2.3 gives the HSDPA categories and corresponding downlink speed [35].

HSDPA Categories	**speed (Mbps)**
Category 1	1.2
Category 2	1.2
Category 3	1.8
Category 4	1.8
Category 5	3.6
Category 6	3.6
Category 7	7.2
Category 8	7.2
Category 9	10.2
Category 10	14.4

Table 2.3: HSDPA Categories and speed

HSUPA enhances uplink performance. It increases throughputs, reduces latency and improves spectral efficiency. To achieve such enhancements, it implements approaches such as enhanced dedicated physical channel (EDCH), short transmission time interval (TTI), fast Node-B based scheduling and fast hybrid ARQ. HSUPA can be used for uplink with or without HSDPA in downlink, mostly together. Similar to HSDPA, HSUPA provides different speed based on number of codes used, TTI value, spreading factors of the codes and transport block size. Table 2.4 gives the HSDPA categories and associated uplink speed [35].

HSUPA Categories	**speed (Mbps)**
Category 1	0.73
Category 2	1.46
Category 3	1.46
Category 4	2.93
Category 5	2.00
Category 6	5.76
Category 7	11.5

Table 2.4: HSUPA Categories and speed

Evolved HSPA (HSPA+) is designed to exploit existing radio access technologies significantly increasing DSP (Digital Signal Processing) power. The notable technical enhancements in HSPA+ are advanced receivers, continuous packet connectivity, MIMO (Multiple-Input Multiple-Output) and higher order modulation[34]. With these techniques, HSPA+ enables packet-only mode for both data and voice; facilitates operation between LTE and HSPA+ by providing smooth inter-networking between them; uses full potential of CDMA technology, eases migration between HSPA and HSPA+, and makes itself backward compatible without performance degradation. Table 2.5 lists the throughput of evolved HSPA with different Releases [34].
M

2.1.3 CellID and Location Area Code (LAC)

In GSM or UMTS, cell is a base station having coverage of small geographic area, is a part of location area uniquely identified by code called location area code (LAC) [47] . CellID along with location area code (LAC) uniquely identify the Base Station (BS). Group of base stations share Base Station Controller (BSC) in GSM and Radio Network Controller (RNC) in 3G UMTS. LAC is broadcasted by base stations in regular intervals by BTS in GSM and Node B in UMTS. When a mobile node moves from one location area to another, it informs new as well as old location area to network through location update procedure together with temporary mobile subscriber identity (TMSI)[37].

Location area should be of average size. There will be very high paging traffic If it is too big, since many mobile nodes are operating simultaneously. This results

Technology	**Downlink peak data rate (Mbps)**	**Uplink peak data rate (Mbps)**
HSPA as defined in Release 6	14.4	5.76
Release 7 HSPA+ DL 64 QAM, UL 16 QAM, 5/5 MHz	21.1	11.5
Release 7 HSPA+ 2X2 MIMO, DL 16 QAM, UL 16 QAM, 5/5 MHz	28.0	11.5
Release 8 HSPA+ 2X2 MIMO DL 64 QAM, UL 16 QAM, 5/5 MHz	42.2	11.5
Release 8 HSPA+ (no MIMO) Dual Carrier, 10/5 MHz	42.2	11.5
Release 9 HSPA+ 2X2 MIMO, Dual Carrier DL and UL, 10/10 MHz	84.0	23.0
Release 10 HSPA+ 2X2 MIMO,Quad Carrier DL, Dual Carrier UL, 20/10 MHz	168.0	23.0
Release 11 HSPA+ 2X2 MIMO DL and UL, 8 Carrier DL, Dual Carrier UL, 40/10 MHz	336.0	69.0

Table 2.5: HSPA+ Throughputs

in wastage of bandwidth and power in mobile requiring to listen broadcast message very often. If it is too small, mobile node needs to contact the network frequently while changing the location, resulting wastage of power in mobile.

2.1.4 Receiver Signal Strength Indicator (RSSI)

Receiver Signal Strength Indicator (RSSI) measures the signal strength of perceived radio signals. Strength of radio frequency signal can be measured in different ways. Signal strength can be measured in mW, dBm (db-milliwatts) and RSSI integer value. In MW, signal is measured as energy where as dBm is logarithmic measurement of signal strength. In RSSI integer value, one byte integer range from 0 to 255 (RSSI_Max) but normally RSSI_Max is lower than 255 and vendor/technology dependent, like CISCO chooses 100 as RSSI_Max i.e. value range is 0-100. Some MBB systems uses range 0 to 31 (0 means "-113 dBm or less" and 31 means "-51 dBm or greater" For UMTS).

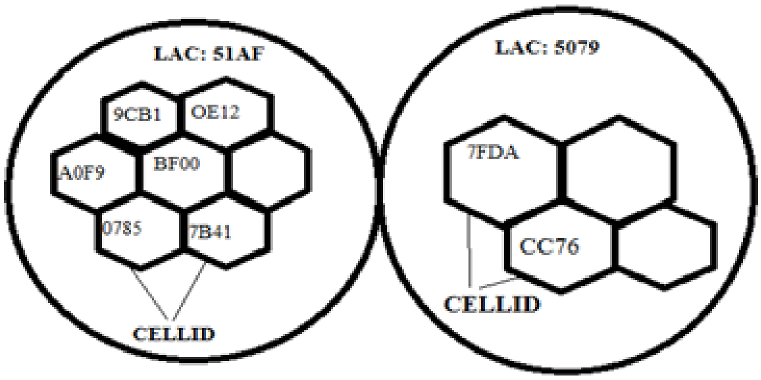


Figure 2.7: Example LAC and CELLID, Telenor Norway

2.1.5 Mobile Country Code (MCC) and Mobile Network Code(MNC)

Mobile Country Code (MCC) is a code to identify a country which a mobile subscribers belongs to. When MCC is combined with Mobile Network Code (MNC), it can uniquely identify a mobile subscriber network [36]. MCC/MNC is also called Home Network Identity (HNI). When MCC/MNC is added with Mobile Subscriber Identification number (MSIN), International Mobile Subscriber Identity (IMSI) is formed. IMSI is unique number, usually 15 digits, of GSM or UMTS network mobile system to identify subscriber and is stored in Subscriber Identity Module(SIM).
MCC of Norway is 242 and list of MCC/MNC[3] for mobile subscribers in Norway are depicted in Table 2.6.

2.2 Nornet Edge- MBB measurment platform

Nornet Edge (NNE)[1]is dedicated testbed to measure the performance metrics of multiple operational MBB networks simultaneously. NNE consists of NNE nodes and NNE backend system as shown in Fig 2.8 [1]. NNE node measures MBB network performance and NNE backend stores, processes and visualizes measured data.

Nornet EDGE has already deployed more than 400 nodes in more than 80 communes of Norway for static measurements to support electronic voting

[3] http://www.mcc-mnc.com

MCC	MNC	Network / Mobile Providers
242	01	Telenor
242	02	Netcom
242	03	Teletopia
242	04	Tele2
242	05	Network Norway
242	6	ICE
242	07	Ventelo
242	08	TDC Mobil
242	23	Licamobile

Table 2.6: MCC-MNC of Norway

providing multihoming. The measured performance can be influenced by MBB modems, radio-access network, operating system, transport protocol and MBB core network.

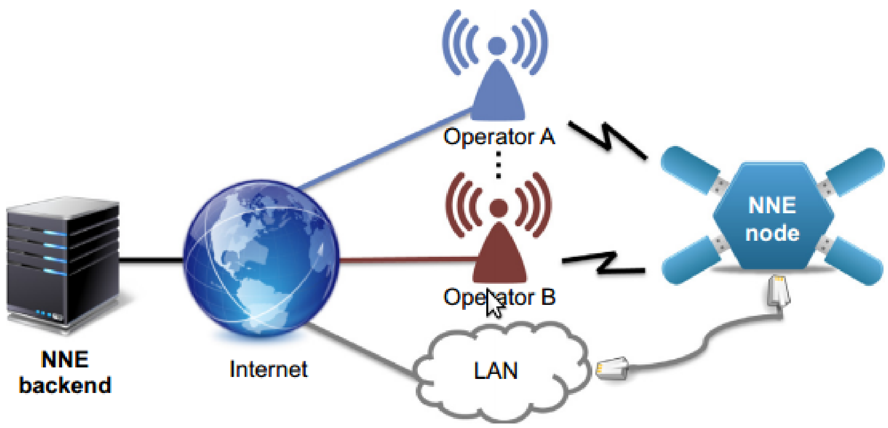


Figure 2.8: NNE Infrastructure

2.2.1 NNE Node

An NNE node is a small computer which runs standard Linux distribution, currently kernel version 3.0.8. Node is standardized with single hardware configuration for easy administration of node. It is single board computer with Samsung S5PV210 Cortex A8 1 GHz processor. One Fast Ethernet port, optionally a Wi-Fi module and 7 USB ports are embedded on the node. Node has 512 MB RAM , 512 MB Flash memory and 16 GB SD storage.

1 to 4 UMTS modems (chosen for four RNC network operators of Norway: Telenor, Netcom, Tele2 and Network Norway) which support up to HSPA+ (3.5 G) and 1 CDMA (1 x EV-DO) modem (for ICE data service) are used in node to measure MBB parameters. For MBB measurement under Mobility, a GPS dongle is also connected to one USB port. Each NNE node has given unique ID like NNE306. Apart from above technical specifications, there are different software components running on NNE node providing management and support functions, some of these functions are listed below [1].

- *SSH connection*: NNE node can be accessed with reverse SSH via autossh, as most of the nodes don't have fixed IP address. SSH connection is established with default route with lowest metric, in case of more than one route available and if default down, autossh process restarted to make SSH connection through next available connection with lowest metric.
- *Usbmodem-listener*: Modem management, cellular connection management and metadata management functions are handled by Usbmodem-listener, a daemon written in python. Such metadata information might be CellID, LAC, Signal Strength, connection mode and submodes and RRC state parameters.
- *MULTI*: MULTI [3] is command line network manager for Linux with multihoming support and used to manage network connections. It automatically detects when interfaces are connected/disconnected and configures routing tables after acquiring IP addresses.

2.3 Transport Protocols and Mobility Support

There are different transport layer protocols that can be used by different applications. The same set of protocols can be used for mobility support with single end-to-end connection path. Mostly used such mobile transport protocols are:

Transmission Control Protocol (TCP)

TCP is connection oriented transport layer protocol normally used for loss sensitive and delay tolerant applications such as email, web, file transfer etc. It provides reliable means of end-to-end transmission with flow control and congestion control mechanism. With the support of TCP along with IP, users at application layer can send byte stream to the destination [42]. In TCP transmission, lost packets are retransmitted to provide guaranteed delivery, but may introduce some delay and performance issues. In TCP/IP, byte stream includes minimum 40 bytes header, including TCP header of 20 bytes. Standard TCP is for single one to one connection which does not support multipath and multihoming [41].

User Datagram Protocol (UDP)
UDP is connection less transport layer protocol for loss tolerant and delay sensitive applications such as real time traffics, multimedia applications, VOIP etc. UDP does not provide reliable data transmission and lacks flow control as well as congestion control mechanisms. UDP , like TCP, doesn't support multihoming. It allows to transfer data without connection setup and in unordered way contrary to TCP. Since the header size of UDP is only 8 bytes, UDP is more simpler packet format and fast as compared to TCP because there is no need to establish connection.[41]

Stream Control Transmission protocol (SCTP)
SCTP is connection oriented transport layer protocols initially designed to send PSTN signals into IP packet network which can also be used for multipath communication. It provides congestion control, flow control and reliable ordered data delivery similar to TCP [43]. Additionally, SCTP provides network level fault tolerance with multihoming support. Though standard SCTP supports multiple IP address, there is no means to use them all at the same time. Concurrent Multipath Transfer SCTP (CMT-SCTP) facilitates multiple end to end data transfer using multiple address at same time [44]. But CMT-SCTP has performance issues over wireless networks [45].

Mobility
Mobility is very important and unavoidable component of today's communication. The notable advantages of mobility are:

- users can be connected to network anywhere within operators radio access network

- services are maintained to the users by handover to the cells closer to the users when users move

- users are able to communicate via visiting foreign operators networks in case of international roaming services

so seamless mobility and smooth handover are important design requirements of all cellular networks. Some of mobility design requirements are:

- non-real time data should not be lost during service break during handover
- service break, failures and drops should be minimized even in case of real time data, as tearing down and setting up new connections may cause significant degradation of performance
- handovers should work on Make-before-break principle

Mobile IP
Mobile IP (MIP) is implementation of scalable mechanism of mobility support in network/Internet layer and defined for both IPV6 and IPV4. A mobile node having MIP moves in different areas in changing its point of attachment with Internet and preserving established communications [5]. When MIP in use there are different components involved such as Mobile Node (MN), Correspondent Node (CN), Home Network (HN), visited Network (VN), Home Agent (HA), Home Address (HoA), Care of Address (CoA). HoA is stable address for MN whenever it is within its HN. While MN moves from HN to VN, it acquires CoA which is used for all communications between MN and CN. However, those communication normally go through HA and HA tunnels the data/packet destined to MN to its new location, CoA [5].

MIPv4 only supports communication between CN and MN through HA, where as MIPv6 supports two ways: direct communication between CN and MN, called Route Maximization (RO) mode and routing through HA, called Bidirectional Tunnel (BT) mode as shown in fig 2.9 [5]. But due to the security mechanism called Return Routablity (RR) in MIPv6, CN exchanges some security check via HoA. So the entire communication is not independent of HA.

2.4 GPS, Latitude and Longitude

Latitude and longitude are coordinate system written in degree system to represent the geographical location. In map, latitude lines are horizontal

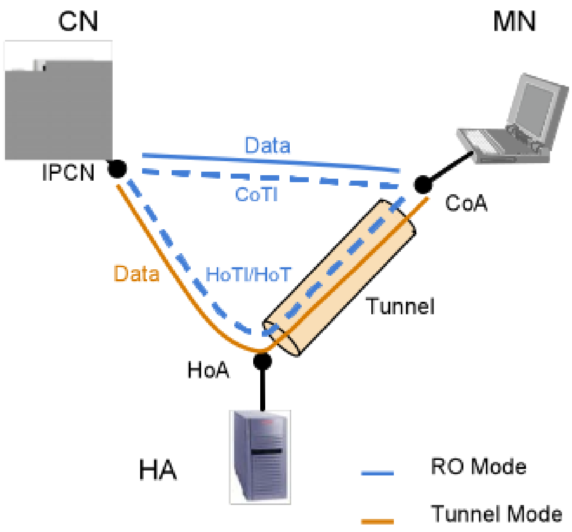


Figure 2.9: MIPv6 Operation

parallel lines equidistant from each other[46]. In latitude, each degree is approximately equal to 69 miles, little variation due to the shape of the earth not exactly sphere. 0 degree latitude is imaginary line equator and goes till 90 degree in both north and south to represent north and south pole respectively. So, latitude is measurement in degree north or south of equator of earth. In other words, latitude is defined as angular distance of any point on Earth measured in degree north or south of equator.

Longitude lines are vertical lines converging at poles, also called meridians, with widest part in equator approximately 69 miles [46]. 0 degree longitude is defined at Greenwich, London and time associated with this location is called Greenwich Mean Time (GMT). The center line meridian passing through Greenwich is Prime meridian and goes 180 degree east and west from that center line to represent longitudes. So, longitude are lines which give angular distance of any point on Earth measured in degree towards east and west of the prime meridian.

Degree of latitude and longitude have been divided into minutes and seconds to precisely locate points on earth surface[46]. Each degree consists 60 minutes and each minute has 60 seconds. Second can be further divided to tens, hundreds and thousands for very precise measurements.

2.5 Related Work

Mobility: A Double-Edged Sword for HSPA Networks A Large-scale Test on Hong Kong Mobile HSPA Networks, Fung Po Tso , Jin Teng, Weijia Jia, Dong Xuan [12]

This research was carried to study MBB HSPA , they called it 3.5G, through extensive field tests in Hong Kong. They virtually covered all possible mobile scenarios in urban areas like trains, city buses, subways and off-shore ferries. They studied RTT, packet loss, throughput in different traffic patterns and network loads and evaluated fairness of bandwidth allocation and behaviors of networks. They concluded that there is both pros and cons of mobility on HSPA networks. The research found that HSPA performance was highly affected by mobility like service deterioration, frequent interruption, unpredictable and often inappropriate handoffs etc. Interestingly, they also found that mobility can improve fairness of bandwidth sharing among users and traffic flows.

Measuring Mobile Broadband in the UK: performance delivered to PCs via dongles/data cards September to December 2010 -Ofcom [13]

This research was carried out to understand the performance of MBB networks using dongles and data cards in the UK. The study was focused on how to measure actual download throughput delivers by MBB providers and number of other performance metrics to understand the consumer experience of using mobile broadband services such as web browsing, downloading files, on-line gaming and streaming video. Measurements were carried out in static probes, driving test (but stopping vehicle) and consumer panel and measured latency, download and upload speed, packet loss and jitter, DNS resolution times and web page download times. The research found that geographic location highly influenced on mobile broadband performance. Type of network connection (2G, 3G or HSPA) also affects significantly on MBB performance. They measured differences in MBB performance delivered by operators for 3G/HSPA. However, the research lacks dedicated testbed to measure performance, as they measure by connecting USB dongles/datacards to laptop. Measurement may be affected by random errors due to unseen process/applications running in background of laptops. Importantly, this research didn’t study the performance of MBB networks under mobility.

Performance Measurements and evaluation of Video Streaming in HSPDA Networks with 16QAM Modulation- Haakon Riiser, Pål Halvorsen, Carsten Griwodz, Bjørn Hestnes [14]
This research was about measuring HSPDA performance of Telenor, Oslo in the context of video streaming in 2007. They measured the network characteristics such as packet loss, latency, jitter, and bit-rates to evaluate the suitability of HSDPA networks for real-time video streaming and suggested some improvements. They found that unfair bandwidth allocation between different streaming users, severe fluctuation of bandwidth during handover and saw-toothed loss patterns on congestion. However, the measured packet latency and per user bandwidth suggested that on-demand video streaming with 200kbps is possible in area with good coverage. But this research is only study about Telenor but not other 3G providers of Norway. This study also focused only in HSPDA performance in the context of video streaming, missing other broader context.

Characterizing Data Services in a 3G Network: Usage, Mobility and Access Issues Zhichao Zhu, Guohong Cao, Ram Keralapura and Antonio Nucci [11]
This research studied 3G network trace collected from MBB service provider in North America for analysis of mobility patterns, service usages and access issues such as termination failures & frequent registration. They found that some users experienced high network failure rate due to frequent handoffs. They suggested to design resource provision mobility management appropriately based on data service types and device types.

Measuring the QoS Characteristics of Operational 3G Mobile Broadband Networks, Simone Ferlin, Thomas Dreibholz, Özgü Alay, Amund Kvalbein [9] This research was to measure QoS characteristics of operational 3G MBB networks in Norway utilizing MPTCP. They examined QoS characteristics such as delay, packet loss, bandwidth of 4 3G UMTS and 1 3G CDMA2000 in static scenario and discussed their comparative observations. They found that different MBB providers have different QoS characteristics despite the same underlying technology. They observed that packet loss was low in both uplink and downlink and lower in uplink. There is similarity to take time to be stable throughput after initial state transition phase. Similarly, delay in uplink and downlink is stable but uplink delay shares more on RTT. This research didn't study MBB characteristics in mobile scenario i.e. pedestrian to vehicular mobility. This research is lacking to present less-predictable network traffic patterns, like weekend traffic, congested traffics etc.

Most of the these related research works were conducted for static scenario and failed to study MBB performance under mobility. Few research was carried out in mobile scenario as well, but not on MBB providers of Norway and there was no dedicated testbed to carry out the research. So this thesis uniquely tried to overcome the limitations of those researches by studying multiple operational 3G networks performance under mobility simultaneously using dedicated testbed, NorNet Edge [1].

Chapter 3

Methodology and Approach

This chapter covers approaches involved in overall research from the beginning to end. This study has gone through different processes as building blocks of this thesis from problem definition to conclusion as shown in Fig 3.1. Moreover, this section includes deliveries from the research, type of study, measurement setup, measurement procedures, desired data, analysis models, assumptions, limitations and expectations and connects problem statement with them.

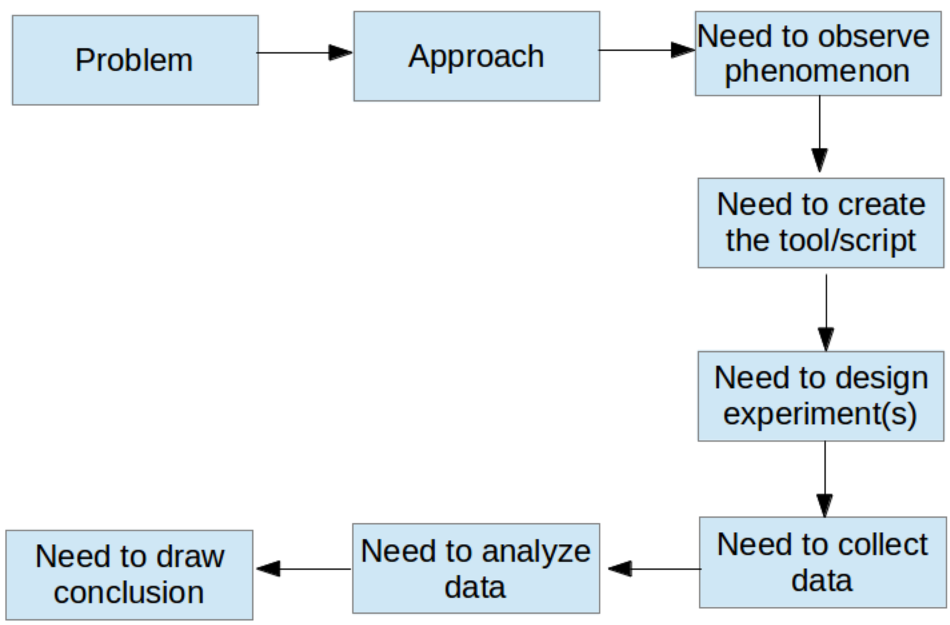


Figure 3.1: Overall Research Process

As mentioned in the Problem Statement, performance of MBB networks under mobility was studied in this thesis. The first purpose of this research is to provide data related to performance metrics of Mobile Broadband networks in Norway and the second purpose is to deliver knowledge and analysis from the collected data.

To fulfill the first purpose, different performance metrics like connectivity, delay (RTT), packet loss, MBB mode and submode, RRC state, Cell and LAC and RSSI were collected in mobile scenario for Four UMTS operators in Norway. The second objective was maintained by extracting information from collected data applying different statistical analysis model followed by investigating information in connection with problem statement for desired knowledge.

The study is primarily comparative type where performance metrics were compared in static versus mobile scenario. Performances were also compared between different operators in Norway under mobility in different speeds. Later, behaviors of MBB networks such as handover, loss patterns as well as coverage in different geographic locations were investigated. So, the study performed on this research is comparative type along with some investigations.

3.1 Measurement Setup

The measurements were carried out in Nornet Edge (NNE) testbed under mobility for four UMTS operators which have their own radio access network (RAN). Among these four networks, Telenor and Netcom have 2G/3G/4G coverage nationwide in Norway. However, Tele2 and Network Norway are extending their infrastructure for nationwide coverage and when their customers are outside their networks, they are comping on Netcom and Telenor respectively.

3.1.1 Hardware

The list of hardwares used in measurements are:

- **NNE node**: This is the most important hardware used for measurement. GPS receiver and 3G modems equipped with operator's SIM cards were connected in USB ports. NNE node has explained more in section 2.2.1

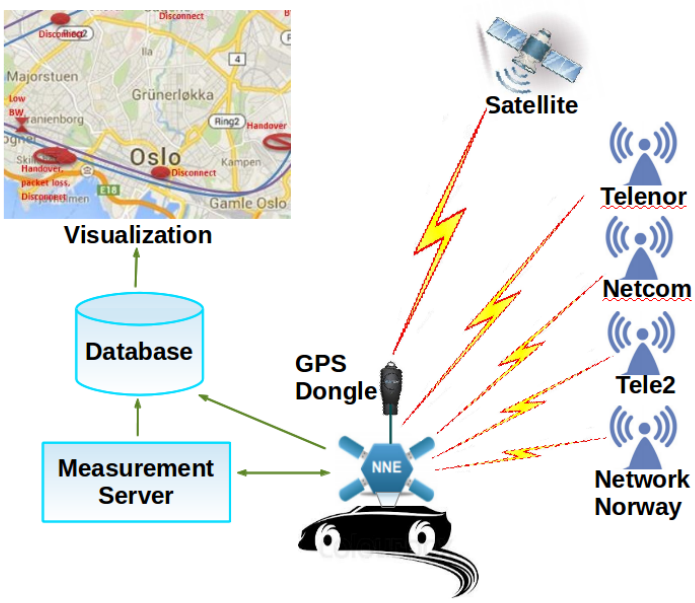


Figure 3.2: Measurement setup

- **NNE Backend Systems**: Measurement server is most crucial component of NNE backend systems. A VM in Simula was used as measurement server that runs Ubuntu 13.04 release with 3.11.10+ kernel version . It has x86_64 processor, 1GB memory and 60GB hard disk.

- **Modems**: HUAWEI E353 HSPA+ usb modems were used that supports UMTS/WCDMA (HSUPA, HSDPA, HSUPA+HSDPA, HSPA+) and GSM(GPRS, EDGE) standards. The modems consists led display to indicate 3G or 2G network available.

- **GPS Receiver**: BU-353 GPS receiver, which supports most NMEA complaints third party software, was connected to USB port of NNE node without external power.

- **Laptop**: Laptop was used to make ssh connection to NNE node and measurement server. Laptop running Ubuntu 12.04.4 release with 3.5.0-45 kernel version, processor with i5 2nd generation @ 2.5 GHz, 4GB memory and 128 GB disk space.

- **Battery set**: NNE node was powered with battery during the measurement in mobility. 5 V output was given to NNE node from four cells Lithium Polymer 14.8 V and 5400 mA rechargeable battery.

3.1.2 Software

Python was chosen as programming language as it is flexible to design tests so that test scripts can be developed quickly with rigorous system testing. It is well suited for both object-oriented as well as structured programming paradigm. Other reasons to choose python are: wider implementations of it in network and sockets programming; it's interactive mode and author's familiarization to it.

R was chosen for statistical analysis and creating graphs/plots from result data set. The motivations behind selecting R are: it includes wider set of data manipulation, statistical model and chart; it creates beautiful and unique data visualizations; it gives better results quickly; it is open source and it is widely popular among research scientists.

There are different tools available to measure performance like iperf, pchar, MGEN, pathchar, speedtest, MTR etc. One of the tools or combination of them could be chosen along with tcpdump (optionally) to measure performance metrics as per our requirements. However, in this thesis, measurement scripts/tools were developed to avoid possible errors associated with these built-in tools; to enjoy the freedom of flexibility and to reduce dependency.

Softwares components that are already running in NNE node are: Usbmodem listener, MULTI[3] which have discussed more in section 2.2.1. To utilize functionalities and capabilities of MULTI and Usbmodem-listener, two scripts were developed in python, as base scripts that are imported by measurement scripts developed as per the experimental requirements.

interfaceinfo.py [Appendix 7.1]
It utilizes functionality of MULTI to detect if interfaces are up or down and control them as per experimental requirement. Additionally, it configures routing tables with lowest metrics as default route after acquiring IP address by each interface.

pathinfo.py [Appendix 7.1]
This script utilizes capability of Usbmodem-listener for modem management, cellular connection management and metadata management. Such metadata

information might be CellID, LAC, Signal Strength, connection mode and submodes and RRC state parameters. This script can be used to map MCCMNC-PPPX or vice versa. IP address associated with PPP interface can also be obtained using this script.

Four modems connected to NNE node were recognized as ppp0, ppp1, ppp2, and ppp3 by mapping with MCCMNC within pathinfo.py script as shown in Table 3.1.

Operator	MCCMNC	Interface
Telenor	24201	PPP0
Netcom	24202	PPP1
Tele2	24204[1]	PPP2
Network Norway	24205	PPP3

Table 3.1: MBB operators mapped in Interface for measurement

3.2 Measurement Procedure

Measurements were carried out by hooking Measurement Box in public buses in Oslo, Norway. Measurement box includes NNE node equipped with 3G modems with SIM cards associated with four MBB operators and GPS receiver. NNE node was powered by battery set which was also included in measurement box.

3.2.1 Data of Interest

Following data/parameters are desired in this project.

Connectivity
Connectivity was measured as consecutive number of packets received without loss from client file. Since experiments had conducted with several (more than 30) repetition which increased coverage, more than 32000 UDP packets were received for each operator.

[1] Assigned MCCMNC for Tele2 Norway is 24204, but 24007 was recored in actual measurement.

Delay
The Round-Trip Time (RTT) of each packet that was sent from node to sever and received back in node were logged in client file. One way delay (uplink) for all received packets were logged in server file. One way delay (downlink) can be calculated by subtracting owd-uplink from rtt for respective packets.

Packet loss
Total packet loss for each MBB networks can be calculated by subtracting total packet received in all runs from total packets sent. Packets can be lost randomly or in different events like cell change, lac change, mode change, submode change etc.

MBB radio conditions
Apart from above three performance metrics, MBB metadata parameters also called radio conditions like RRC, mode, submode, cell, LAC, RSSI etc were also measured.

3.2.2 Measurement Methodology

The desired data were measured by sending 1460 bytes[2] UDP packets from mobile node to measurement server and replied back to node upon arrival at server. These UDP packets were sent in each second for defined interval using client script in node and received and replied by server script run in measurement server placed in well-provisioned research network at Simula. UDP was chosen over TCP to observe absolute performance of MBB networks ignoring protocol-specific effect such as congestion control, flow control, retransmission etc.

For unbiased, independent and reliable data, several experiments were conducted in different days, time, places and duration with random interval between each experiments to avoid stateful nature of MBB networks. Measurement samples were collected in week days and weekend; morning, daytime and evening; in different geographic coverage; in different speeds; and with sufficient repetition for reliability, validity. For fairness, measurement scripts were started at same time for all operators and run for equal interval. The measurement has done from February to April 2014, in most of the city

[2] Size of the UDP packet including padding, which was defined in beginning of each scripts.

area of Oslo.
The list of scripts developed to measure desired data are as follows:

server.py [Appendix 7.1]
server script was written in python and executed with following arguments.
#python server.py server-ip server-port server-interface total-packets repetition server-file

Server script accepts different arguments while executing on server such as server-IP-address, server-port-address, interface on which server receives packets, total number of packets it receives for one run (or interval), number of runs (repetition), and file name as depicted below. After receiving arguments, server side UDP socket was created in server and bound to IP and port. Server then waits for UDP packets from node on given port. When server receives a packet, it keeps packet statistics (sent time, received time, packet-number, epoch etc.) and replies packet back to node. Finally, packets statistics were logged in file. In server's file, one way delay (uplink), timestamp, packet-number, jitter e logged as depicted in Table 3.2.

Timestamp	Epoch	Pkt-Nr	Delta	Jitter(s)	OWD-Uplink(s)
1395808895	1	757	1.9086511135	0.9086511135	0.8436131477
1395808895	1	758	0.2798588276	-0.7201411724	0.1225199699
1395808896	1	759	0.8609051704	-0.1390948296	0.0168008804
1395808900	1	760	3.9700329304	2.9700329304	2.9514019489
1395808900	1	761	0.0321209431	-0.9678790569	1.9832749367
1395808900	1	762	0.020275116	-0.979724884	1.0026350021
1395808900	1	763	0.0196900368	-0.9803099632	0.0220971107
1395808901	1	764	1.2438688278	0.2438688278	0.2647659779
1395808902	1	765	0.6779830456	-0.3220169544	0.0585341454
1395808903	1	766	0.9825410843	-0.0174589157	0.076225996

Table 3.2: Sample data logged in Measurement server

client.py [Appendix 7.1]
client script was also written in python and executed with passing arguments similar to server script as depicted below.
#python client.py server-ip server-port node-interface total-packets repetition client-file

The node-interface provided here is either one of ppp0, ppp1, ppp2, and ppp3, representing modem associated with each MBB networks. After receiving such arguments, client side UDP socket was created, IP address associated to given interface was obtained and bound to socket along with port. When packets were received backed in node, packet statistics were logged in client-file. In client's file, timestamp, packet-number, rtt, jitter, mode, submode, cellid, LAC, RSSI, RRC were logged as depicted in Table 3.3.

Sent-time	Received-time	RTT	Epoch	Pkt-Nr	RRC	Mode	Submode	Cell	LAC	RSSI
1395808894	1395808895	1.001	1	757	DCH	WCDMA	HSPA+	DA8D	51A5	26
1395808895	1395808895	0.244	1	758	DCH	WCDMA	HSPA+	DA8D	51A5	26
1395808896	1395808896	0.114	1	759	DCH	WCDMA	HSPA+	DA8D	51A5	26
1395808901	1395808901	0.375	1	764	DCH	WCDMA	HSPA+	4593	52D1	26
1395808902	1395808902	0.064	1	765	DCH	WCDMA	HSPA+	4593	52D1	26
1395808903	1395808903	0.054	1	766	DCH	WCDMA	HSPA+	4593	52D1	26

Table 3.3: Sample data logged in client (Node)

gpsdata.py [Appendix 7.1]
To identify location uniquely, another script gpsdata.py was developed, which measure timestamp, latitude, longitude and speed as depicted in Table 3.4.

3.3 Analysis models/tools

Statistical analysis models/tools that were applied on collected data to investigate problem are discussed in this chapter.

Histogram with varying-width bin
Firstly, all received data set were observed with Histogram to decide the variable bin width for different speed data to make almost equal frequency on each class taking in mind that wider bin in case of low density reduced noise due to sampling randomness and narrower bin for high density data gives

Timestamp	Latitude	Longitude	Speed (kph)
1395808894	59.937014234	10.783364941	30.2112
1395808895	59.936971311	10.783242783	30.2112
1395808896	59.9369238	10.78313485	29.3328
1395808897	59.936880876	10.783012693	27.9864
1395808898	59.936840995	10.782908107	25.7184
1395808899	59.936807292	10.782824438	23.3028
1395808900	59.936744382	10.782657101	19.2636
1395808901	59.936744382	10.782657101	19.2636
1395808902	59.936721353	10.78259435	17.1684
1395808903	59.936681472	10.782489765	10.1196

Table 3.4: Sample data received from GPS receiver

greater precision to the estimation of density. Thus, varying-width bin was used here even though equal-width bins are widely used in statistics.

Mean and Standard deviation

Mean, also called average, is most commonly used measure for central tendency of data set and computed with the sum of observations divided by number of observations. Sample mean is given by

$$\overline{X} = \sum_{i=1}^{N} x_i$$

Standard deviation (SD) measures the variation or dispersion of data points from mean. A low SD means data are close to mean value where as high SD indicates data are widely spread. Low standard deviation indicates more consistent data. Standard deviation also used to show margin of error. Unbiased sample standard deviation is given by

$$S = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \overline{x})^2}$$

Box plot

The distribution of data are graphically represented by box plot in convenient way without making any assumption of statistical distribution. It groups data with quartiles, median as 2nd quartile and bottom and upper part of box as 1st quartile and 3rd quartile. Distribution of data above 3rd quartile is given by upper whisker and below 1st quartile is given by lower whisker in box-with-whisker plot. Box plot was chosen as it can depict distribution of data in better way than mean. Mean may mislead sometimes due to few number of very high or low outliers. Dispersion and skewness of data distribution can be easily observed in box plot. Box plot is quick way of examination using small space and useful more on comparative study, like ours.

Cumulative distribution function (CDF) plot

The CDF of a random variable X with real-valued is the function given by

$F_X(x) = P(X \leq x)$,

where P is the probability of random variable X takes on a value less than or equal to x. The probability of X within semi-close interval (a,b] is given by

$P(a < X \leq b) = F_X(b) - F_X(a)$

where a < b

The CDF of a continuous random variable X, CDF can be given by the integral of its probability density function f_x as given by

$F_X(x) = \int_{-\infty}^{x} {}_X(t)dt$

CDF plot was chosen for analysis as it is easy to visualize and find data distribution of any percentile like median or 95 percentile. For example, it can be easily found that 90% of RTT values are less than 150 millisecond. CDF plot is non-parametric plot and no need to decide bin width. In CDF plot both slope of curve and the number of curves gives information about data distribution. More uniform distribution is indicated by broad slope where as clustered data set is indicated by steep slope. It is extremely useful to plot and compare multiple variables like connectivity parameters of different operators in our case.

Visualization on Google Map

Measured parameters and events can be visualized in Google maps. Location points can be drawn with latitude and longitude and major events such as LAC change, cell change, mode change, submode change. Packet loss associated with those events and random packet loss were visualized in maps so that it can be easily observed where handover takes place for each operators and how much packets were lost on such events. Do operators really have 3G in all places or they are providing 2G also can be found on maps. Which operators is strong and in which area can be visualized with map coverage. So such visualization is very effective, unique and interesting analysis model in our research.

3.4 Assumptions, Limitations and Expectations

There are not sufficient researches in past to collect data and to observe MBB performance under mobility, which is supported by very few publication(s) on mobility performance of MBB networks exists and some of them are listed in Literature section. Measurement environment for this project mimics to real users' mobility experience. It was hoped that our results, analysis, discussion and conclusion provide knowledge to data science and applicable to real life. The report has prepared on the assumption that reader knows the basic concepts of MBB networks with fundamental knowledge on literature.

The research has some limitations as well. Performance measurement was on sending regular UDP packets but users may have different experiences while loading applications. The measurements cover mostly the city area of Oslo but very few in countryside where performances can be different. Our gps dongle was not able to get data in subway and tunnel and measurements were focused on open roads/area. so subway/tunnel performance may not be same as the results presented in this thesis. Data were measured from Feb to April of 2014 not throughout the year or longer time, which might vary results.

Some expectations were set before the real measurements and analysis. It was expected that delay, disconnections and packet loss might be increased in mobility as compared to static. Within mobility, it was anticipated that Connection failures, delay and loss may be higher in case of high speed, congestion and cell change (handover). Link stability might be affected by handover and congestion. It was also expected that mobility performance between operators is different though they have based on same technology and standards.

Chapter 4

Results and Analysis

This section presents the results of the measurements carried out from the experiments described in section 3.2.2 followed by the analysis of those results using statistical analysis tools explained in 3.3 to evaluate MBB performances for Netcom, Network Norway, Tele2 and Telenor. Connectivity, loss and delay as well as radio conditions such as LAC, Cell, signal strength, mode and submode for all four MBB operators under investigation are examined and presented in this chapter.

Since, the study is mainly of comparative type, MBB performance between all operators in similar scenario are scrutinized. Delay, loss and connectivity in mobility versus static scenario are evaluated. In mobility, performance metrics in different speed, different modes and submodes are compared. 3G versus 2G performance (if 2G data available) are also compared. Later on, some important characteristics and behaviors of networks are investigated and visualized in Google maps.

In order to get required results, raw data as shown in section 3.2.2 were observed and processed. Since the raw data set are high enough to trace (32000 plus rows for each operator) in each file obtained from client.py, server.py and gpsdata.py, some scripts were developed to present results and analysis. First, files received from client and server along with GPS data were combined by deploying *combine.py* [Appendix 7.2] script where timestamp in log files are matched. Then, mobile data having speed greater than 0 kph are extracted using *mobility.py* [Appendix 7.2].

The speed of the moving node (vehicle) was calculated with measured latitude, longitude and timestamps with following formula, which is also known as haversine formula [1].

$$Speed = (6371.0 * (2 * asin(sqrt(sin((lat2 - lat1)/2) * *2 + cos(lat1) * cos(lat2) * sin((lon2 - lon1)/2) * *2))) * 3600.0)/(t2 - t1)$$

where lat1, lat2, lon1, lon2 and t1, t2 are latitude, longitude and timestamp of first and second location respectively and 6371 km is mean earth radius. The above formula gives speed in kph. The speed were also measured with by gps receiver and verified with above haversine formula.

To examine data at different speed under mobility, *speed.py* [Appendix 7.2] was deployed. For almost equal data distribution in different speed bin, four speed buckets were defined: up to 5kph, 6 - 20 kph, 21 - 30 kph and above 30 kph. To separate data by mode and submode, script *separate.py* [Appendix 7.2] was developed.

4.1 Connectivity

Connectivity was measured as **consecutive number of packets received without loss** for each MBB networks under mobility. This parameter shows how stable and reliable a network is, especially in case of sensitive applications. If a network disconnects frequently, it is not possible to perform jobs with satisfactory level and considered as unreliable. On the other hand, if desired application can be run without or negligible disruptions for longer time in a network, then the network is considered as reliable. To extract such connectivity data, script *connectivity.py* [Appendix 7.2] was deployed, and data distributions were plotted for all operators to compare them.

In static measurement, it was observed no or negligible connection failures i.e out of 100 test runs, almost all packets were received without loss in 99 times. So, no results are presented here to compare connectivity between static versus mobility.

[1] http://rosettacode.org/wiki/Haversine_formula

In Fig 4.1, packets received without loss for all four operators under mobility are presented in CDF plot where X-axis represents number of packets and Y-axis represents probability of cumulative density. This graphical representation of distribution of connectivity reveals the commulative probability for particular connectivity value or less than that. For example, 95 percentile connectivity value indicates that there is 95 percent probability that connectivity is equal to this value or less than that.

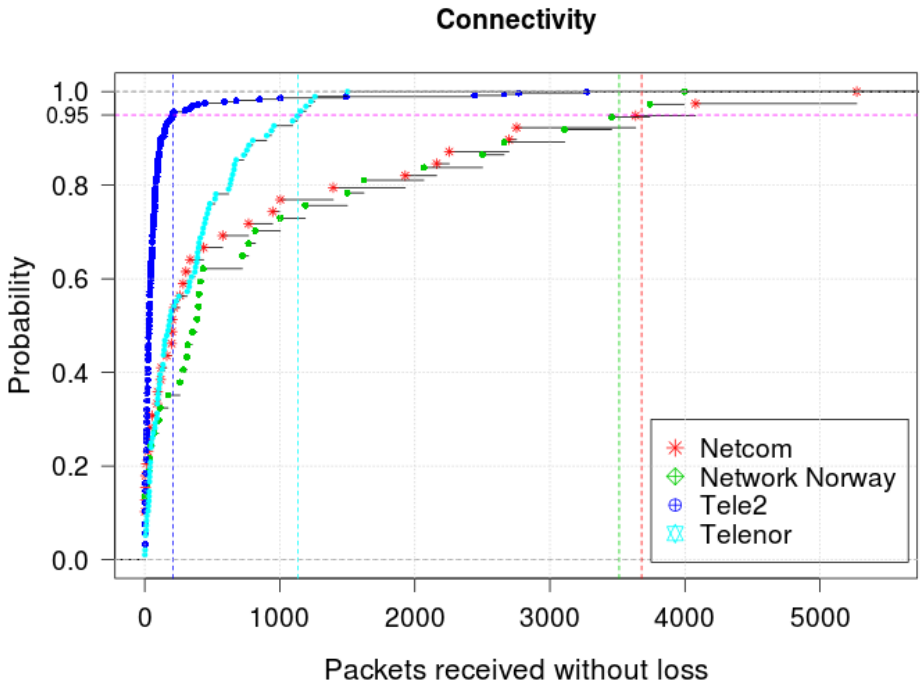


Figure 4.1: Connectivity: consecutive packets received without loss

As per the data points presented on this plot 4.1, Netcom and Network Norway performed well with more than 60 percentile of connectivity data greater than 200 packets without loss. In 95 percentile connectivity cummulative probability, 3500 or less packets have received without disconnection. Both Netcom and Network Norway have almost similar distribution of connectivity but Network Norway marginally outperformed Netcom. Looking into 35 percent of good data, Network Norway has more than 800 packets but Netcom has only 500 plus packets.

In Tele2, 95 percent of connectivity data were distributed below 200 packets indicating frequent disconnection. In Telenor, 50 percent of connectivity data were distributed about 200 packets and 95 percentile data are about 1200 packets i.e. well below than Netcom and Network Norway but sufficiently greater than Tele2. In case of 35 percent good data, Telenor received 450 packets without loss i.e slightly weaker than Netcom for equal percent of good data.

Fig 4.2 depicts how different speed affects on connectivity experienced as end

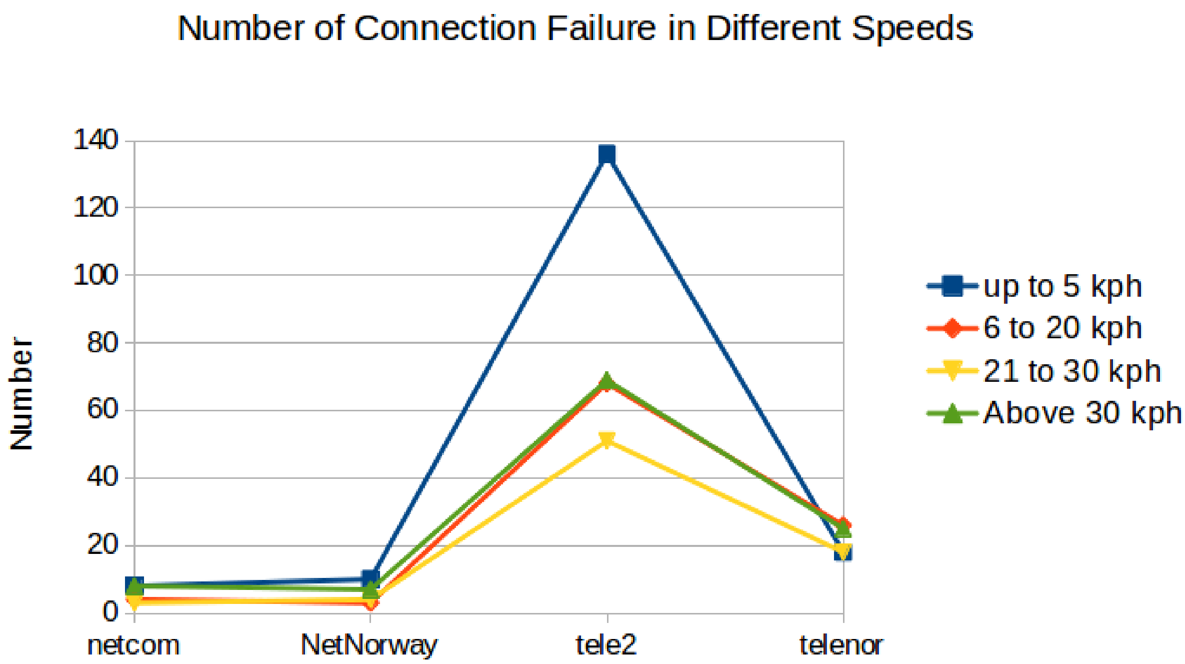


Figure 4.2: Connection failures at different speed experienced in Node

user. From this plot, it is seen that initial movement from static position i.e. up to 5 kph caused more connection loss followed by higher speed. In Tele2, more number of connection failures were observed in all speed followed by telenor. Netcom and Network Norway have comparatively low number of connection loss.

It is worth to know when these connections are lost: while sending packets from node to server or from server to node? i.e. which path is more reliable: uplink or downlink? The percentage of outages or connection failures in

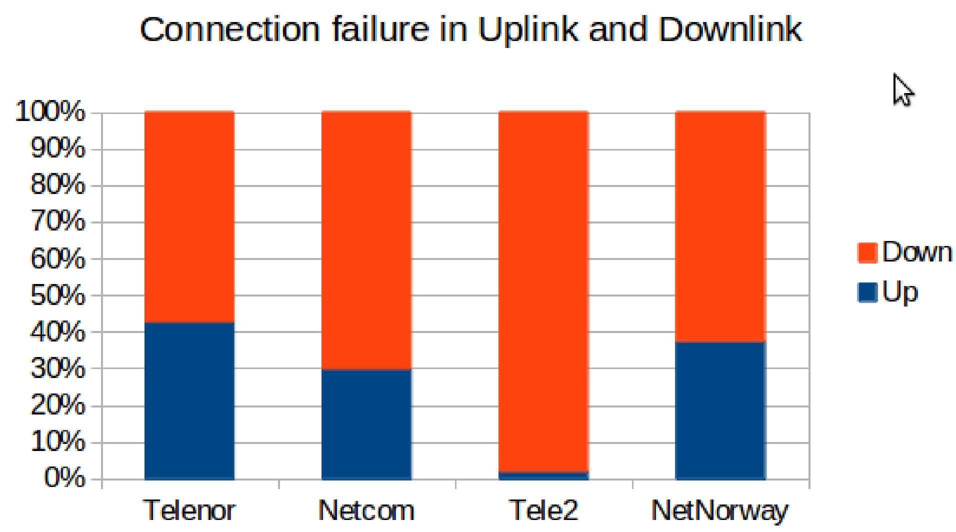


Figure 4.3: Connection failures Uplink versus Downlink

Uplink and Downlink are shown in Fig 4.3. As per this chart, major outages are in downlink. Percentage connection failures measured in downlink was more than 95 % in Tele2 which was about 60 % in other three networks.

4.2 Packet Loss

Loss was measured as **packet(s) that is sent but not received**. Total number of packet loss was computed using *loss.py*[Appendix 7.2] and percentage total loss was calculated for whole data set i.e. 32000 plus packets sent for each networks. It was observed that negligible packet loss, i.e. 0.05 percent or less, in static scenario. So no results presented here comparing packet loss between static and mobile scenario.

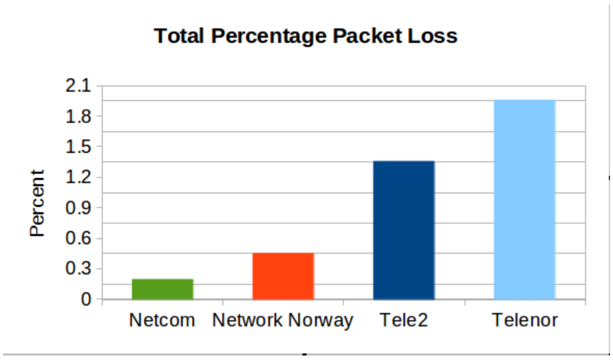
While deepening the study on packet loss under mobility, it was found that packets were lost either randomly or caused by mobility event(s). Under mobility events, it was observed that packets are lost by mode change (WCDMA in 3G and GSM in 2G), submode change (HSPA+, HSDPA, HSUPA, HSDPA+HSUPA and WCDMA within 3G) and LAC & cell change. During LAC and cell change, node was reselecting cells/base stations (Node Bs in UMTS) which is also studied as handover.

In this section, different characteristics of packet loss are presented. Percentage total loss and losses contributed by different events depicted in charts for all MBB networks and compared. Then, total number of handovers and number of handovers that caused packet loss are examined with charts. Afterward, losses in different speed are compared for all operators. Moreover, handovers and loss associated with them are visualized in Google maps.

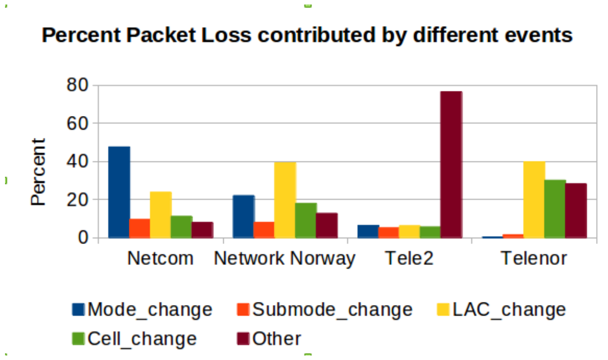
Fig 4.4 shows overview of packet loss. In Fig 4.4(a), total percentage packet loss for all operators are presented in comparative bar-chart. From this bar-chart, Netcom has the lowest percent i.e. below than 0.2 percent and considered as negligible loss. Telenor has the comparatively more packet loss i.e. about 2 percent. On the basis of total percent loss performance, Network Norway also performed well with less than 0.5 percent i.e. slightly higher than Netcom. Tele2 performed average with total loss about 1.3%.

How those different events contributed on loss are depicted in Fig 4.4(b). Loss due to mode change contributed highest percent in Netcom, more than 40 percent of total loss. Mode change also contributed significant loss in Network Norway, i.e. more than 20 percent of total loss, but only about 10 percent in Tele2 and almost negligible in Telenor. Loss contributed by submode change is about 10 percent in Netcom & Network Norway, less than 10 % in case of Tele2 and almost negligible in Telenor. LAC and cell change combinely contributed significant loss, about 70 percent loss on Telenor, nearly 60 percent in Network Norway, greater than 30 percent on Netcom and less than 20 percent on Tele2. Apart from those events, it was noticed random loss, which is above 75 percent of total loss in Tele2, considerably high and frequent. Random loss, which is labeled as 'other' in plot, is also significant in Telenor, i.e about 30 percent in total loss but low in Network Norway and Netcom, just above and below of 10 percent respectively.

Handover in mobility and packet loss contributed by those handovers are depicted in Fig 4.5. As per those results 4.5(a), more than 70 percent losses are due to handovers except Tele2 where only about 20 percent losses are contributed by handovers. Even though, there is considerably high losses due to handover, all handovers didn't cause packet loss as shown in Fig 4.5(b). Handovers that caused packet loss are less than 50 percent in case of Netcom

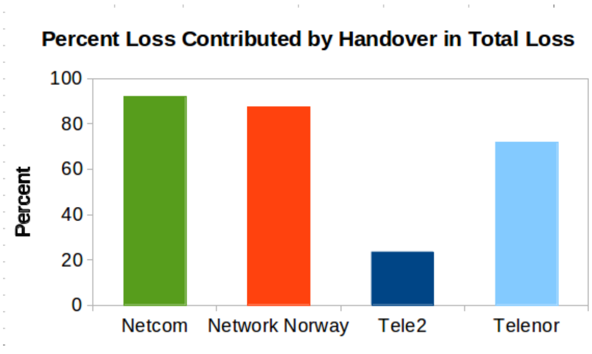


(a) Total percent loss (32000 plus packet sent)

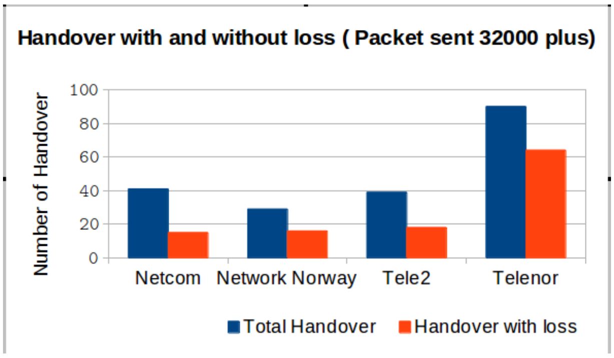


(b) Packet loss by different events

Figure 4.4: Packet loss



(a) Loss contributed by handover



(b) Handover with and without loss

Figure 4.5: Handover and Loss

and Tele2, about 50 percent in Network Norway and more than 65 percent in case of Telenor which is highest among all four operators.

Were more packets are lost in uplink or in downlink? To answer this , one way loss was calculated for node to server (uplink) and server to node (downlink) and plotted as depicted in Fig 4.6. From this graph, it was observed that more packets are lost in downlink as compared to uplink in all networks. Percentage packet lost in downlink in Tele2 is about 70 % and more than 55 % in all other three operators under mobility.

Packet loss variation by speed are presented on results 4.7. As per this result, Netcom has comparatively higher loss in initial speed, i.e. up to 5 kph, and higher speed, i.e. above 30 kph. Both Network Norway and Tele2 have more loss in starting speed bucket, 0 - 5 kph. Similar to connectivity performance

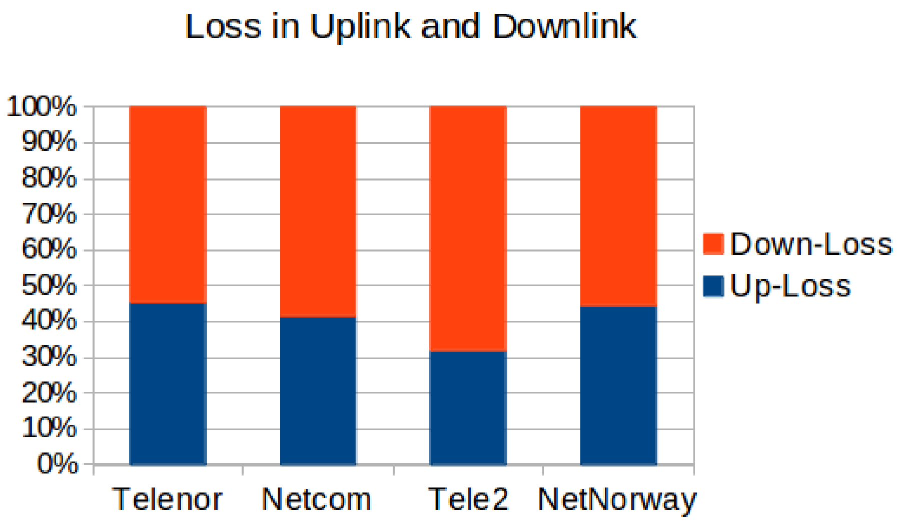


Figure 4.6: Percent loss in different speed

in different speed, loss also varies in different speed and in most operators it seems that more packets were lost in speeding up and in higher speed.

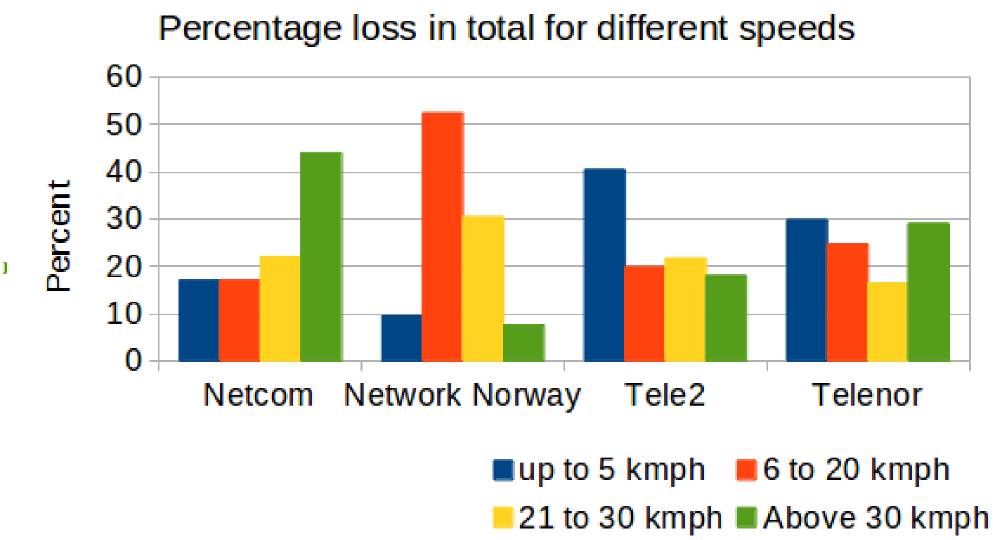


Figure 4.7: Percent loss in different speed

Major events occurred under mobility during measurements like LAC change, cell change, mode change, submode change, random packet loss and latitude & longitude associated with those points are plotted in Google maps by putting data on fusion table with some customization on display features and markers as shown in Fig 4.8. Large red, large green, large yellow and large blue are used for Telenor, Netcom, Tele2 and Network Norway respectively as shown in legend. If particular marker point is clicked on map, details information of that point is displayed as shown in Figure. This map also shows the coverage of measurements in Oslo city.

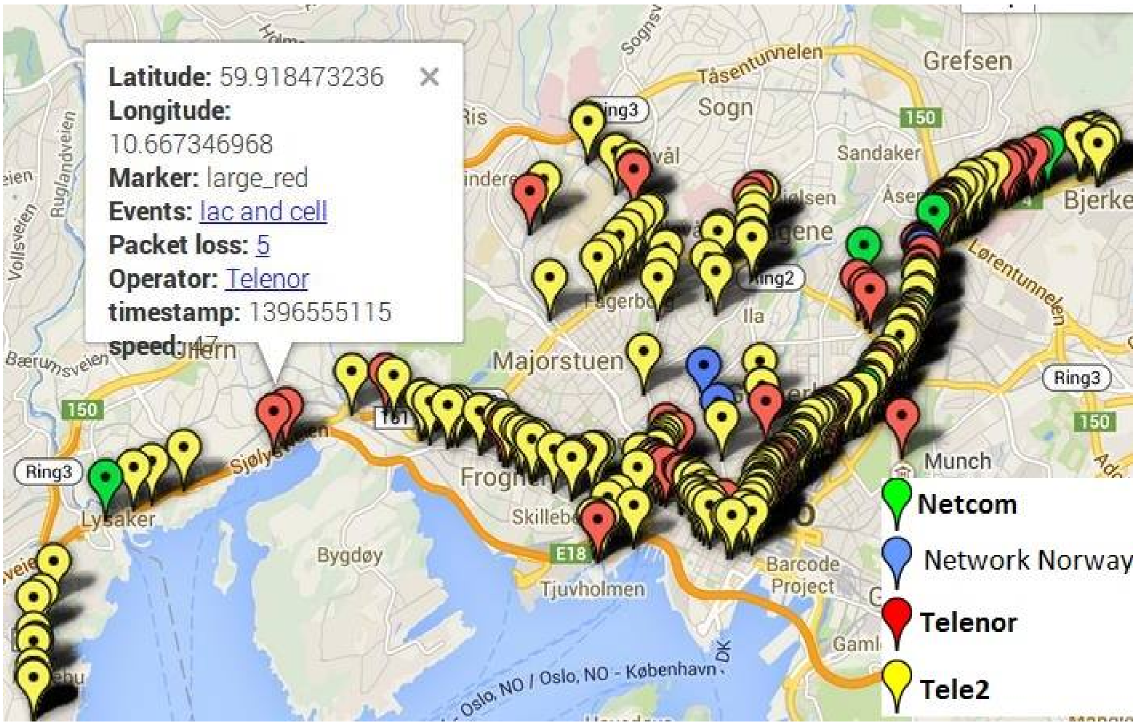


Figure 4.8: Visualization of loss and handover with coverage

From the map, it seems that there is more random loss and disconnections in Tele2 irrespective to spatial variation. More handovers and loss associated with those handovers were observed in Telenor as compared to Netcom and Network Norway, strengthening the analysis presented above. This coverage map indicates that almost similar pattern of loss and events measured in different locations for each MBB networks, for example, Tele2 has frequent loss in all places but network Norway and Netcom have very few throughout the coverage.

For validity & reliability of measurements and robustness of results & analysis, measurements were repeated several times (10 times) on particular route for different days, times of the days and displayed in Fig 4.9. This map represents the major events and associated packet losses on those repetitive measurements conducted between Bjerke to Jernbanetorget (Oslo Central). Similar patterns of loss and events were observed in this map as well like total coverage map presented above.

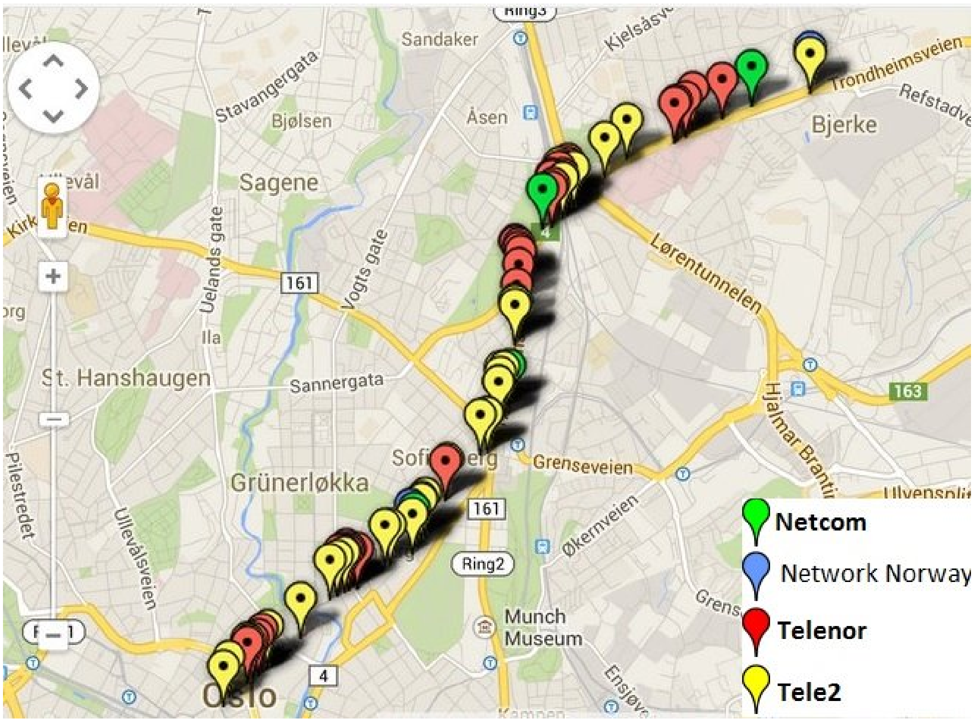


Figure 4.9: Visualization of loss and handover on repetitive measurement

4.3 Network coverage and packet distribution

It is interesting to see if data collected were all 3G or not? On the packets distribution depicted on Fig 4.10, all operators have provided 3G networks in most of the locations in city area. It was observed that more than 2 % packets were collected in 2G with GSM mode and EDGE submode except Network Norway which indicates that operators have provided 2G networks if 3G is not available .

In 3G data set, most of the packets collected in all operators were HSPA+ and few packets were with one or more submodes of WCDMA, HSDPA, HSUPA, HSDPA+HSUPA. The percentage submode distribution of 3G packets received

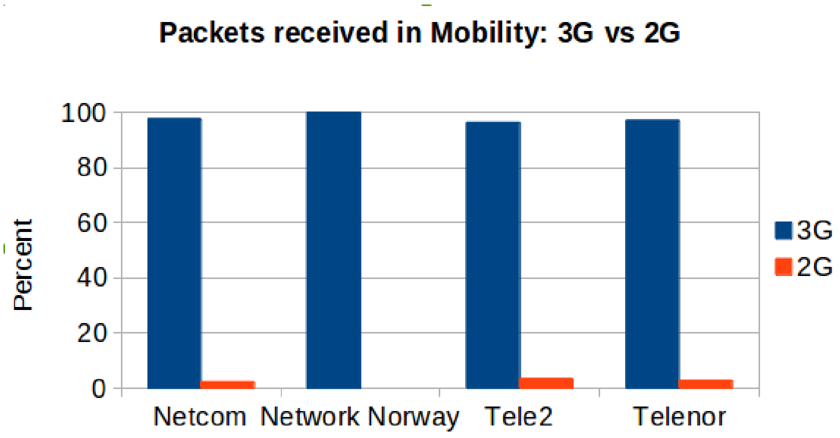


Figure 4.10: Packets Received: 3G Vs 2G

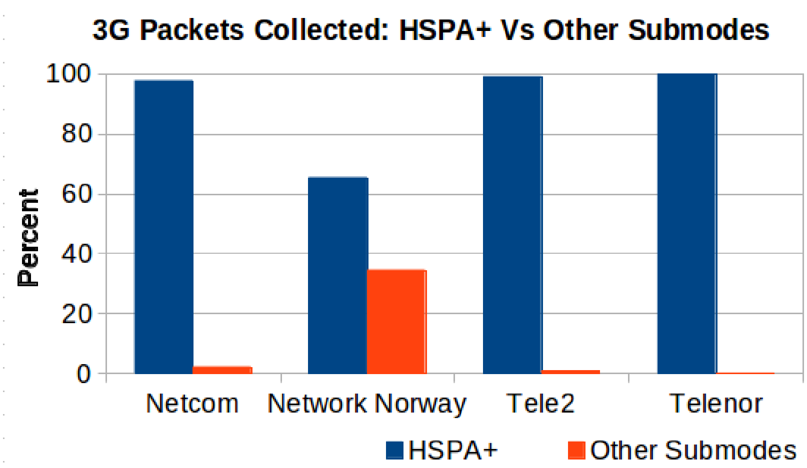


Figure 4.11: Data Distribution in 3G: HSPA+ Vs other Submode

are shown in Fig 4.11 which shows about 98 % packets within 3G were HSPA+ apart from Network Norway, where more than 1/3 packets were other than HSPA+ which were mostly HSDPA and WCDMA.

4.4 Delay

The thesis work has focused on delays on different MBB networks that are mainly measured and analyzed for round-trip time taken by a UDP packet sending from measurement node (client) to measurement server and returned back. Comparisons have done for different speed, submodes, modes, operators and more importantly between mobility and static environment.

During delay analysis, it was observed that RTT values are not normally distributed. Means and standard deviations were calculated and sample of them are depicted in Fig 4.12 for two weeks period. This chart represents data collected in week and weekend, different times of a day i.e. Morning, Day and Evening, so that temporal variance can be observed. From this Fig, it seems that Netcom performed best among the four networks. These sample mean values looks more smooth in Netcom and more variance in other three networks. Population mean and standard deviation were computed from total RTTs in mobility for each operator and depicted in Table 4.1 along with p-value and 95% confidence interval. From this table, it can be observed that all p-value are very low than 0.05 (which is normally taken as threshold for statistical significance). So, in all operators, Null Hypothesis (i.e. mean = 0) can be rejected i.e. alternative hypothesis is accepted and data are found statistical significant.

Looking more into RTT distribution, it was observed that mean and standard deviation may not be suitable approach as mean may sometimes mislead. Here also, for example, it was noticed that mean delay (population mean) for Telenor networks under mobility is 516 msec where as 75 percent of delays are distributed below 134 msec as shown in summary of distribution below.

```
>summary(telenor)
Min. 1st Qu. Median Mean 3rd Qu. Max.
0.0280 0.0560 0.0800 0.5168 0.1340 49.5600
```

So, median and percentile are better ways to analyze delay distributions in this project. That's why, Box-plot-with-whiskers and Empirical CDF are used in rest rest of the delay analysis.

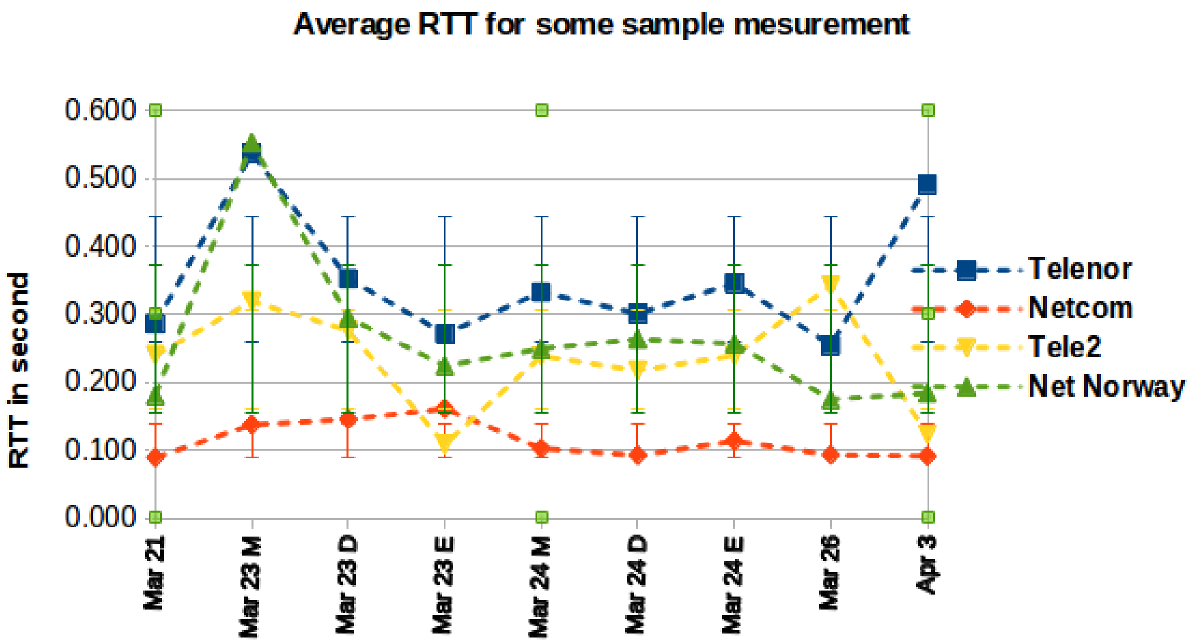


Figure 4.12: Sample average RTT

Statistics	Telenor	Netcom	Tele2	Net Norway
Mean	0.516	0.143	0.146	0.287
Standard Deviation	3.087	0.559	0.406	1.008
95% Confidence Interval	0.472 - 0.562	0.135 - 0.151	0.141 -0.152	0.272 - 0.301
P-Value	< 2.2e-16	< 2.2e-16	< 2.2e-16	< 2.2e-16

Table 4.1: Population Mean and Standard deviation with confidence interval

Mobility Vs Static

First, how delays are affected in mobility was observed. For this, delays in mobility versus static were compared as shown in Fig 4.13 and observed that RTTs are not affected significantly for all networks though static delays are slightly lower than mobility. It was observed from box plot that median values of RTTs under mobility are greater than static values by small amount which can also be verified by table depicted in 4.2. But from the same table, if 95 percentile RTT values are compared, reasonable difference can be found i.e RTT under mobility is higher than static.

In delay, Netcom performed very well in both static and mobility followed by

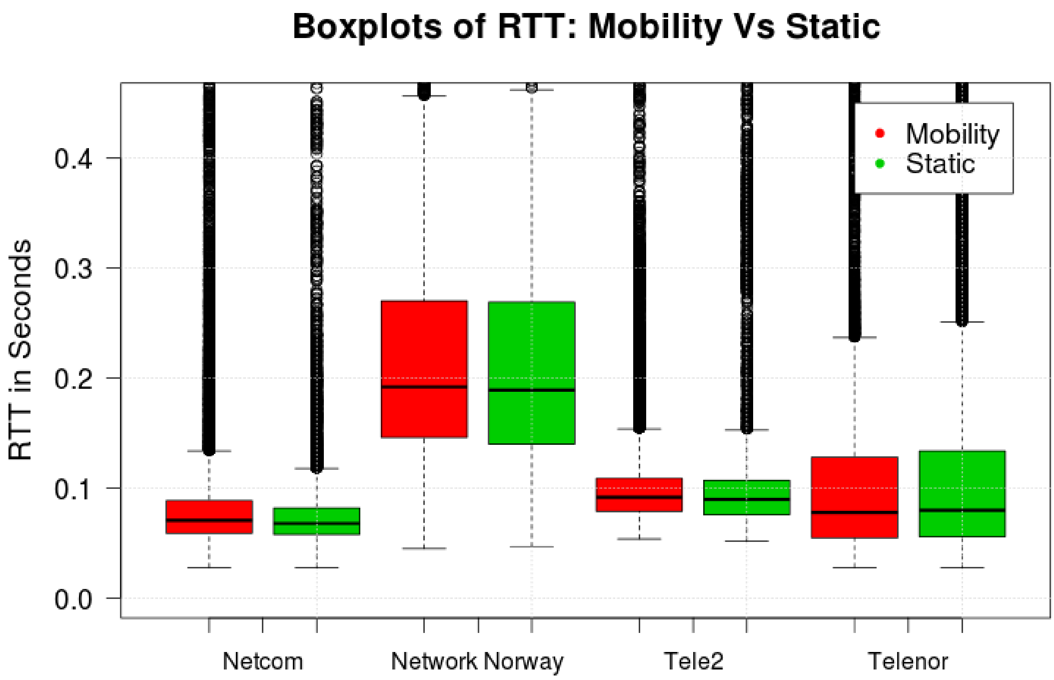


Figure 4.13: RTT Mobility Vs Static

Tele2, Telenor and Network Norway while looking on overall distribution, minimum, median and 95 percentile values. Minimum RTT for Netcom is 28 msec in both static and mobile that is equal to Telenor. But in median value, Netcom outperformed Telenor. Though minimum RTT value for Tele2 is higher than Telenor, Tele2's overall distribution of RTTs is better (closely distributed) than Telenor as shown in Fig 4.13. In case of Network Norway, overall RTT distribution was observed higher than other operators both in static and mobility. If RTTs are observed with their spreadness, networks with more spreadness to less are Network Norway, Telenor, Tele2 and Netcom respectively.

During measurement, only 3G packets were collected in case of Network Norway as discussed in section 4.3. Delays comparing 3G versus 2G are

Description	Netcom	Network Norway	Tele2	Telenor
Static median	68	189	90	74
Mobility median	71	192	93	80
Static 95 percentile	179	497	332	418
Mobility 95 percentile	312	591	377	599

Table 4.2: Median and 95 percent RTT values in mili second

depicted in Fig 4.14 for Netcom, Tele2 and Telenor. As per this result, RTT distribution in 3G are reasonably low than 2G for all three operators, which is more obvious and correlate well with the literature presented in section 2. The median RTT values are less than 100 msec in 3G data set which are greater than 400 msec in 2G data set for all three operators. The skewness of boxplot, here, indicates that data distribution are not uniform between different quartile range.

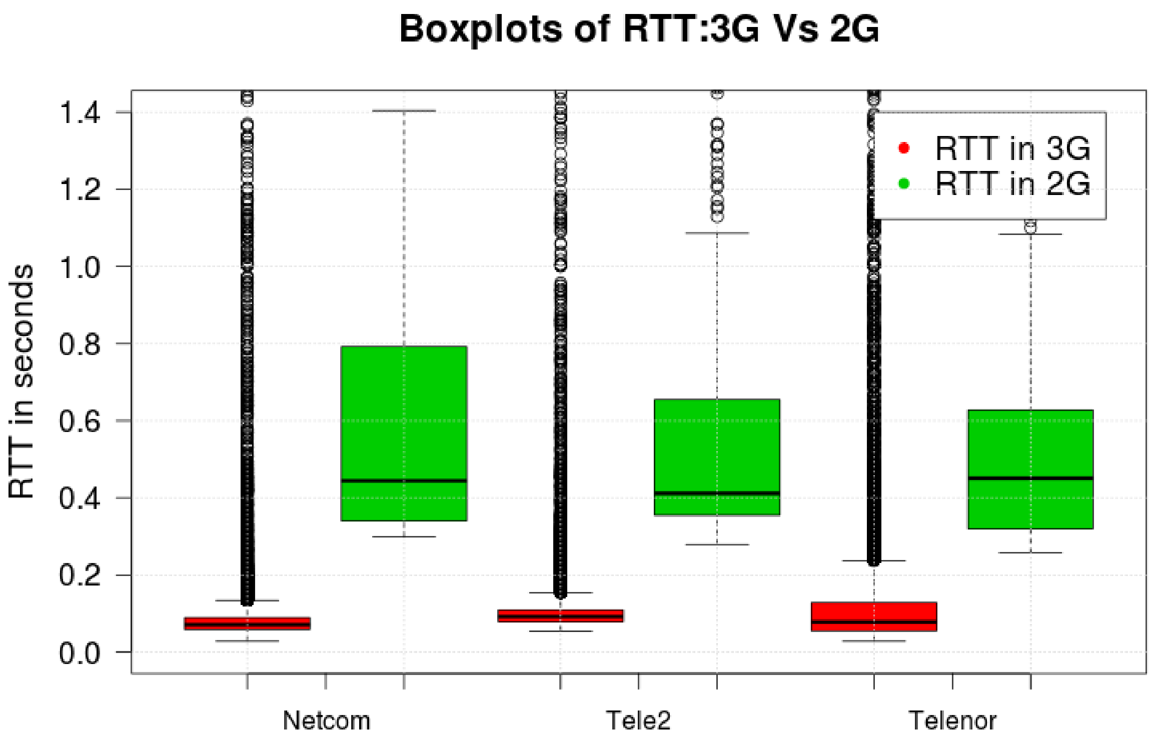


Figure 4.14: RTT: 3G Vs 2G

Comparing RTT under mobility in 3G

In literature, it was discussed that MBB networks performs better in HSPA+ submode than other submodes in 3G. Similar result was observed in Fig 4.15 for all operators except Telenor. The unlikely result in case of Telenor is most probably by very small number of packets (i.e. 33) in other submodes than HSPA+ where no any events like handover, disconnection or packet loss occurred so RTT seems comparatively good. All 33 packets (i.e. 0.2 % of total 3G packets) were collected with WCDMA for both mode and submode without cell and LAC change.

For more detail analysis along with more fair comparison, HSPA+ data were

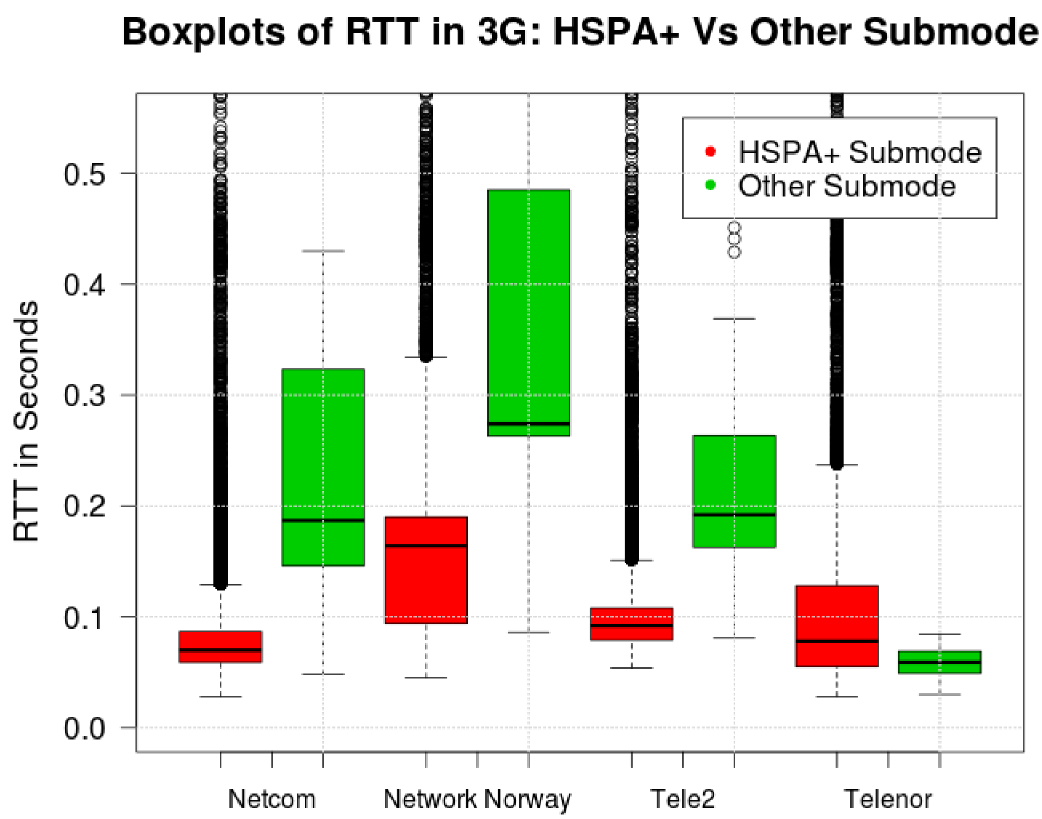
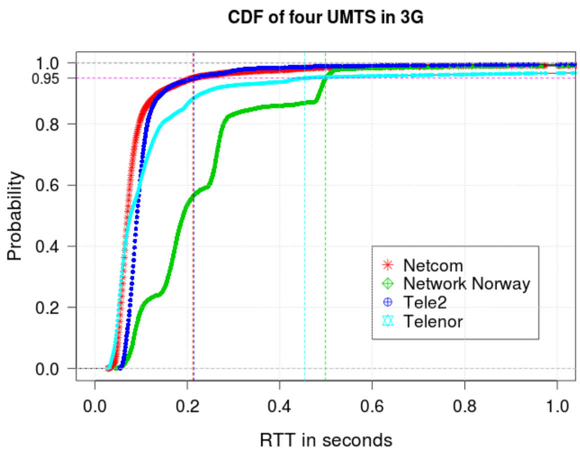
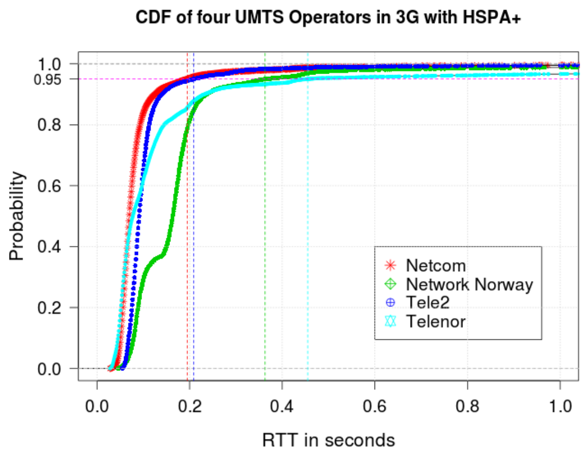


Figure 4.15: RTT in 3G: HSPA+ Vs other Submode

compared with all 3G mobility data with CDF plots 4.16(a) and (b). As per these plots, Netcom and Tele2 have almost similar distribution (slightly different) of RTT values in both all 3G data and HSPA+ only data. In case of all



(a) RTT for four operators in 3G



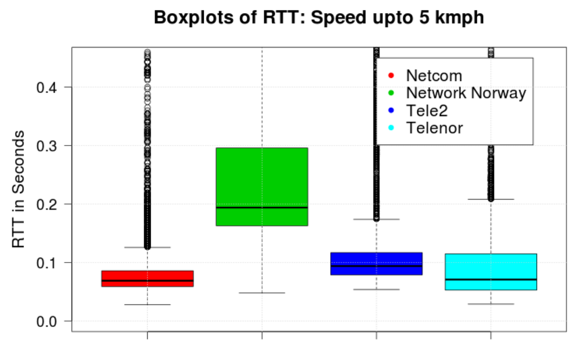
(b) RTT for four operators in HSPA+ submode

Figure 4.16: CDF plot showing RTT for 3G and HSPA+ submode

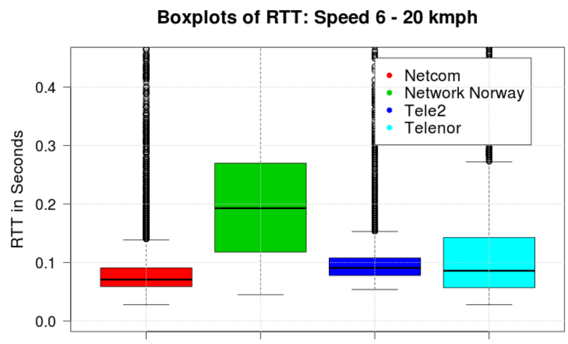
3G data (a), Netcom performed little better than Tele2 for below 90 percentile values where as almost same performance above 90 percentile values. But in HSPA+ only data (b), it was seen some difference even in 95 percentile data for these two operators i.e. RTT value less than 200 msec for Netcom and greater than 200 msec for Tele2. *In case of Telenor, RTT values in HSPA+ are lower than all 3G data that contradicted unlikely observation in 4.15 and correlated well with literature*. 95 percentile RTT values for Telenor in HSPA+ are well below than 400 msec but well above than 400 msec in all 3G data. In Network Norway, about 80 % RTTs distribution are below 200 msec in HSPA+ and less than 60 % RTTs distribution are below 200 msec in case of all 3G data indicating delay performance is significantly better in HSPA+. Moreover, in HSPA+, Network Norway outperformed Telenor in above 90 percentile data unlike all 3G data.

Another noticeable observation is spreading of data shown by slope of CDF plot. More steep slopes for operators except Network Norway up to 75 % RTT indicates that data are clustered and slowly scattered above 3rd quartile which can also be observed in Fig 4.15. Variable and wide CDF slopes, in case of Network Norway, pointed out that all RTT values are more scattered.

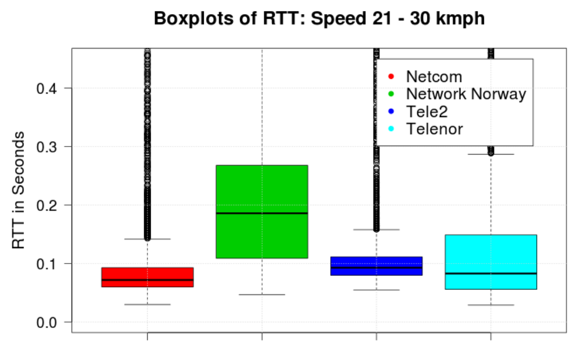
Effect of speed on delay performance is as depicted in result 4.17. RTT distributions in Netcom and Tele2 are clustered where as in Telenor and Network Norway they are more scattered. In all speed blocks, i.e. at 0 - 5 kph,



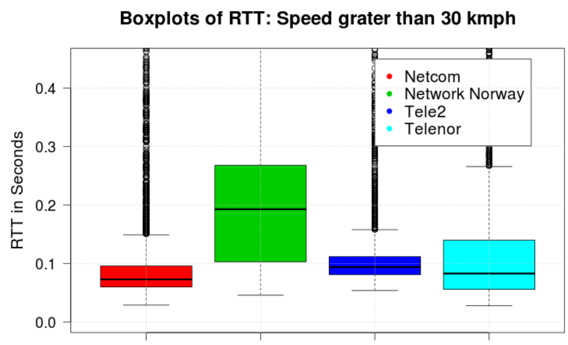
(a) RTT for upto speed 5 kph)



(b) RTT for speed 6- 20 kph



(c) RTT for speed 21- 30 kph

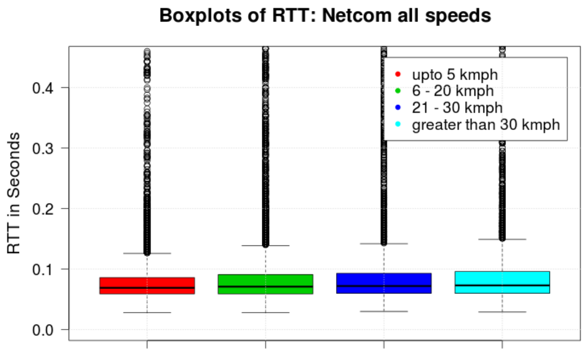


(d) RTT for speed greater than 30 kph

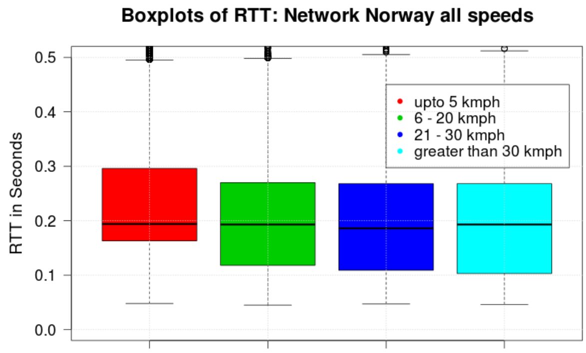
Figure 4.17: Delay in different speed for four UMTS operators

6 - 20 kph, 20 - 30 kph and greater than 30 kph, operators with low to high RTT distribution are Netcom, Tele2, Telenor and Network Norway. Although Telenor's median RTT value (85 msec) is lower than Tele2's median RTT (95 msec), overall distribution is more clustered in Tele2 with 3rd quartile distribution below 115 msec than Telenor's 140 msec. So Tele2 is, arguably, considered better than Telenor in delay.

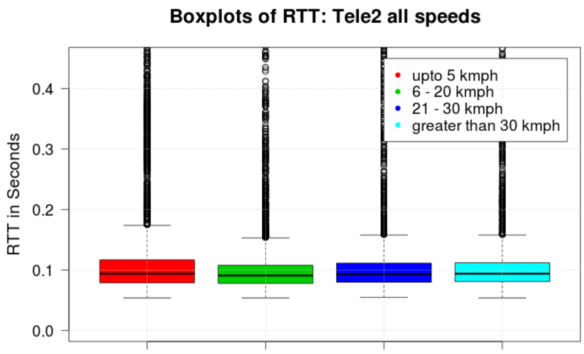
Comparison of effect of speed on delay performance within same operator is depicted in Fig 4.18. In case of Netcom and Telenor, RTT values are slightly higher while increasing speed, but seems reverse in case of Network Norway. Tele2 has almost unchanged performance while increasing speed. So far, RTT distributions in different speed presented in Fig 4.17 (a), (b), (c), (d) and in Fig 4.18 (a),(b),(c),(d) reveals that there is no significant variation in RTT in different



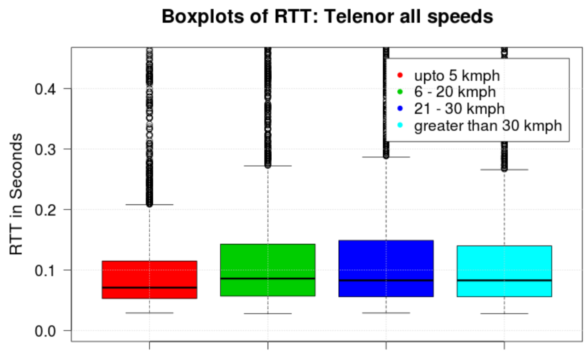
(a) RTT for Netcom in different speed)



(b) RTT for Network Norway in different speed



(c) RTT for Tele2 in different speed



(d) RTT for Telenor in different speed

Figure 4.18: Delay in different UMTS operators in different speed

speed. But, measurements were performed via public transport which rarely goes above 60 kph, it is difficult do analysis here about the effect of very high speed.

4.5 Additional Observations

In some cases, bunch of packets were received back to back in node as piled up fashion with high latency as shown in table 4.3. Here, 49 packets were received at same time from telenor network. If one way delay is observed in such high latency case, two scenarios were observed. If there is some events at that instance such as change of mode, submode, LAC and cell, the high value of delays are in uplink. But if none of these events at that time, high latencies are in downlink.

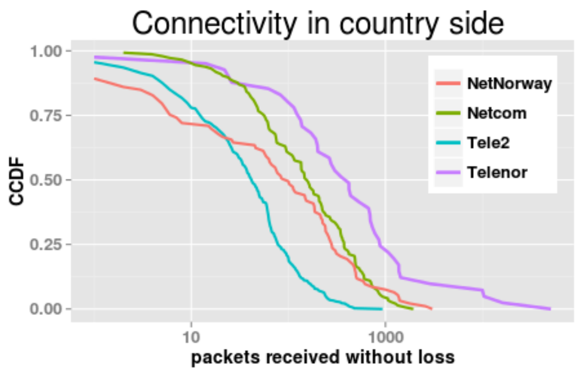
Sent-time	Received-time	RTT (sec)	Pkt-Nr	RRC	Mode	Submode	Cell	LAC	RSSI
1396584254	**1396584303**	**49.557**	762	DCH	WCDMA	HSPA+	D44DC7	52D1	20
1396584255	**1396584303**	**48.567**	763	DCH	WCDMA	HSPA+	D44DC7	52D1	20
1396584256	**1396584303**	**47.576**	764	DCH	WCDMA	HSPA+	D44DC7	52D1	20
1396584257	**1396584303**	**46.586**	765	DCH	WCDMA	HSPA+	D44DC7	52D1	20
1396584258	**1396584303**	**45.595**	766	DCH	WCDMA	HSPA+	D44DC7	52D1	20
1396584259	**1396584303**	**44.605**	767	DCH	WCDMA	HSPA+	D44DC7	52D1	20
:	:	:	:	:	:	:	:	:	:

Table 4.3: Multiples packets received in same time

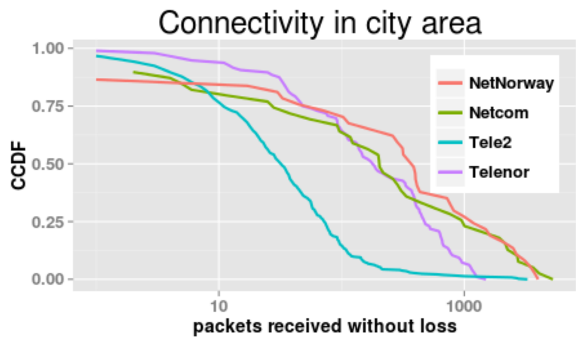
It was observed same base stations (Node Bs) used by more than one network. While looking into more details it was noticed that outside the network coverage of Tele2, it is camping on Netcom. Similarly, Network Norway is camping on Telenor when mobile nodes are outside its network coverage.

It was also observed, sometimes, IP change in Telenor. But it found difficult to figure out exact interval between IP change, i.e sometimes about 30 minutes, sometimes 60 minutes, and mostly within that period. While sending packets, operators' IPs were bound to client sockets to select particular interface among different active interfaces in node, so change in IP halted measurement procedure for some times. This issue was simply handled with destroying previous socket and create new socket and bind with new IP. The exact reason behind changing IP could not be known, but at least it is found that this IP change is not related to mobility. Packets that were not collected in such events are not counted in loss since these packets were not actually lost but not measured due to interface down. However, such interface down may impact connectivity performance as consecutive packets are discontinued.

It was also measured RRC states and Signal level and found that almost all collected 3G packets are in active DCH state and good signal level in mobility with median RSSI value is about 22. At least it was not found any mobility issues on signal strength and RRC states.



(a) CCDF for connectivity: Country side



(b) CCDF for connectivity: City area

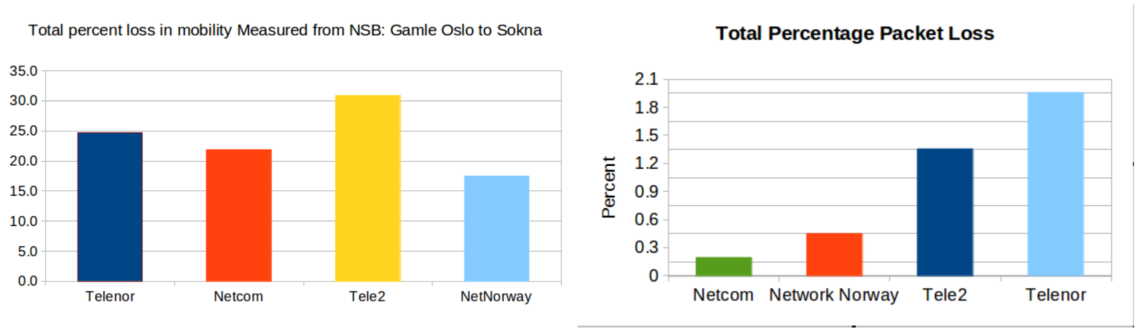
Figure 4.19: CCDF plot showing connectivity: packets received without loss

4.6 MBB performance in countryside

Up to this section, results and analysis have presented for MBB performance metrics measured from city area of Oslo which was focused in this thesis. As an extension of this study, initial measurement has done little outside of Oslo i.e. from Gamle Oslo to Sokna, about 88 km, from NSB high speed train. This measurement is different from previous measurement in city are with three senses: country side, very high speed, and tunnel. The results from this initial measurement are presented here with comparison to city area performance. The initial results look interesting and added more excitement to carry out extensive study in remote area.

Connectivity performance in country side are compared with city area connectivity in Fig 4.20. From this plot, Telenor looks better in remote area compared to other networks. The connectivity data seems little better in city than remote for all operators. Moreover, 25 % connectivity data were more than 1000 packets without loss in city for Netcom and Network Norway, which was not observed in country side for any network.

Overall packet loss is very high in country side measurement than city area which is depicted in Fig 4.20. From this graph, it can be seen that there is more than 15% loss in country side in all operators where as maximum loss is 2 % in city area. From this result, total packet loss looks highly affected in country side. Moreover, on the basis of total loss metric, Netcom seems better in city



(a) Packet loss: Country side

(b) Packet loss: City area

Figure 4.20: Total percentage loss: city versus remote area

where as Network Norway is comparatively better in remote.

RTT distribution is also seems significantly affected in remote area than city area as depicted in Fig 4.21. As per result, RTT values are significantly higher in remote than city except Network Norway. Comparing operators in delay performance, Network Norway seems the best in remote where as Netcom in city. Network Norway's city performance is almost similar to it's remote area i.e slightly better in city. For other three networks, in remote area, median RTTs are more than double to city and overall RTT distribution seems to be shifted (increased) by more than 150 msec in these networks.

It is believed that the performance is not only affected by remote area network coverage but also by high speed on NSB train and frequent tunnels on its way, where performance was expected to be poor. As mentioned before, these country side results are just from preliminary measurements to see the possible performance, so may not represent true performance until extensive measurements.

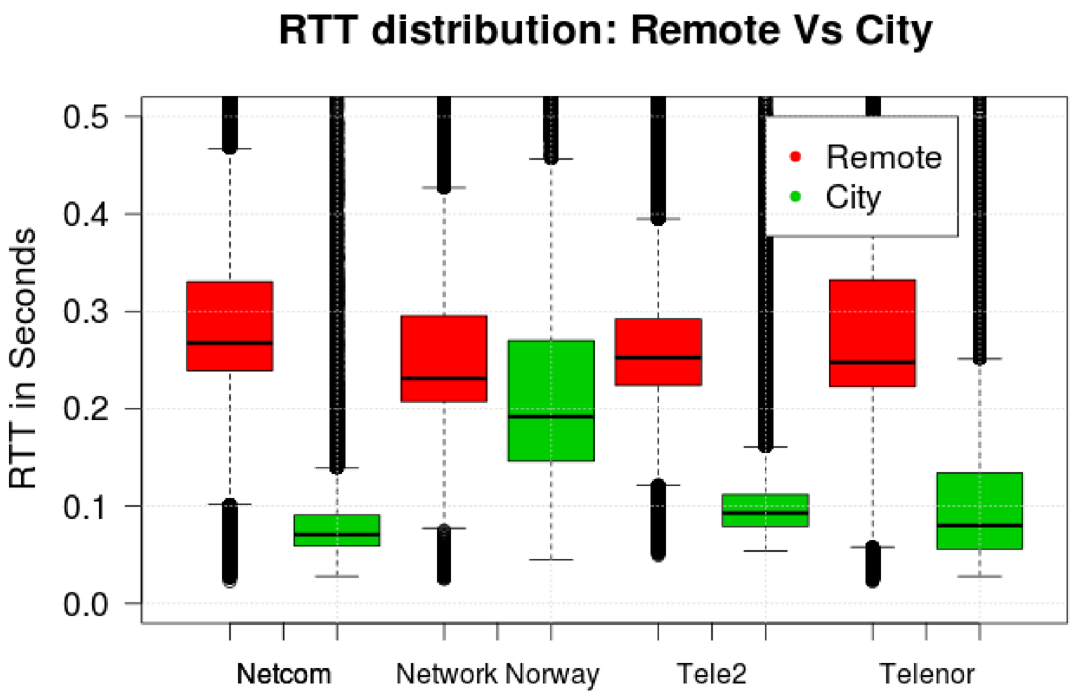


Figure 4.21: Delay(RTT) distribution: remote vs city

Chapter 5

Discussion and Future work

5.1 Project evaluation and its usefulness

In this project, Norwegian MBB networks under mobility were evaluated with regards to connectivity, packet loss and delay and compared with static performance. Moreover, the MBB behaviors in mobility like handover, signal strength, RRC, mode and submode were studied. The four networks who share more than 80 % mobile broadband market share in Norway [48][49] were compared. These networks are characterized in different places and speed with measurements in week days and weekend, peak hours and off-peak hours keeping in mind that off-peak measurements are almost free from impact of the background traffics where as peak measurements represents more congested environment.

During measurements, packets were collected mostly in 3G and few in 2G except Network Norway where all packets were in 3G. Most of the packets in 3G were in HSPA+ except Network Norway where 1/3 packets were with WCDMA and HSDPA.

Different performance metrics were affected differently in mobility. Connectivity, measured as number of packets received without loss, seems significantly affected under mobility. Almost all packets were received without loss in static scenario, where as significant connection loss were observed in mobility. If works are ranked networks based on their connectivity performance in mobility, Network Norway outperformed other operators. It was also observed that more connections are lost in downlink as compared to uplink in all operators.

Similar to connectivity, packet losses were also observed more in mobility. In static, the measured values showed almost negligible packet loss in all operators. But in mobility, noticeable losses were observed with the more in Telenor, i.e. about 2 %, followed by Tele2. Packet loss in Netcom was very low, which can be arguably negligible. Loss in Network Norway was quite lower than Tele2 but higher than Netcom. It was observed that majority of packet losses were caused by handovers except Tele2, where random loss was very high. Additionally, more packets were lost in downlink than uplink, though the difference was not big.

Unlike connectivity and packet loss, overall delay distribution was not significantly affected under mobility despite some performance degradation compared to static. While comparing RTT distributions among networks, Netcom outperformed other operators. While comparing latencies between packets received in 3G and packets received in 2G, results show that RTTs in 3G are significantly lower than 2G, as per expectations. Moreover, RTTs in HSPA+ were significantly lower than other submodes within 3G packets. Due to the time difference in server and node, most of one way delay (OWD) were off-sync and discarded. But from preliminary observation it seems that uplink delays contributed more than downlink similar to discussion in [9].

All measured performance metrics i.e. delay, loss, connectivity etc. were slightly deteriorated in initial movement from static (speeding up) and in higher speed in most of the operators. But the results didn't indicate significant variance by speed on all measured performance. But, measurements were performed via public transport which rarely goes above 60 kph, it is difficult do analysis here about the effect of very high speed.

Handover behaviors on MBB networks were also studied and found that all handovers didn't cause packet loss. Approximately 55% handovers caused packet loss in an average, which are believed as hard handovers. Handovers that were not affecting MBB performance are believed as soft handovers that were discussed in section 2.1.1.2.1. More frequent handovers were noticed in telenor as compared to other networks and 2/3rd of them caused packet loss, giving the highest number of loss among all four operators. It is believed that Telenor has more clustered base stations in city area that caused more handovers as compared to other networks. RTTs were also significantly increased in most of the handovers, but few handovers didn't affect RTTs similar to packet loss. Connectivity performance, which was correlated well with packet loss, was also affected due to handovers.

Frequent packet loss and connection failures were observed in Tele2 that discussed before as random loss. In most of such cases, it was observed that Tele2 and Netcom are using same Node Bs (base stations) which means Tele2 is camping on Netcom outside its coverage. It was also observed/verified that outside the coverage, Network Norway is using Telenor's network.

RTT estimates degree of network congestion i.e. low RTT means good QoS particularly for VOIP/Video conferencing. It is believed that packets are lost mainly due to handover and deep fading in mobility as anticipated. Since packets were sending using UDP, reasonable packet loss was expected as there is no mechanism like congestion control and retransmission in UDP. Frequent handovers indicated rapid change of radio environment in mobility. The prescience of these MBB characteristics has great potential while estimating network link/path stability based on connectivity, delay and packet loss.

It is believed that the results and analysis discussed in this project are of significant importance for different stakeholders related to MBB networks. End users can choose operators that suit them as per their requirements. MBB network providers can use these results to identify problems on their networks and make possible improvements before customer complaints. This results with some additional research can guide tech business firms to develop robust products and services compatible to the available networks. Application designers will get guideline to develop efficient network/communication applications considering the underlying characteristics and behaviors of networks.

5.2 Review of overall process

5.2.1 Limitation/weakness on Experiments

Complete MBB performance can only be evaluated if all possible type of traffics, parameters, conditions are considered with full coverage. But experiments were designed to measure only UDP echo traffic for normal traffic condition and focused in city area of Oslo. Experiments were designed to measure only delay, loss and connectivity but not throughput. Experiments also failed to measure brusty nature of UDP/TCP traffics. So, performance on congested environments, performance on TCP-based traffics, performance in remote area were not measured. Networks may perform differently on throughput, though RTT and packet loss significantly affects throughput [50]. These are considered as weakness of experiments and the main reason behind this is the time constraint. Study area is also limited to focus more detail research on smaller part which is believed as better approach than surfacial study on bigger area.

5.2.2 Limitation/weakness on data collection

In this project, data sets were collected by carrying measurement box in buses, which required human involvement during all the measurements. Log files containing raw data were collected one by one from measurement node/server and analyzed, again need more human involvement. But data collection could be done with hooking our measurement box equipped with modem for each operators along with GPS receiver in public buses and trains and kept them running. Measurement tools could be run in both node and server and data could be logged all time. Automatic tools to scanned logged directory could be deployed in both node and server which could be run periodically and upload scanned raw data to the database. This automation of data collection reduces human involvements and errors associated with them . It makes data collection possible both in city area, country side and places where performances are expected as poorer like tunnels with variation of times, days, locations and speed. This data collection approach increases project efficiency with more validity and reliability on research. Additionally, throughput (Uplink and Downlink) and TCP data set could be collected deploying separate scripts along with previous measurement tools with/without additional node/modems in same run.

5.2.3 Likelihood of errors on data

There might be small chances of errors in data due to stateful nature of MBB networks and its tendency to reserve resources, though random period of time was waited between consecutive measurements to return into idle state. First few seconds' data might not be stable due to initial channel acquisition and may contain errors . The size of the buffers used in networks also may leave errors which is more explained in section 5.2.4. There are huge discussion about accuracy of time.sleep() in web and as per module docs, it can be off by small unknown amount of time (1 to 10 msec) every call. So it is likely that some small errors may present in delay.

5.2.4 Surprising results

Very high latencies (RTT) were observed in some cases, up to 49 secs. Few of these are associated with mobility events such as mode change, submode change, LAC and Cell change. In such events, delays are high in uplink and significantly low in downlink. But if there are no such mobility events associated with very high delay scenario, then delays are high in downlink and significantly low in uplink. It is presumed that this might be due to too high buffers used in networks which is also called buffebloat. This phenomenon is observed in all networks and more often in Telenor. If it is bufferbloat, it increases latency and reduces overall network throughput so the network operators need to take appropriate measures (such as network scheduler) to alleviate such problems.

5.2.5 Alternative Approaches

Apart from approach used in this thesis, the MBB performance can be measured with different approaches, some of which are listed here as alternative approaches.

- Client-server approach with ping and traceroute packets. Laptop equipped with modem for each operator can be used as client.
- Data trace of packets exchanged are captured with Tcpdump/Wireshark and Tcptrace to analyze data. Data might be from different application like web, mail, SMS, VOIP etc.

- Crowd-sourcing using different monitoring tools. Users can run different network monitoring applications like pchar, speedtest, iperf, MTR, MGEN etc. on their mobiles/laptops to measure MBB performances.

All these approaches are rejected due to some limitations prevailed on these approaches. Laptop can be used as client but there might be some laptop-specific issues which might very from laptop to laptop. Similarly there might be some background processes which may affect performances. Crowd-sourcing needs several users in different locations, might be expensive and time consuming. The data collected from crowd-sourcing is difficult to verify and might be biased.

5.2.6 Experiences and Learnings

The project work was carried out in Simula, a world-class research environment, with frequent field visit for measurements. It was really a good opportunity to learn research methodology and accomplish some challenging tasks under the pressure of short deadline. It was immense experience and good motivation for future research works.

Working on the first research work, its little difficult to define volume of the work within specified topic in the beginning. So, final project work is as a result of some minor expansions and reductions of the tasks with frequent feedbacks from supervisors and others. After exploring practical problem, problem statement was defined and redefined before going into design phase. Extensive review of literature and related works helped to get right direction to address the problem. Then, experiments for measurements along with performance metrics were designed, possible approaches were listed, studied and discussed well before choosing reasonable one. Measurement scripts/tools were developed with series of testing before actual measurements.

Desired data sets were collected using selected approach, and tried to understand raw data followed by series of recollection to meet requirements, to avoid missing and to provide more reliability. Raw data sets were converted to results and pivotal information were extracted applying suitable statistic analysis tools/models, which was considered as crucial and challenging part of this project. Observed results were analyzed with different prospects for each performance metrics along with some important observations. Finally, MBB operators under mobility were compared and explored usefulness of this work on real life and scientific research.

Numerous shortcomings and mistakes were committed as a novice researcher and learned that disciplined approach need to follow to complete tasks successfully within defined time. The importance of innovation was realized and basic skills for scientific writing and skills to work independently were developed from this project. More importantly, motivation and inner interests for future research were developed form this thesis work.

5.3 Future Works

Due to the time constraint, this thesis could not cover some research possibilities on MBB performance under mobility and they are proposed for future works.

We measured performance by sending packets in every seconds which just gives performance in normal traffic condition, not for brusty traffic. So we could measure performance by sending different packets per seconds, like 5 pkt/sec or 100 pkt/sec or can saturate the links as future work. Moreover, we proposed to measure other QoS parameters than connectivity, delay and loss like bandwidth, stability, reliability etc. in coming days.

Since we measured performance using UDP protocol, a transport layer protocol used by loss tolerant and delay sensitive applications like multimedia, VIOP etc. But we may get different results for loss sensitive delay tolerant applications such as web, file transfer, email etc. So, We proposed future research for MBB performance under mobility using TCP protocol.

There are also good prospects of future research of MBB performance measurement in remote areas and subways where performance might be poorer than city area. We also recommend research with alternative approaches with more end users' experiences and involvements like crowd sourcing, application load time etc.

We observed that different operators behave differently. If we can combine them, we can achieve more reliable communication through multipath. So MBB performance/QoS under mobility using multipath/MPTCP is highly recommended as future work. It is also advised for future research on 4G networks when 4G networks is widely deployed by MBB operators.

Chapter 6

Conclusion

In this project, performance of mobile broadband networks under mobility were studied and compared with static. Mobility performances were also compared between networks with regard to connectivity, packet loss and delay. Moreover, handovers and radio conditions were observed to characterize operational MBB networks under mobility. MBB performance metrics were measured in week days and weekend, different times of a day to represent peak and off-peak performance using public transport available in Oslo, Norway.

It is shown that in mobility, connectivity and loss are more affected than delay performance. Significant packet loss and connection failures were observed in mobility, which was negligible in static. Delay performance under mobility is slightly poorer than static in all networks. Moreover, all performance parameters are affected by small amount in initial speeding up and in higher speeds.

Even though underlying technology is same, reasonable differences were observed in all measured performance metrics in different networks under mobility. Frequency of handover is different and unpredictable in different networks. Despite these differences, highly scattered delay distribution were observed in all networks. Significantly high delay values were observed frequently in all networks, contributed more by uplink in case of handovers and by downlink if no handovers, which is believed as bufferbloat. Although major losses were contributed by handovers in most of the networks, it is also noticed that all handovers didn't cause packet loss and disconnection meaning that handovers with and without loss were measured in all operators. It is noticed that in an average packet losses and connection failures are more in downlink than uplink.

It is also found that most of the packets collected are in 3G with few in 2G outside 3G network coverage. Moreover,it was observed that majority of the packets within 3G are HSPA+, which shows better performance than other packets, like HSDPA, HSUPA, WCDMA etc, as per expectation. It is found that some networks are camping to others outside their network coverage. It is also observed that, from the preliminary observation, high speed country side performances are weaker than low speed downtown which need to be validated with extensive study.

Chapter 7

Appendices

7.1 A

Following scripts were used as measurement tools. These are placed in Github repository for references. https://github.com/yubars/mbb/

interfaceinfo.py
pathinfo.py
client.py
server.py
gpsdata.py

7.2 B

Following scripts were used during results and analysis. These are also placed in Github repository for references. https://github.com/yubars/mbb/
combine.py
mobility.py
speed.py
separate.py
connectivity.py
loss.py

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