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Latency analysis of LTE network for M2M Smart Grid applications

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ABSTRACT OF THE MASTER'S THESIS

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The benefits of reliability, pervasiveness, efficiency and mature ecosystem of LTE make it the major candidate to support M2M applications in the future. LTE MTC is a part of upcoming release 13 of global 3GPP standard, making LTE to coexist with M2M applications. In LTE, power enhanced power modes are introduced which extend the battery life but on the cost of increasing latency. M2M requirements are more towards the low throughput and low latency applications. Therefore, it is necessary to investigate the performance of commercially available LTE network in terms of latency. This thesis work presents the results of the measurement campaign which included latency measurements in the commercially available LTE networks with the emulated M2M traffic types in different kinds of coverage conditions.

In the context of the thesis, smart grid is taken as one of the use cases in M2M communication. Smart Grid companies are looking for the long term solution for communication infrastructure to support remote control, automation and monitoring use. But, they are not putting hands in rising technology in the M2M world i.e. LTE, although it has been proved to be promising technology for mobile broadband communication for H2H communications. The latency results presented in this work are expected to provide utility companies a foresight about performance of public LTE network to support delay sensitive applications. Moreover,the results also demonstrate the necessary optimizations required from network operator side to support M2M applications.

Keywords: LTE, latency, Machine-to-Machine Communication, Smart Grid

Preface

This master thesis has been carried out in VTT Finland for the project CLEEN SGEM (Smart Grid Energy Market) as a background study for future works. I express my sincere gratitude to Seppo Horsmanheimo, who has been my instructor at VTT, for his guidance and supervision of the work. Moreover, I am very thankful for his patience while conducting the measurements, feedbacks and thesis correction.

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Finally, I want to thank my parents and friends for all their support throughout my work.

Otaniemi, January 2015
Niwas Maskey

Contents

List of Figures

List of Tables

Abbreviations

3GPP	Third Generation Partnership Project
AMI	Advanced Metering Infrastructure
ARQ	Adaptive Repeat Request
BSR	Buffer Status Report
BTS	Base Transceiver Station
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CONCARI	Communication and Control for Critical Infrastructures
CQI	Channel Quality Indicator
C-RNTI	Cell Radio Network Temporary Identity
CSP	Connection Service Provider
DA	Distribution Automation
DC	Dual Cell
DRX	Discontinuous Reception
DSL	Digital Subscriber Line
EPC	Evolved Packet Core Network
EPC	Evolved Packet Core
E-UTRAN	Evolved-Universal Terrestrial Access Network
FDD	Frequency Division Duplex
FTP	File Transfer Protocol
GOOSE	Generic Object Oriented Substation Event
GPS	Global Positioning System
GPSD	Global Positioning System Daemon
GSM	Global System for Mobile Communications
H2H	Human-to-Human Communication
HARQ	Hybrid Adaptive Repeat Request
HSDPA	High-Speed Downlink Packet Access
HSPA	High Speed Packet Access
HSS	Home Subscription Server
ICMP	Intenet Control Message Protocol
ICT	Information and Communication Technology
IEC	International Electrotechnical Committee
IoT	Internet of Things
IP	Internet Protocol
KPI	Key Performance Indicator
LTE	Long Term Evolution
LTE-A	Long Term Evolution-Advanced
M2M	Machine-to-Machine Communication
MAC	Medium Access Control
MIB	Master Information Block
MME	Mobility Management Entity
MMS	Multimedia Messaging Service

MTC	Machine Type Communication
MTCe	Machine Type Communications Enhancements
NACK	Negative Acknowledgment
NIMTC	Network Improvements for Machine Type Communication
NTP	Network Time Protocol
NTPD	Network Time Protocol Daemon
OFDM	Orthogonal Frequency Division Modulation
OWD	One Way Delay
PAPR	Peak to Average Power Ratio
PCI	Physical Cell ID
PCI	Physical Cell Identity
PCI	Peripheral Component Interconnect
PDC	Phasor Data Concentrator
PDCCH	Physical Downlink Control Channel
PDCP	Packet Data Control Protocol
PLC	Power Line Communication
PLMN	Public land mobile network
PMU	Phasor Measurement Unit
PPS	Pulse Per Second
PSS	Primary Synchronization Signal
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
QAM	Quadrature Amplitude Modulation
QoS	Quality-of-service
QPSK	Quadrature Phase-shift Keying
RACH	Random Access Channel
RA-RNTI	Random Access Radio Network Temporary Identity
RB	Resource Block
RB	Resource Block
RLC	Radio Link Control
RN	Relay Node
RNC	Radio Network Controller
RRC	Radio Resource Control
RS	Reference Signal
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RSSI	Received Signal Strength Indicator
RTT	Round Trip Time
RTU	Remote Terminal Unit
SCADA	Supervisory Control and Data Acquisition
SCFDMA	Single Carrier Frequency Division Multiple Access
SGEM	Smart Grid Energy Markets
S-GW	Serving Gateway
SIB	System Information Block
SIMTC	System Improvements for Machine Type Communication

SINR	Signal to Interference Noise Ratio
SNR	Signal to Noise Ratio
SPS	Semi-persistent Scheduling
SR	Scheduling Request
SSS	Secondary Synchronization Signal
TCP	Transmission Control Protocol
TMSI	Temporary Mobile Subscriber Identity
TTI	Transmission Time Interval
UDP	User Datagram Protocol
UE	User Equipment
UMTS	Universal Mobile Telecommunications System
UTC	Coordinated Universal Time
WAN	Wide Area Network
VLAN	Virtual Local Area Network
VoIP	Voice over IP
VTT	Valtion Teknillinen Tutkimuskeskus

1 Introduction

The recent advances in M2M technology have led to unprecedented increase of data traffic involving only machines without any human intervention. M2M has already been introduced in various sectors like health care, vehicular, smart homes and so forth. The next generation electric distribution system, Smart Grid has also realized the significance of M2M technology to modernize their infrastructure by the use of automated and intelligent power management system. The introduction of smart grid offers numerous advantages over the conventional system in terms of digitalization, flexibility, resilience, sustainability, and customization. However, the realization of smart grid requires the robust and reliable communication technology to facilitate M2M communication among boundless number of devices as well as the enhancement of existing standards and networks to inherit the advantages of all systems [1].

1.1 Background

Machine-to-Machine (M2M) communication aims to enable ubiquitous communication between machines without human intervention. M2M communication aims to connect billions of devices enabling in parts the Internet of Things (IoT) [2]. This form of communication finds its significance in remote devices, which are acting as interfaces to end customers and utilities. It has enabled the creation of unprecedented applications and has opened doors to new business models, which were not envisioned in the past.

One of the major fields of application of M2M services has been smart grid [3]. Smart grid is considered as the future proof enhancement of the current electricity distribution network. Smart Grid has been looking for future-proof, cost effective and wide coverage communication solutions for remote monitoring and automation of distribution entities. Modern energy grid requires pervasive data communication, which connects millions of smart meters and thousands of sensors on the low and medium voltage lines, devices and stations. *"Two way communications (bidirectional) along the power flow between consumer and grid"* is the key aspect for realizing smart grids [3]. Therefore, the underlying communication network must be able to support adequate networking resources for smart grid features like data collection and task execution by assuring adequate bandwidth, availability, latency and guaranteeing application QoS requirement [4] [5].

The existing communication enabler for current power system is limited to Power line communication (PLC) and the Supervisory Control and Data Acquisition (SCADA) which do not meet the performance requirements for future automated and intelligent large scale power system [6]. The performance of the modern smart grid is largely dependent on latency and bandwidth offered by the communication enabler as automation tasks require real-time bidirectional communication. The International Electrotechnical Commission (IEC) has defined various smart grid applications and functionalities along with their communication requirements in terms of latency.

1.2 Motivation

Various communication technologies have been used to support communication network for the electric distribution system, such as PLC, Ethernet, Optical fibres etc. But, the utility companies are looking for a reliable and ubiquitous communication technology to meet the long-term requirements of the modern electric grid. Due to rapid development and wide deployment of 3GPP cellular networks, LTE network is expected to be a significant part of the M2M communication, which is able to provide main advantages of low latency, high capacity and wide coverage [7]. Therefore, LTE is expected to be major communication technologies for M2M services in future due to its wide adoption and M2M friendly features. However, LTE has been designed and optimized for broadband communication services for H2H (Human-to-Human) applications which are not same as the Smart Grid data traffic, whic are used for automation and real-time monitoring purposes. Hence, 3GPP (3rd Generation Partnership Project) is trying to extend LTEs' further releases to support M2M service characteristics under Machine Type Communication (MTC), coexistence with concurrent communication services. Moreover, Network operators are also expected to expand their services beyond the conventional voice and broadband services to open new form of revenues. Therefore, M2M communication via cellular networks has promising and strategic values for mobile operators as well.

This thesis conducts experimental trials in LTE public commercial networks to evaluate the performance of LTE in terms of latency to support smart grid applications, and attempts to answer if LTE technologies are already ready to offer smart grid services with current deployment with LTE 800 network with required latency.

1.3 Thesis Outline

The remainder of the thesis is organized as follows.

Chapter 2 presents the problems addressed in this thesis as well as discusses the research questions addressed by this thesis work. Relevant works done on this particular field are also presented.

Chapter 3 provides the technical overview of LTE along with its key characteristics to support M2M applications. The LTE features which are related to latency are also described in this chapter.

Chapter 4 describes the M2M architecture in LTE network and associated latencies concerning LTE.

Chapter 5 describes the smart grid application along with their communication requirements. The communication technologies available to support smart grid applications are discussed along with their pros and cons.

Chapter 6 describes the measurement setup and provides the experimental results along with the evaluation of measured performance metrics.

Finally, Chapter 7 outlines the conclusion of the thesis and future research works.

2 Problem Formulation

There are still debates going on among utility companies if it is too soon to utilize LTE network to support automation and intelligent management system in Smart Grid (SG). Although there has been quite a lot of research works for feasibility study of using LTE network to support SG applications, there are still many technical challenges which are waiting for solutions. Therefore, this chapter describes one of those problems that is addressed in this master thesis and research questions that are posed.

2.1 Problem statement

3GPP has defined M2M communication as a form of communication which involves one or more entities and requires no manual intervention. MTC (Machine Type Communication) is the term used for M2M in 3GPP [8]. There are billions of machines in the world which need to communicate autonomously with other machines Therefore, M2M communication is not a new term, but until now it has relied on industry specific communication technologies to support M2M communication. However, M2M applications are now being supported by cellular network technologies and gaining popularity in the recent years. The Ericsson mobility report 2014 revealed that the number of active cellular M2M devices will increase 3-4 times by 2019, from 200 million at the end of 2013 [9]. Majority of cellular M2M devices today are utilizing GSM network only, but by 2016 it is expected to shift to 3G/4G networks which will serve majority of M2M applications [10].

This thesis investigates the traffic characteristics of data services currently used in smart grid applications and simulate similar traffic in commercially deployed public LTE network, and finally evaluates the performance of LTE in terms of latency to see if it is capable to meet all the requirements for such applications. Latency is considered as the key issue for most of the smart grid applications and in particular to those associated with monitoring and remote automation functions, as the stability of the smart grid depends on the capability to detect and act on anomalies as soon as possible. LTE latency involves control plane latency and user plane latency. This thesis investigates both types of latency, measured in LTE network against several use cases. The bottlenecks in LTE performance are found if present in currently available commercial LTE networks.

Recent commercial deployment of LTE 800 possesses large coverage area and low penetration loss. Government of Finland has given guidelines to all network operators to cover 95% of national coverage (population) in 3 years and 99% in 5 years [FICORA]. Moreover, there is an indoor coverage obligation as well. Since there is spectrum scarcity for operators, they are planning to either completely turn off GSM network to replace with LTE or frequency refarming in GSM spectrum to support LTE network [11]. Therefore, in next 5 years, LTE network would be the dominant network providing broadband services to users.

Majority of smart grid devices are located indoors and in remote rural areas where the coverage of LTE network is challenging. The measurements are done in various places both indoors and outdoors with unique propagation environment, to observe if poor radio conditions and coverage affects the performance of LTE. LTE KPIs(Key Performance Indicators) are identified which affect the latency of the network and variation of such KPIs with coverage is also studied. A large number of MTC devices are expected to be deployed in specific area which increases network traffic and eventually radio network congestion may happen. This causes intolerable delays, packet loss or even service unavailability. Therefore, random access channel of LTE is prone to congestion in M2M communication scenario, which is addressed by this thesis through the measurement of KPIs to evaluate the performance of random access channel in LTE. These factors impose challenge in the network to guarantee network availability and meet performance requirement during MTC load conditions.

2.2 Research Questions

This thesis aims to answer several research questions regarding feasibility of use of public LTE networks for smart grid applications.

1. What are the basic communication requirements and challenges for supporting remote control communication for smart grid applications over LTE?
2. What are the technical factors which affect the latency in LTE network?
3. How LTE latency reacts to LTE specific features like Discontinuous Reception (DRX), transition between RRC (Radio Resource Control) states and random access?
4. What are the potential bottlenecks and limitations in the LTE network architecture to satisfy performance requirements imposed by IEC?
5. What are the possible solutions to overcoming above bottlenecks and limitations?

The literature survey indicated that, the performance of LTE networks for M2M applications has been evaluated in dedicated research networks or laboratory environment which allows the full control of the traffic and user behaviour in the network [12] [13]. But, public networks are characterized by additional inevitable factors and unknown number of users competing for the network resources. Therefore, the main motivation behind this thesis is to perform LTE performance measurement in public networks to see if they meet the requirements set by M2M standards in live network environment.

2.3 Relevant Works

Authors have presented anticipated traffic types to support smart grid applications along with their QoS requirement [14]. The challenges and research opportunities for different communication options to support those applications were also discussed. Kansal and Bose classified smart grid applications according to their latency and bandwidth requirements; simulation work was done to determine parameters to simulate a communication system for power grid [15]. Authors also concluded that average link bandwidth should be around 5-10 Mbps and latency within 100 ms to support all smart grid applications. The series of experiments done in NS-3 simulator to evaluate performance requirements of IEC 61850 MMS in LTE system were performed in [16] which showed that LTE can satisfy all the performance requirements of smart grid applications. The use of flattened architecture in LTE significantly reduces the RAN latency and promotion delay (connection establishment delay) in compared to GSM/UMTS [17]. The latency and reliability analyses were performed for LTE 3GPP release 8, for making LTE as a promising candidate to build WAN network for smart grid [18]. IEC 61850-5 standard has defined communication requirements for substation automation systems by classifying all functions into performance classes based on transfer time for different message types.

With the introduction of large number of M2M devices, congestion in the network happens which will have impact on H2H communication. Therefore, novel congestion algorithm is required to handle such a huge amount of traffic such that both MTC and non-MTC users can co-exist together. The PDCCH of LTE may become a bottleneck when a large number of devices want access to the network, which may cause random access failure. [19]. Laya et al have surveyed alternatives for the efficient operation of random access channels in LTE and LTE-A for M2M communication, with their strengths as well as weaknesses. Additionally, they also pointed out delays and energy efficiency will play key role in the deployment of LTE networks for M2M. The optimization is needed to find best tradeoff between latency and power saving mode like Discontinuos reception (DRX) based on operator's power saving preference and latency requirement of traffic [20].

The term "Cellular IoT" was introduced which covers new ecosystem of M2M devices supported by cellular network providing lower cost connectivity, true "plug and play" experience, increased battery life, robust authentication and reliable connectivity [2] . A study was performed to clarify the current state of M2M utilization rate in terms of traffic, subscriber numbers and radio performance which showed that GSM was the dominant cellular network supporting most of the smart meters.

2.4 Previous Works

In SGEM project [21], study was made about the feasibility study of using cellular networks for remote automation of distribution network in urban and suburban areas. The real time storm outages were simulated and analysis were made about the inherent redundancies present in cellular networks which can be utilized to reduce the outage period during storms. [22] [23]. Moreover, coverage and latency measurements were also done in urban area and distribution entity indoor premises which showed the that variable indoor coverage environment affects QoS performance of cellular network [24].

In CONCARI project, research was made to study the inter-dependencies between mobile communication networks and electricity distribution network. The simulation works were conducted to exploit the SON (Self Organizing Network) features of LTE network to automate the healing of coverage holes of networks and hence, reducing the outages caused during storm by distribution network failure.

At the time of research being done, there have been limited studies of practical measurements in LTE public network for its feasibility to support smart grid applications. In our previous works in SGEM and CONCARI, latency was identified as the key constraints that modern grid automation introduces and is the principal research subject of this thesis work. This work also closely looks through the current status and future expectation of utilizing public cellular networks to support Smart Grid applications.

3 Long Term Evolution: A Technical Overview

In this chapter, a brief introduction to LTE is presented along with its key features which enable the integration of LTE with M2M systems.

3.1 Introduction

To meet the increasing demand for wireless capacity and higher data rates, 3GPP started working towards 3GPP LTE in 2004 even though High-Speed Downlink Packet Access (HSDPA) had not been commercially deployed yet [25]. LTE was developed to deliver superior performance than the existing 3GPP release 6 i.e. High Speed Packet Access (HSPA), which allowed peak user throughput of 100 Mbps in downlink and 50 Mbps in uplink. Moreover, a simple and flattened network architecture was also required to reduce network latency for improved user performance. Backward compatibility with previous generation networks (GSM/UMTS) was also necessary to make LTE technology future proof and commercially successful. The motivations behind the development of LTE network are summarized below:

- High spectral efficiency to support more users with broadband applications,
- User demand for higher data rates and Quality of Service (QoS),
- Backward compatibility and interworking with 3GPP earlier releases (GSM & UMTS) to ensure the competitiveness and cost reduction,
- Optimized packet switching,
- Streamlined architecture to reduce complexity,
- Optimized terminal power efficiency

3.2 Key Features in LTE to support M2M communications

LTE has been in the limelight as it has been deploying commercially over all round the world. Smart grid utilities are also keeping eye on LTE development as a potential wide area communication network to support their applications. LTE has been a global standard, is planned to offer low cost services for enhanced Quality-of-service (QoS) requirements. This subsection discusses the key features of LTE which are instrumental for M2M applications [26].

3.2.1 Flat network architecture

LTE is characterized by a flat network architecture which is divided into four high level domains: i) User Equipment (UE) ii) Evolved-Universal Terrestrial Access Network (E-UTRAN) iii) Evolved Packet Core Network (EPC) iv) Services Domains as shown in Figure 3.1.

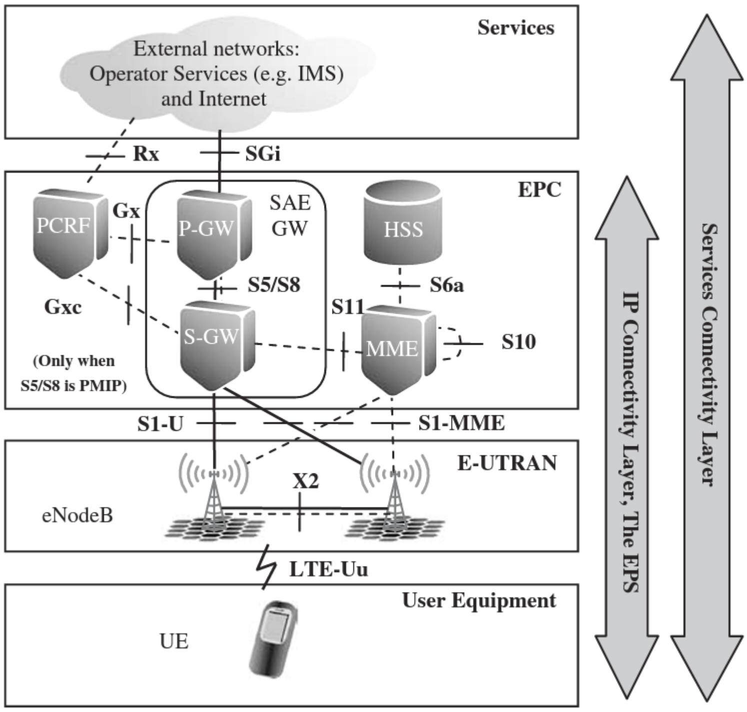


Figure 3.1: LTE network architecture [25].

1. **E-UTRAN:** E-UTRAN provides the air-interface between LTE network and user terminal (UE) and constitute the radio access parts of the network. All the radio related protocols for e.g. PHYsical, Medium Access Control (MAC), Radio Link Control (RLC), Packet Data Control Protocol (PDCP), Radio Resource Control (RRC) are defined between the UE and E-UTRAN Node B (eNB). The RLC layer provides the reliability services through segmentation and reassembly. The RRC protocol serves to maintain multiple radio bearers services (Radio Resource Management) as well as handle handovers (Mobility Management) whereas PDCP provides IP header compression service and enables ciphering of data to maintain the integrity of the messages. It can be noted that in LTE, intelligence is distributed among the eNodeB unlike GSM/UMTS which has centralized intelligent controller as Radio Network Controller (RNC). Therefore, since eNodeB can make decisions without consulting another network node, connection setup time, time required for handover and latency is decreased.

2. **Evolved Packet Core Network (EPC) :** EPC supports E-UTRAN through reduction of network elements, simplification of functionalities which allow seamless connections to other fixed-line and wireless technologies. EPC comprises of multiple logical nodes Serving Gateway (S-GW), Packet Data Network Gateway (P-GW), Mobility Management Entity (MME) and Home Subscription Server (HSS). S-GW handles routing and forwarding of data packets

which enable mobility of users between eNodeBs and provide compatibility with other 3GPP radio access technologies. P-GW is the edge router between EPS and external Packet Data Networks (PDNs) which acts as the IP point of attachment for UE. It also acts as a filter gate for the services provided to users. MME is responsible for mobility management which tracks the locations of all UEs in its service area, performs authentication for users and manages subscription profile of a user in the network. HSS is the database server which maintains records of all subscriber profiles.

3. **Service Domains:** The service domain may include various logical nodes which may provide IMS (IP Multimedia Subsystem) based operator services or non-IMS based services. The operators can provide UE specific services by placing servers in this domains, e.g., Smart Grid services can be handled by a server placed in this domain which provides smart grid services to grid entities.

3.2.2 Multiple access based on OFDM

Orthogonal Frequency Division Modulation (OFDM) is used for downlink multiple access in LTE where data are transmitted in multiple narrowband subcarriers (15 KHz) which are orthogonal to each other [27]. Orthogonality among subcarriers provides the resistance to inter-symbol interference in the frequency domain. Furthermore, LTE network can allocate resources efficiently among the users according to the data rate requirements by scaling the system bandwidth (5 MHz-20 MHz) and accordingly adjusting the allocated sub-carriers. The Single Carrier- Frequency Division Multiple Access (SCFDMA) is used for uplink multiple access to reduce Peak to Average Power Ratio (PAPR) and allows the use of efficient power amplifiers in user terminal.

3.2.3 Dynamic Scheduling

The schedulers have the significant role for efficient utilization of radio resources as the radio resources are limited and a large numbers of users with various performance requirements compete for network access. It has to consider both accommodating users in the network as well as ensure requested QoS to the users. The scheduler should also consider that if the requested QoS from the user can't be complied then, users should be dropped (Admission control). As discussed in subsection 3.2.2, the use of OFDM allows the dynamic scheduling of resources for users according to user application needs. Therefore, users are not assigned any dedicated resources, rather both uplink and downlink data channels are shared among all the users. The scheduling is required to allocate the resources to the users, keeping in mind the available resources and number of users in the network. In LTE, scheduling is performed in every sub-frame i.e. 1 ms which is Transmission Time Interval (TTI). Shorter TTI facilitates lower user plane latency which is critical for latency-dependent applications. In the frequency domain, resources are allocated on a block basis where each block corresponds to 12 contiguous sub-carriers (180 KHz). Therefore, 180 KHz in frequency domain and 1 ms in time domain constitutes a Resource Block (RB) shown in Figure 3.2. The scheduler allocates the resources to users in the multiples of RBs. The number of available RBs depends on the available bandwidth and ranges from 6 (5 MHz) to 110 (20 MHz).

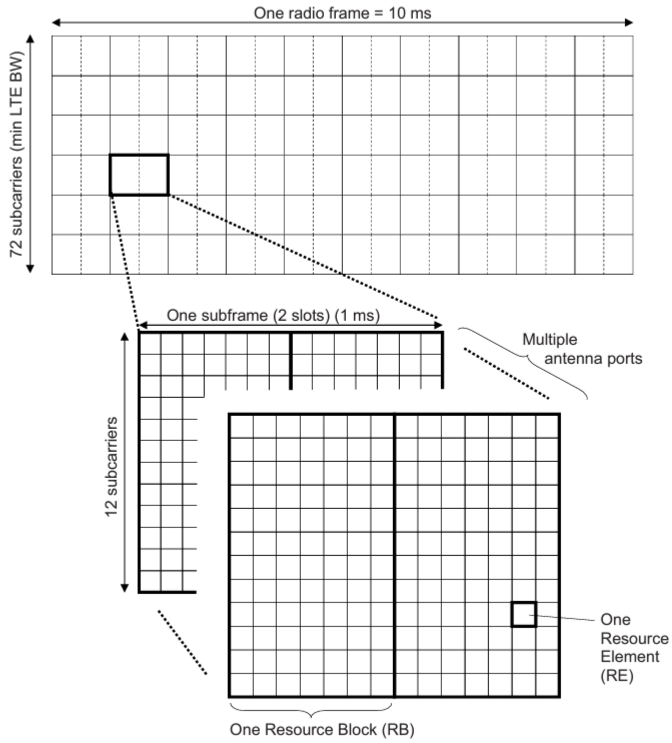


Figure 3.2: LTE Resource grid [25].

The scheduler can exploit both time and frequency variability of channels to decide allocation of resources, for e.g., scheduler can allocate more blocks in time or frequency domain to those UEs with favourable transmission conditions. The channel information is obtained by scheduler as Channel Quality Indicator (CQI) from UE to make enhanced scheduling decisions. The scheduler for smart grid traffic is likely to be different as they have unique traffic characteristics and QoS requirements which will be discussed in Chapter 5. Several studies have been done to design a novel scheduler for M2M specific applications [28] [29] [30].

3.2.4 Link Adaptation

Link adaptation refers to changing the modulation and coding schemes based on the instantaneous radio channel conditions [27]. More robust coding scheme like QPSK with low data rates are used for poor channel while less robust but capable of high data rates coding scheme like 64QAM is used for favourable channel conditions. A device has to report the measurement results in terms of channel quality to eNB to assist in link adaptation. Link adaptation is helpful to optimize user and system performance of mobile devices which possess time varying channel conditions. However, most of the M2M devices are fixed and the devices cannot take advantage of time variability of radio channels. Therefore, measurement reporting frequency can be optimized to reduce signalling load in the network.

3.2.5 Hybrid ARQ (HARQ)

In LTE, both uplink and downlink data transmission is acknowledged by the receiver by sending ACK to sender, if NACK is received, the sender will retransmit the packet along with a set of redundancy bits for forward error correction [27]. This procedure is called Hybrid Adaptive Repeat Request (HARQ). Since HARQ Round Trip Time (RTT) is 8 ms, the retransmission occurs 8 ms after the previous retransmission or may take even longer due to scheduling and queuing delays. HARQ facilitates error free transmission which increases reliability of communication link used in M2M. However, HARQ may introduce additional latency which may be critical for delay-sensitive applications.

3.3 LTE Random Access Procedures

Once the user terminal is switched on, it starts searching for the network. Since there are many frequencies from different operators, UE needs to synchronize to each frequency and check if frequency is from intended operator and network (Synchronization process). During synchronization process, UE acquires physical cell ID (PCI), time slot and frame synchronization which will enable UE to read system information blocks from a particular network. After the synchronization process is completed, UE reads the master information block (MIB) and system information blocks (SIB) to check whether it has connected to correct PLMN or not. Then, random access procedure starts when network knows that someone is trying to connect or get access to network. Following steps occurs before terminal attempts for random access channels (RACH): [27]

- **Cell Synchronization:** During cell synchronization, UE receives Physical Cell ID (PCI), timeslot and frame synchronization which enable UE to receive system information from a network. Cell synchronization is done using primary and secondary synchronization signals (PSS & SSS). After UE gets PCI for a given cell, UE also knows reference signals which are used for channel estimation, cell selection/reselection and handover procedures.

- **Master Information Block (MIB) in LTE**: After the initial cell synchronization is completed, UE reads the master information block (MIB) on BCCH (Broadcast Control Channel), BCH (Broadcast Transport Channel) and PBCH (Physical Broadcast Channel). MIB uses resource element in the first OFDMA symbols of second slot of first sub-frame of a radio frame. MIB carries basic information required by UE for initial access as follows.

    1. Downlink channel bandwidth in terms of Resource block

2. PHICH (Physical Hybrid-ARQ Indicator Channel) configuration (PHICH duration and PHICH resource)
3. System frame number

- **System Information Block 1 & 2:** After getting PCI (synchronization procedure) and MIB, UE read system information block to obtain cell access related parameters.

After synchronization procedure, random access occurs before data transmission begins. Random access (RA) procedures happen in two ways, contention based or contention free [27]. In contention based, many UEs send access requests at a same time, therefore, there is the possibility of collisions between requests. In second scenario, network informs UE unique ID to UE to avoid request collisions. During random access procedure, UE sends specific pattern or signature called RACH preambles. There are 64 unique preambles available to UE for random access to avoid collision. UE decides preambles randomly in contention based Random Access (RA) procedure while network will decide the UE preambles in contention free RA procedures. Contention free RAs are used during handovers. Contention based Random access procedures complete in following four steps as shown in figure 3.3.

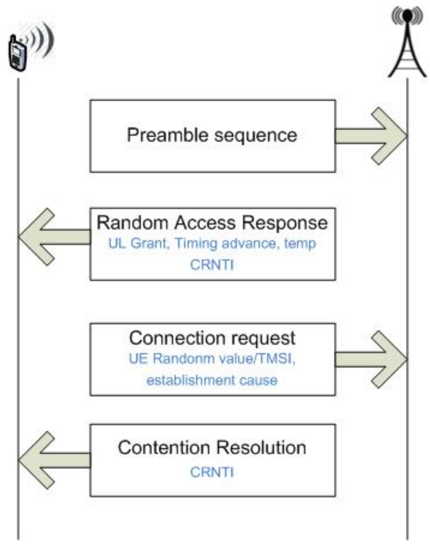


Figure 3.3: Contention based random access in LTE. [27]

Step 1: Msg1

- UE randomly select available RACH preambles
- UE identify itself to network using RA-RNTI (Random Access Radio Network Temporary Identity)
- UE ramps up power and resends the preamble if it doesn't receives any response from the network

Step 2: Msg2

- In reply to RACH preambles, eNodeB sends random access response addressed to RA-RNTI
- This message carries temporary C-RNTI (Cell Radio Network Temporary Identity) which gives identity to UE for further communication, timing advance details and uplink grant resource.

Step 3: Msg3

- UE sends RRC connection request to eNodeB along with UE identity TMSI (Temporary Mobile Subscriber Identity) and connection establishment cause.

Step 4: Msg4

- eNodeB acknowledges to msg3 with contention resolution message. After UE receives msg4, it will decode RRC connection setup message.

Random access delay is defined as time difference between msg1 and msg4. This delay is affected if there is a collision during random access. Collision may occur if following scenarios happen:

- Two UEs trying to access network use same preamble in step 1
- Two UEs receives same C-RNTI and uplink grant in step 2
- eNodeB might be unable to receive msg3 due to bad radio conditions/interference
- If UE fails to receive msg4, it will back-off after RACH specific timers.

All above scenarios will be more relevant in M2M communication where there are thousands of terminals in a single cell which are attempting to connect to the network at a same time.

3.4 Radio Resource Control in LTE

In 3GPP LTE, the radio resource control (RRC) sub-layer performs control plane functions such as system information broadcast, paging, establishment, maintenance and release of an RRC connection between UE and E-UTRAN, signalling radio bearer management, security handling, mobility management including UE measurement reporting and configuration, and QoS management [31]. A 3GPP LTE compliant UE has two steady-state operational modes: RRC_CONNECTED and RRC_IDLE. UE is in RRC_CONNECTED mode when RRC connection (control-plane) has been established; otherwise UE is in RRC_IDLE mode. The transient procedures for cell search and re-selection are not designated as 3GPP UE states. Salient features of each RRC state are listed below in figure 3.4.

LTE provides a set of functionalities i.e. DRX (Discontinuous reception) to make UEs perform sleep events during RRC_IDLE and RRC_CONNECTED state, to

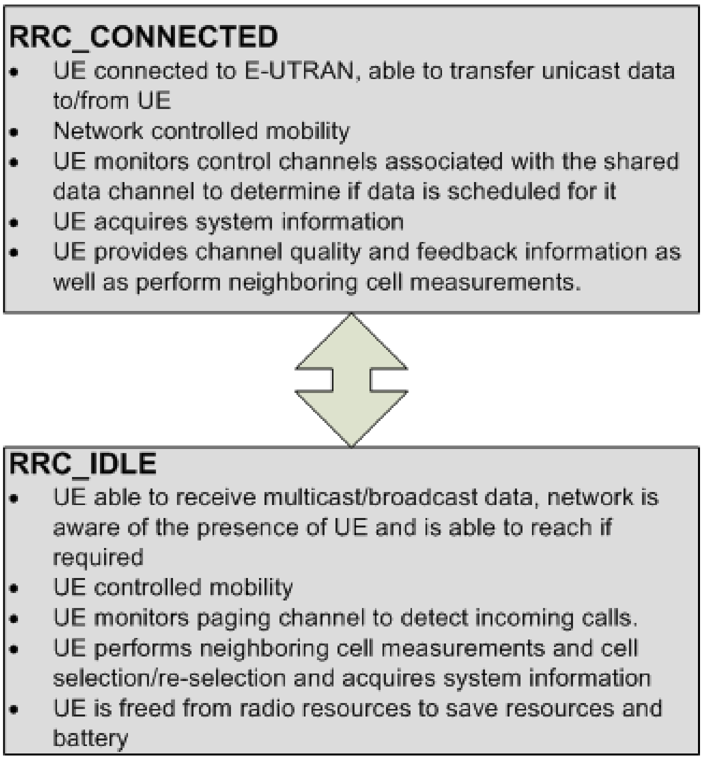


Figure 3.4: LTE RRC states [31].

save battery guaranteeing QoS and connectivity. During DRX, UE is not monitoring the PDCCH (Physical Downlink Control Channel) and is allowed to go to the power saving mode. Table 3.1 describes the user specific DRX parameter which is configured via higher layer signalling.

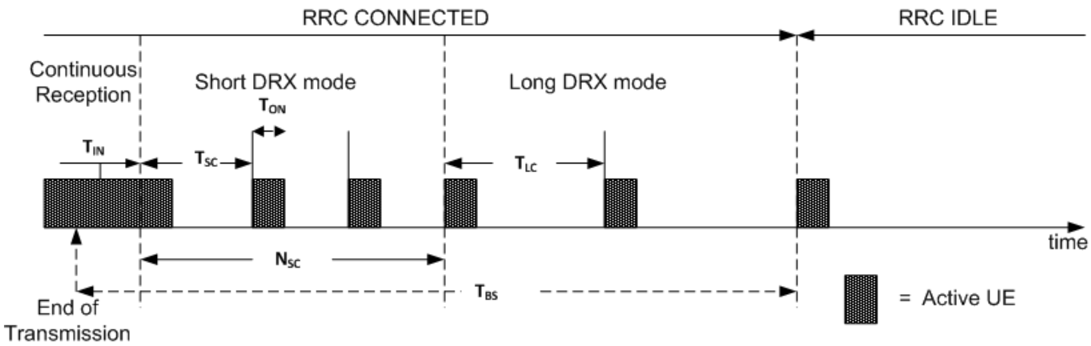


Figure 3.5: LTE DRX cycle [32].

Figure 3.5 shows the details about DRX phenomenon taking place during the transmission of data [32]. During RRC connected state, user activity timer T_{BS} is reset for each packet sent. UE is in "continuous reception" mode as long as it sends or receives data. After UE completes sending data, it starts DRX inactivity timer T_{IN}. When T_{IN} expires, UE starts the short DRX cycle of length T_{SC} during which UE monitors PDCCH only during duration T_{ON}. After predefined number of short

DRX parameter	Description
DRX cycle	Periodic repetition of ON duration and inactivity duration
On Duration timer	Duration of 'ON' time in one DRX cycle. It is the number of consecutive sub-frame UE follows after short DRX inactivity timer expires.
DRX inactivity Timer	Number of consecutive sub-frames in which UE has to be in On state after reception of a PDCCH.
DRX Retransmission Timer	Maximum number of consecutive PDCCH sub-frames where UE expects retransmission after first available retransmission time.
DRX Short Cycle	Periodic repetition of ON duration and period of inactivity.
DRX short cycle timer	Number of consecutive subframe that UE follows during short DRX cycle after expiry of DRX Inactivity timer.

Table 3.1: LTE DRX parameters [25].

DRX cycle, N_{SC}, without any UE activity, UE moves to Long DRX mode of cycle length T_{LC}. After T_{BS} timer expires, RRC connection is released and UE enters into RRC idle mode. T_{BS} is eNodeB parameter which is called user inactivity timer, set by operator which is usually 10 sec.

Based on the traffic type used in UE, basic DRX parameters can be set according to application requirements. HARQ retransmissions are done outside predefined DRX cycle, DRX retransmission also allows UE to send expected retransmission without waiting for DRX retransmission timer to expire. DRX helps in minimizing UE power consumption at the expense of increased latency. Therefore, tuning of DRX parameter needs to be considered for scheduling performance, as well as end to end performance. M2M terminal, once deployed is expected to last for years which requires energy efficiency to allow terminal to last long. The optimization of DRX parameters and user inactivity timer is required for smooth running of M2M terminals.

3.5 Latency in LTE

Latency is a critical issue that should be considered for smart grid applications so that any sudden anomalies can be quickly reported and required action is carried out swiftly [15]. As discussed in subsection 3.3 and 3.4, random access delay, RRC states transition delay and DRX states delay are the major factors which may cause unusual increase in LTE network latency. Network latency consists of both control-plane (c-plane) and user-plane (u-plane) delays. C-plane latency is defined as the transition time between two states, RRC_IDLE or DRX to RRC_CONNECTED. In LTE, transition time from RRC_IDLE to RRC_CONNECTED should be less than 100 ms while from DRX to RRC_CONNECTED depends on DRX cycle period. The user plane latency is defined as one way transit time between packet availability at the IP layer of sender and availability of packet at the IP layer of receiver [33]. User plane latency is also known as transport delay. The specifications target is to achieve a 5 ms user-plane latency in under-loaded condition for a small IP packet without payload [34].

- **Downlink Latency:** In downlink LTE, resource allocation is done in every sub-frame (1ms), therefore the minimum LTE latency is 1 ms. However, in practice, there are other sources of latency at radio interface. When eNodeB has data to be sent to a user, user device has to wake up from its discontinuous reception (DRX) cycle. The eNodeB knows the exact sub frame when device will wake up from DRX cycle to receive data, but it might be in any sub frame in same DRX cycle or might be in next DRX cycle. Furthermore, eNodeB can delay sending data immediately if there is congestion in the network or if there are other devices with high priority data transmission. Therefore, there are additional delays due to eNodeB scheduling function. Associated sources of downlink delay is shown in Figure 3.6.

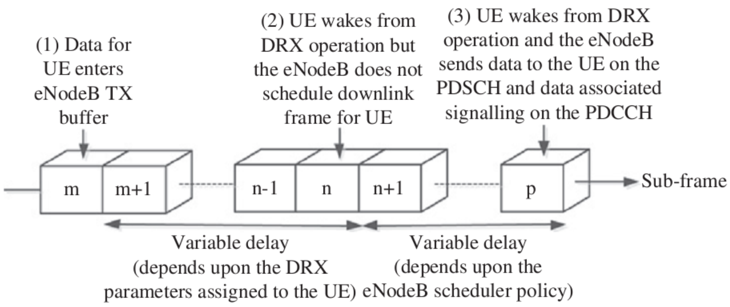


Figure 3.6: LTE downlink latency [26].

There are other potential sources of downlink delays as well which have to be considered. If UE enters into LTE network, before UE starts transmission of data, it has to register to the network and receive the bearer connection from the network. The UE should compete for the radio resource which brings random access delay, discussed in subsection 3.3. Another source of delay is RRC state transition delay which occurs when UE makes transition from RRC_IDLE to RRC_CONNECTED when UE wants to start data transmission in uplink or downlink direction. RRC state transition may vary between 50 ms and 100 ms [33]. HARQ retransmission is used in LTE for increasing reliability of data transmission, however it can cause additional delays during retransmission of packets. Finally, large packet size has to be split into two or more fragments which will be sent in different sub-frames causing additional delays.

- **Uplink Latency:** If UE doesn't have PUSCH resource, UE has to send Scheduling Request (SR) to eNB when UE wants to send data in uplink direction. UE is allowed to send to SR in PUCCH only in certain interval in sub frame, which can be in the same SR cycle or have to wait for another cycle. In SR, UE only send a request for resource to send the uplink data, it doesn't contain any information about amount of data. After eNB receives SR from UE, it sends an uplink grant to the device. The UE in turn sends Buffer Status Report (BSR) which includes the volume of data to be send and the priority of data. After receiving the uplink grant by UE, a fixed delay of 4 ms is used as UE processing delay. When retransmission occurs, an additional 8 ms is added as a fixed delay. The Figure 3.7 shows the source of access delays in uplink direction in LTE.

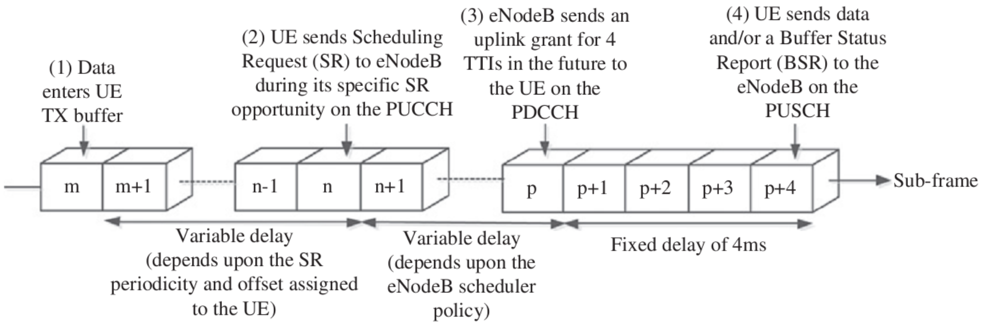


Figure 3.7: LTE uplink latency [26].

The Table 3.2 shows the end-to-end delay budget which includes the user-plane latency including both uplink and downlink delays. The table shows the latency with scheduling as well as pre-allocated resources which reduces uplink delay by scheduling time. Figure 3.8 shows the C-plane flow for the LTE_IDLE to LTE_ACTIVE tranistion in LTE based on the random access and RRC transition procedure defined in above sections. The figure also shows the approximate delay for each flow during C-plane establishment.

Delay component	**Delay value**
Transmission time uplink + downlink	2 ms
Buffering time (0.5 x transmission time)	2 x 0.5 x1 ms = 1 ms
Retransmissions (10 % of retransmission probability)	2 x 0.1 x 8 ms = 1.6 ms
UE delay estimated	4 ms
eNodeB delay estimated	4 ms
Core network (may vary according to geographical location of remote server)	1 ms
Total delay with pre-allocated resources	13.6 ms
Uplink Scheduling request)	0.5 x 5 ms = 2.5 ms
Uplink Scheduling grant)	4 ms
Total delay with scheduling	20.1 ms

Table 3.2: Break down of LTE user plane latency [25].

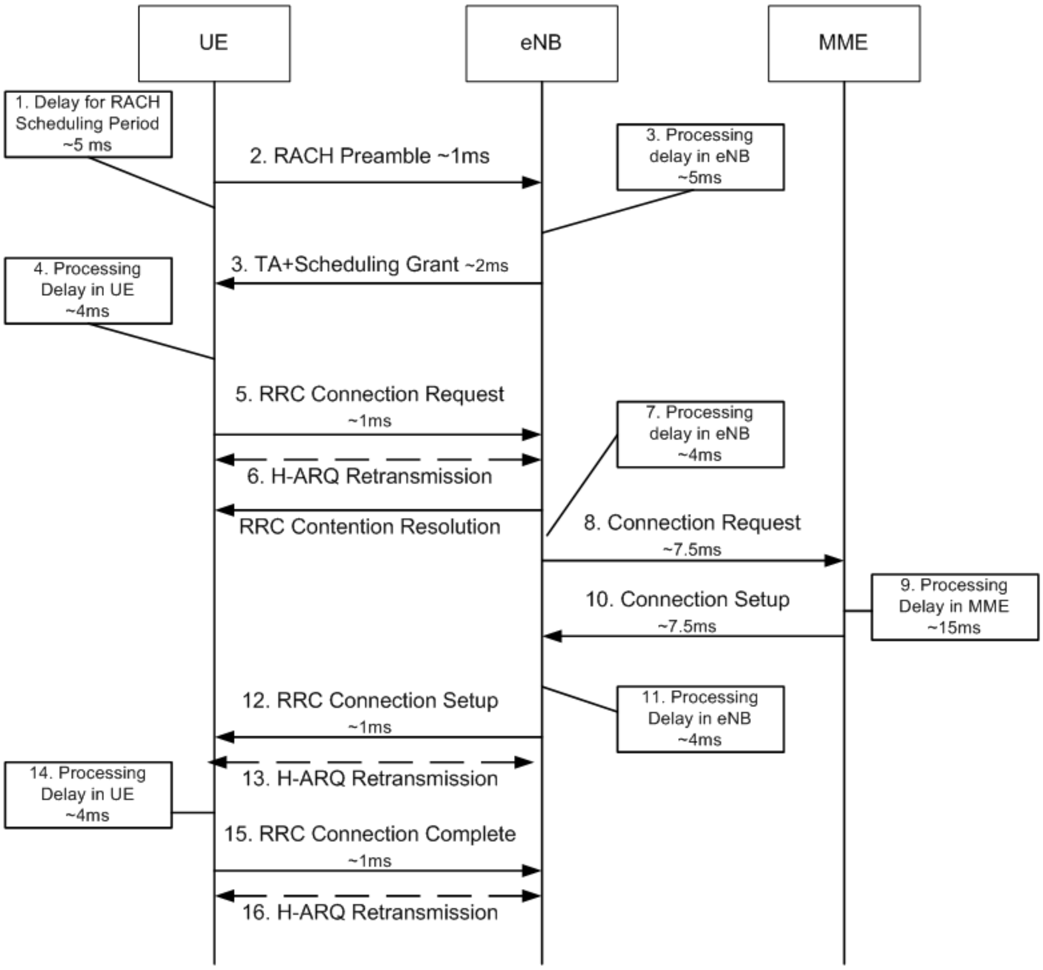


Figure 3.8: C-plane activation procedure [35].

4 M2M Communications

4.1 Introduction

3GPP has defined M2M communication as a form of communication which involves one or more entities and requires no manual intervention. MTC (Machine Type Communication) is the term used for M2M in 3GPP [8]. There are billions of machines in the world which need to communicate autonomously with other machines Therefore, M2M communication is not a new term, but until now it has relied on industry specific communication technologies to support the communication. However, M2M applications are now supported by cellular network technologies and gaining popularity in the recent years. Currently, communication service providers are looking for new opportunities as voice and data service revenues are declining and saturating.

M2M communication will span a wide varieties of fields which include automotive, intelligent building, smart metering, smart city, health-care and consumer electronics. Today, the majority of cellular M2M devices are utilizing the GSM network only. As the M2M market is evolving, M2M applications need to run with strict QoS requirements, which may not be met by the current GSM/UMTS networks as they are optimized for H2H communications and mobile broadband communication. M2M communication introduces high number of users, which increases signalling load on the network and hampers the H2H communication which service providers don't wish to happen. Moreover, they are not able to provide deep coverage to support large number of optimal low energy and low cost terminals. Although there has been development of light-standardized system which operates in license-exempt spectrum, there has been limitation in transmission power and no guarantee of reliability and coverage . Therefore, cellular network operating in licensed spectrum offers the best and low cost connectivity, with "plug and play" experience and reliable authentication and robust connectivity [2].

4.2 M2M traffic characteristics

It is important to consider and study about M2M specific applications which are different from traditional H2H communications which the cellular networks were initially designed for. Following points are salient features for M2M communication in which it differs from H2H communications [36]:

1. **Traffic Characteristics:** M2M traffic follows very specific traffic patterns. The amount of traffic transmitted is very small. The frequency of data transmission ranges from few milliseconds to seconds. Majority of M2M applications are uplink dominated in contrast to the most cellular network data traffic where downlink traffic dominates. Devices may be grouped into clusters, therefore, use of multi-cast, policing and charging can be different.

2. **Distribution and number of terminals:** M2M devices are distributed over indoor to remote outdoor places where there is difficulty to guarantee

coverage of the network. Moreover, each network cell might have multitude of distributed M2M terminals which increases congestion in the network.

3. **Low terminal power consumption and long life:** Once deployed, M2M terminals are destined to work for long without regular recharge. This requires energy efficient hardware with long life battery.

4. **Low radio access and terminal cost:** The multitude of M2M terminals will be deployed which continuously monitor and report information. Radio access's and terminal's cost should be minimum to carry out economically sustainable business.

5. **Mobility and Event driven applications:** Mobility won't be a big concern for M2M communication as most of the terminals would be static. Event driven applications will dominate the majority traffic.

6. **Location specific trigger:** There is a need of triggering of MTC devices in a particular area, e.g. wake up the device from sleep mode.

Currently, as mentioned earlier, most of the M2M applications use GSM/GPRS network which provides better coverage, lower cost and lower power consumption in comparison to 3G and 4G networks. But, GPRS offers poor performance in terms of spectrum efficiency and has high connection initiation and release times which can be critical for latency sensitive applications. 3G/HSPA networks offer improved spectrum efficiency but little improvement in connection setup time. 4G/LTE network offers higher spectrum efficiency and has a flat mobile architecture. The simplified all IP architecture helps in reducing latency of all radio interface operations and reduce connection time to as low as 50 ms. It is likely that if a significant proportion of M2M traffic is carried over cellular networks, LTE is the best option to which M2M devices should migrate without any compromise for spectrum efficiency and capacity. At the moment, for mission critical M2M applications, utility companies have been using their own network to ensure high quality of service (QoS). However, prioritised access to public networks and use of shared radio spectrum are the alternative solutions which can be integrated with LTE networks to offer better services to utilities.

4.3 M2M ecosystem

M2M is driven by increasingly complex relationship between networks, service providers and a huge number of devices connected to the network as shown in Figure 4.1. The success in M2M depends on the ability to form strategic alliance among the key players to deliver M2M services to customers and end users. Connection Service provider (CSP) plays a critical role in this ecosystem to ensure a seamless and reliable connection to all distributed M2M devices and to integrate them to make up the M2M ecosystem. Application developer, standardization and equipment vendor can provide service to specific industry with narrow use cases required for M2M applications. Hardware vendors are also split into equipment vendors which provide user terminal hardware to support M2M applications and network equipment vendors providing the network connectivity for ubiquitous connections. Therefore, M2M ecosystem covers a wide range of products, services and solutions, which opens rooms for companies with their own specific roles or acting as system integrators. Along with opportunities, it also brings about the challenges for seamless integration of solutions as well as business plan to make M2M ecosystem commercially successful [10].

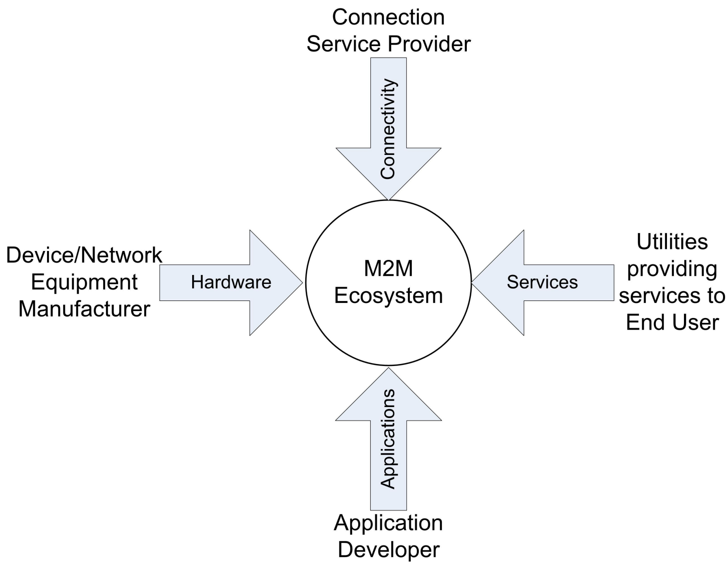


Figure 4.1: M2M ecosystem.

4.4 Challenges

Although cellular technology has vast opportunities and prospects for M2M communications, there are still technical challenges which still have to be addressed. The requirements for the technology are as follows [2] [37]:

- Use of the licensed spectrum to provide guaranteed quality of service and offer global coverage using the existing infrastructure,
- Support for deep coverage for low-rate services in poor radio conditions area like basements, underground etc.,
- Network planning and dimensioning should also consider the behaviour and localization of M2M devices along with human users,
- Low cost terminals with long life battery,
- Support for large number of terminals per cell,
- Support for swift connection initiation and release time,

- Network more optimized for small payloads with small signalling overhead, support for low latency and high reliability applications,
- Refarming of GSM spectrum to use in other technologies like LTE,
- Backward compatibility with conventional communication technologies,
- Standardization to support M2M communications,

All the above technical challenges are aimed to be met by future releases of LTE standard, which will be discussed in section 5.5. A possible roadmap on how technology evolution will emerge in future for cellular technology in M2M world is shown in figure below [2].

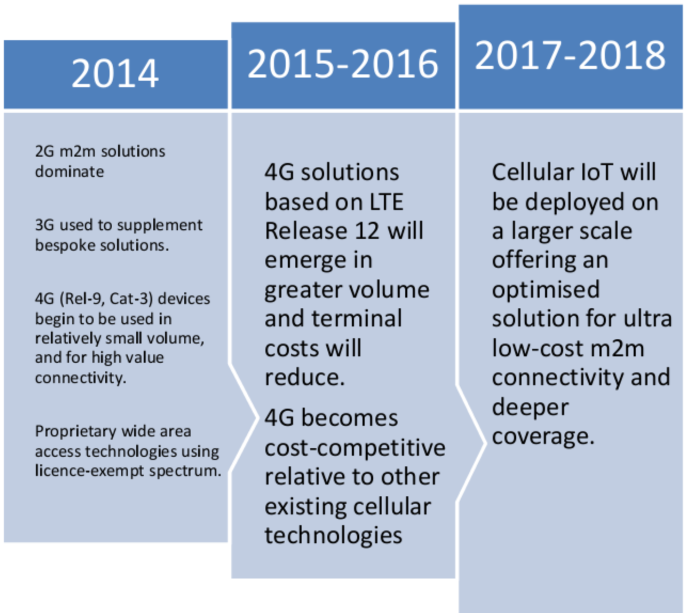


Figure 4.2: M2M roadmap for cellular technology [2].

4.5 M2M system architecture in LTE

3GPP uses term "Machine Type Communication (MTC)" to represent Machine-to-Machine communication which involves all form of data communication which doesn't require human intervention. MTC communication is different from the current mobile communication services, as large numbers of ubiquitous of terminals are distributed widely and consumes little traffic per terminal which increases the signalling load and congestion in the network. MTC devices are usually communicating with MTC server in the network using defined MTC gateways building so-called capillary networks.

M2M system architecture based on LTE/LTE-A [38] is shown in Figure 4.3 to support heterogeneous and distributed features of M2M system. Figure also shows latency incurred in various M2M domain. M2M access domain and M2M core latencies are dominant for end-to-end latency. There might be a latency bottleneck depending on M2M applications. M2M system architecture includes different domains supporting M2M features.

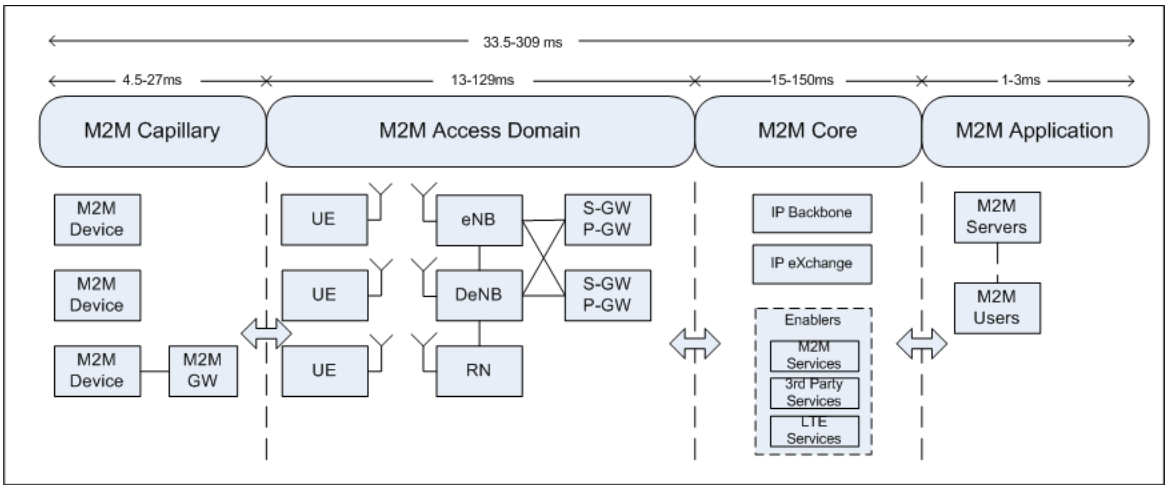


Figure 4.3: LTE M2M system architecture [38].

1. **M2M Capillary networks**: This domain includes all smart devices, wide-range and short-range, which support numbers of M2M applications. M2M system consists of M2M device connected to UE which either directly connects to E-UTRAN or via M2M gateways. The latency in this domain is induced by processing, transferring and gateway delays. Latency value ranges from 4.5 - 27 ms based on the number of M2M terminals attached to the gateways as data may have to be aggregated before being forwarded to M2M application server.

2. **M2M access network**: It includes the support for the access of distributed M2M devices to the network with evolved NodeBs in E-UTRAN. Access in E-UTRAN may also be provided through relay node (RN) which forwards the data between UE and donor eNB (DeNB). eNBs are connected to EPC using S-GW (Serving Gateway) while P-GW (packet gateway) provides connection to IP core network. The latency in this domain depends on the state of UE: RRC IDLE, RRC CONNECTED, DRX states as well as other factors like network coverage, scheduling policy, buffering/processing, number of re-transmissions, IP access delays etc. It includes both C-plane establishment delay as well as U-plane delays. The delay incurred in this domain vary from 13 - 129 ms.

3. **M2M core**: It provides interconnectivity and relevant M2M services (registry, request analyser, control), 3rd party services (location, charging, processing of data) and LTE services. Delays are created in this domain by interconnections required between M2M gateways and servers through IP backbone and IP Packet eXchange (IPX) which vary with the number of nodes in the network, processing delays and region (Europe or North America).

4. **M2M applications**: It serves as the common platform for all M2M applications running in the network. The delay depends on the service publishing and lookup which changes with the number of terminals registered in the network.

5 Smart Grid Communication

5.1 Introduction

Modern energy grid requires pervasive data communication which connects millions of smart meters and thousands of sensors on the low and medium voltage lines, devices and substations. Wide coverage communication also enables remote control and automation of electricity distribution entities. In conjunction with the existing electricity distribution infrastructures, communications networks used to manage the high-voltage transmission lines and devices form a grid which is called a ”smart grid”. Grid constitutes of several domains where many applications are running, and each domain is interconnected by association (secured communication interfaces) having interfaces at both end as shown in Figure 5.1 [39].
According to **IEEE SmartGrid** [40],
“The smart grid has come to describe a next-generation electrical power system that is typified by the increased use of communications and information technology in the generation, delivery and consumption of electrical energy.”

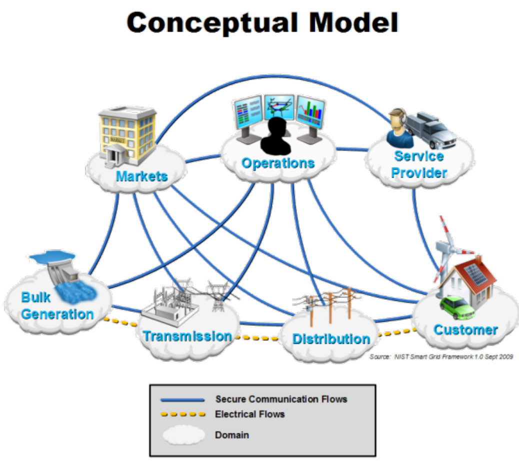


Figure 5.1: Conceptual model of smart grid [39].

5.2 Smart Grid Applications

Smart grid includes components which support monitoring, control and communication of electricity data from consumers to utilities. The key components of the smart grid are discussed below:

- **Phasor measurement unit (PMU):** In order to provide the insight of grid dynamics, it is fundamental for smart grid to collect fast measurements for understanding the grid behaviour. PMU is used for the real-time measurements for collecting information about grid which require strict latency requirement. With the help of PMU, synchronized measurement can be taken about 30-120 samples per second. The successful analysis of grid dynamics requires grid topology information and its states. The topology of grid is static and constant over time while the state of the grid is dynamically changing due to change in loads, switching and generation operations. Conventionally, state of the grid is derived from voltage magnitude (V), real power (P), and reactive power (Q) measurement using a computer program called State Estimator. These measurements are polled into SCADA system every 2 - 4 seconds, which works normally for unstressed grid having steady state conditions. In the modern grid scenario, the fault detection and immediate fault correction are needed to minimize the power outage duration. State-estimator cannot monitor changing state of the system and sometimes fails to converge. However, PMUs distributed across the grid can measure the state of the system many times per second which gives real-time dynamics of the grid system. The resultant sampling frequency would be 60 samples/second (Hz) [15]. These samples are aggregated in Phasor Data Concentrator (PDC) collected from across the utilities and data are synchronized in central facility. (Latency requirement (1000/60)= 20ms). The length of data message would be 52 bytes and 100-200 bytes including IP or TCP header, which also affects the latency.

- **Advanced Metering Infrastructure (AMI):** AMI is an integrated system of smart meters, communications network and data management system that enables two-way communication between utilities and customers. AMI collects the real-time information about consumption records, alarms and status from customers to support energy management applications. Measurements are used to support real time pricing (RTP), time of use (TOU) pricing, and critical peak pricing (CPP) features for billing and demand response applications. Depending on the size of the utility, the number of AMIs in the network can vary from thousands to millions. The response time for AMI can be high (every 10-15 minutes), availability of an individual meter may not be considered too critical to network operations. It is important to note that smart meters is the weakest link in smart grid security, therefore, it should also be considered in the architecture and design of the network.

- **Distribution Automation (DA):** Distribution automation is done typically using reclosers, switches, fault current indicators which are normally located in feeder lines. These devices guarantee reliability and improve network performance and hence, reduces frequency and duration of network outages. However, remote automation requires synchronized operations between these distribution entities, which demands strict guaranteed latency requirements. Moreover, feeder lines are distributed over huge area reaching all residential places. Therefore, a major obstacle to realize automated functions is also the lack of ubiquitous communication network across the distribution grid.

5.3 Communication requirements for smart grid applications

Reliable communication in distribution level is important for smart grid as most of the power interruption happens in feeder lines [15]. It is a challenging task to get reliable information about the distribution component failures at the feeder level due to the lack of wide coverage of communication network. Therefore, most of the information harvesting is done in substation level and limited information is fetched from distribution system [41]. Reliable and pervasive communication infrastructure is needed for better management of distribution failures. This thesis is focused on finding the solution for communication infrastructure in medium and low voltage distribution grid.

Traditional system control and data acquisition are done with SCADA systems, which offer limited bandwidth to support real-time monitoring (fault detection) as well as automation control for asset management and fault correction. Although distribution grid contains the majority of grid assets, the lack of ubiquitous and reliable communication network makes the grid component invisible to operators [3]. The candidate communication technologies for smart grid communication are described in chapter 5.4.

Intra-substation communication is handled by standardized IEC 61850, which uses reliable TCP/IP and priority flags for Generic Object Oriented Substation Event (GOOSE) and sampled measured values using IEEE 802.1 Q (VLANs), providing better security and intelligence to Ethernet switches [42]. IEC 61850 standard has defined stringent requirements for distribution network automation in medium and low voltage grid which helps utilities for swift detection of faults and restoration of power by by-passing the faults. IEC 61850 defines six different performance classes based on the smart grid application supported. Smart grid functions are categorized into requirements for communication within a substation, communication between substations and control systems, collection and dissemination of electricity data, remote control and automation, and communication for protective relaying [43]. Figure 5.2 shows the target values for transfer time proposed by IEC 61850 standards to support various smart grid applications.

The latency evaluation of LTE network using Round Trip Time (RTT) for different packet sizes is shown in [43]. Latency measured was good enough to support tasks of performance class P4-P6. Ericsson lab performed the experiment to demonstrate successful handling of GOOSE traffic over LTE to support fast automatic interaction (class P3), however, they concluded that it requires careful planning of devices, particularly device states.

Performance class	Requirement description	Transfer time		Application
		Class	ms	
P1	The total transmission time shall be below the order of a quarter of a cycle (5ms for 50Hz, 4ms for 60Hz).	TT6	≤ 3	Trips, blockings
P2	The total transmission time shall be in the order of half a cycle (10ms for 50Hz, 8ms for 60Hz).	TT5	≤ 10	Releases, status changes
P3	The total transmission time shall be of the order of one cycle (20ms for 50Hz, 17ms for 60Hz).	TT4	≤ 20	Fast automatic interactions
P4	The transfer time for automation functions is less demanding than protection type messages (trip, block, release, critical status change) but more demanding than operator actions	TT3	≤ 100	Slow automatic interactions
P5	The total transmission time shall be half the operator response time of ≥ 1s regarding event and response (bidirectional)	TT2	≤ 500	Operator commands
P6	The total transmission time shall be in line with the operator response time of ≥ 1s regarding unidirectional events	TT1	≤ 1000	Events, alarms

Figure 5.2: Performance class for smart grid application based on latency requirements [6].

5.4 Communication alternatives for smart grid communication

Information and communication Technologies (ICT) is aimed to provide functionalities of monitoring and remote operating electricity grids which turns a conventional power grid to next generation power grid "Smart Grid". ICT plays a vital role for the deployment of smart Grid, numbers of researches have been made to cover various aspects of ICT for Smart Grid specifically in M2M domain. The feasibility of communication technologies (Wired: fiber, DSL, PLC Wireless: GSM,UMTS, LTE) to facilitate smart grid has been studied and evaluated to offer last mile connectivity.

1. **Fiber optics communication:** Optical fiber is the fastest and highest bandwidth network available, supporting wide range of communication protocols and services. However, penetration of this technology is low due to the cost of deployment of optical fibres. Therefore, from the cost point of view, it's far too expensive to use fiber networks for smart grid purposes.

2. **Power Line Communication(PLC):** PLC is widely used by utilities for remote monitoring and is most popular among utilities as they have complete control over the communication infrastructure for controlling grid operation. It works based on sending modulated carrier signals over power transmission lines. Data signals can't be transmitted through transformers, so communication is limited within line segment between transformers. Moreover, PLC

doesn't guarantee the real-time transfer of data and it is susceptible to interference and outages.

3. **GSM/GPRS:** Even though third and fourth generation of mobile communication (UMTS & LTE) have already been commercialized, GSM/GPRS remains prevailing technology for smart grid applications as it provides good indoor coverage, higher penetration across the country and data services with reasonable cost. In rural areas, GSM network operates in 900 MHz which has comprehensive area coverage. But, GSM fails to meet all the performance requirements of smart grid applications. GSM network was designed for mobile telephony services, and was upgraded to GPRS to support data services. So, GSM network is not able to handle signalling traffic of millions of devices and can't guarantee the QoS requirements. GSM is seen as inferior solution for smart grid functions and utilities are looking forward to find new alternative to GSM.

4. **Long Term Evolution (LTE):** LTE is a global standard which is built upon mature radio access technology and has massive global ecosystem. The functionalities and capabilities of LTE is continuing to evolve. However, the technology platform is stable and mature, and backward compatible with earlier 2G/3G generations making LTE investment future proof. In Finland, LTE networks are currently operating at 800 MHz, 1800 MHz and 2600 MHz. 3GPP has released the frequency allocation for LTE in other bands as well. In urban area, LTE is deployed in 1800 and 2600 band to support more capacity required for more numbers of users. Due to the propagation characteristics of LTE 800 required for indoor coverage, utilities are seeing huge opportunities in this band.

   In Finland, LTE 800 band has already been auctioned to mobile operators, operators are required to have >95 % coverage for LTE throughout whole Finland before the end of 2017. LTE is promising technology which fulfils the performance requirements for latency and bandwidth. LTE is more specifically optimized for H2H applications, not designed for M2M traffic. 3GPP is aware of this problem and has addressed these issues in LTE Release-12 to support MTC applications. As for now, commercial telecommunication operator should be aware of the fact M2M traffic generated by high number of devices like smart meter will use lots of radio resources, which will create congestion in the network and disrupt the normal services of the network. Network should be optimized for M2M traffic and a priority based scheduling should be used to avoid congestion. The second alternative for utilities is to use a private LTE network in licensed spectrum which separates utility traffic from the conventional mobile broadband traffic. It requires utility to license the radio spectrum for its LTE network where there will be no competition for radio resources and hence, maximize network efficiency and maintain reliability.

5. **450 MHz (CDMA and LTE):**Spectrum scarcity has been one of the biggest problems faced by network operators. The 450 MHz frequency band is now

available in most of the European countries which has been either unassigned or underutilized. In comparison to LTE 800 and GSM 900 band, 450 MHz has twice footprint coverage which reduces network investment dramatically and shortens the service launch time as well. Standardization of LTE for 450 MHz has already been done and operators are already planning for deployment as well. However, LTE has yet to be optimized for M2M use cases. The deployment of LTE 450 MHz provides promising future to bring universal broadband to more people and ubiquitous connection for M2M. In Finland, Ukkoverkot has launched a 4G LTE network operating in 450 MHz this year which covers 99.9 percent of Finnish population. It supports only mobile data connection without any voice and sms functions. This network is first of its kind in the world to be deployed throughout whole country which is promising for M2M communication.

5.5 Smart Grid Communication Standardization

Smart Grid with its diverse communication requirements has been one of the key drivers for M2M developments. Different smart grid use cases and requirements have been studied to draft M2M standards. CEN-CENELEC-ETSI smart grids coordination group, which is responsible for coordinating European smart grid standards has studied and analysed the smart grid communication use cases against the existing communication technologies to find if there are any gaps and define communication profile for smart grid such that existing communication technologies can be used [44]. CEN-CENELEC-ETSI has identified 13 different types of networks which can be viewed to form separate logical networks meant for communication in smart grid and showed that 3GPP mobile broadband technologies are capable of fulfilling communication requirement of most of the smart grid communications.

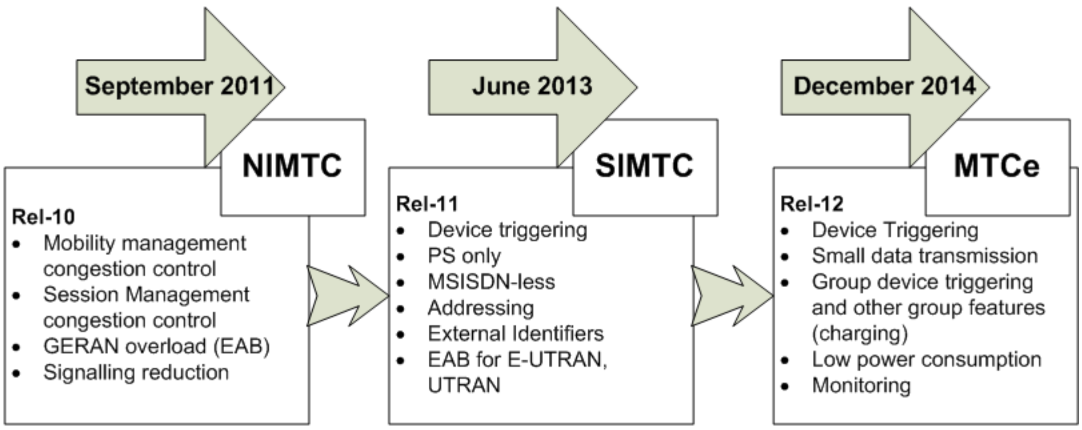


Figure 5.3: Timeline for MTC standardization in 3GPP

Most of the requirements for MTC are also applicable to smart grid communications. 3GPP has been implementing these features for MTC standard in different releases as shown in Figure 5.3. M2M functionality was introduced in Release-10, and the work has continued in Rel-11 and Rel-12. In the release-10, 3GPP studied different M2M application uses cases and recommended the requirements for 3GPP network improvements to support MTC under the umbrella of the feature “Network improvements for Machine Type Communication” (NIMTC). During the release-11 timeframe, 3GPP continued to work on solutions for the most important features such as device triggering, PS only subscription and also addressed the problem faced by operators due to E.164 number shortage under the feature “System Improvements for Machine Type Communication (SIMTC)”. The most current 3GPP release is Release 11 which has already been frozen. Work for release-12 is being developed and is covered by the Rel-12 features “Machine-Type and other mobile data applications Communications Enhancements (MTCe)”. Release-12 aims to improve network to support MTC application more efficiently. With Release-12 expected to freeze as early as December 2014, the discussions for further extension in Release 13 has already been started.

6 Measurements and Results

The aim of the measurement is to get empirical analysis of the performance of LTE in different coverage environments for M2M applications in terms of latency requirements. The measurements were performed at different outdoors and indoors locations having different radio and load conditions. The focus of the measurements was to identify and measure LTE KPIs responsible for latency, which are critical for M2M applications. The key parameters measured were latency and latency related parameters which directly or indirectly affect the performance of the remote automation required for critical M2M applications in smart grid.

6.1 LTE measured parameters

- **RSRP (Reference Signal Received Power)** Reference signal in LTE is used to deliver the reference point for the downlink power for UE. It doesn't carry any control information from higher layers but it is a special signal that exists only in PHY layer. These reference signals are carried by the specific resource elements in each slot. RSRP is the linear average of reference signal power across the bandwidth over specific resource elements. RSRP is an important parameter that UE measures to make decision regarding cell selection, reselection and handover. Note that RSSI (Received Signal Strength Indicator) measures the total power across whole band which includes main signal as well as co-channel, non-serving cell signal, adjacent channel interference and thermal noise as well.

- **RSRQ (Reference Signal Received Quality)** RSRP measures only strength of wanted and desired signal, but doesn't tell us anything about quality of signal. RSRQ is given as

  (NxRSRP)/RSSI

  Where N is the number of RBs over the measurement bandwidth. From the mathematical formula, we can see that RSRQ indicates "what is the portion of pure RS (Reference Signal) power over the whole E-UTRA power received by the UE".

- **CQI (Channel Quality Indicator)** To enable adaptive modulation, UE needs to report the current channel quality to the network. UE calculates CQI based on SNR, which ranges from 0 (poor) to 15 (Good) and sends to network, so that it can transmit data to UE with appropriate transport block sizes which can be decoded correctly with given channel conditions.

- **PCI (Physical Cell Identity)** PCI is the identification of a cell at physical layer which has similar role as scrambling code in UMTS. Physical cell ID is used by UE to decode physical layer data sent by eNB, unlike Cell ID used for eNodeB management in core network.

- **User Inactivity timer** LTE uses user inactivity timer to save radio resources where, if network discovers that no active user packets are being exchanged between UE and network for fixed time period (user inactivity timer expires), network releases default EPS bearer and UE is forced to enter RRC_IDLE mode from RRC_CONNECTED mode. If the terminal wants to initiate a packet connection, UE has to re-establish the RRC connection to regain the bearer services from the network.

- **RRC connection setup time** It is defined as the time taken for establishment of RRC connection. It is calculated as time interval between the receipt of 'RRC CONNECTION REQUEST' and the corresponding 'RRC CONNECTION SETUP COMPLETE' message by the eNodeB. Radio Resource Control setup delay is calculated by

  RRC delay = Radio Resource Attempt (timestamp) - Radio Resource Success (timestamp)

- **Random access delay** Random access delay is defined as the time beginning from UE entering into the network (UE selecting RACH preambles) to before RRC connection is established. The detailed process was discussed before in section 3.3.

6.2 Measurement tools and setup

Nemo Outdoor was used as a primary measurement device to record measurement data. Nemo outdoor 7.0 records all the physical parameters, signalling and data traffic between UE (User Equipment) and BTS (Base Station). For post measurement analysis, a parser was created to parse Nemo measurement files to extract the required parameters. Nemo scripts were used to control the UE behaviour like start packet session, initiate FTP/UDP/ICMP ping/video calls connections, exchange of RRC messages etc. For data analysis and presentation, MS-EXCEL and MATLAB were used to show measured parameters in graphical form.

Measurements were primarily done in LTE-800 network for Elisa operator at outdoor and indoor locations, selected based on RSRP (Reference Signal Received Power) and RSRQ (Reference Signal Received Quality) which show the coverage and signal quality of the location. The UE used in LTE measurements was the commercially available Huawei E398 LTE Multi-mode USB Modem and Samsung S4 plus (I-9506). Table 6.1 shows the technical specification of UEs used in the measurement.

In the measurement, latency in LTE 800 network was assessed over different radio conditions with different traffic behaviour. RRC states transition, DRX states and random access delays, which play a major role in determining the LTE latency were also studied. Variations of the above mentioned parameters with changing radio conditions were analysed and co-relations among the parameters were studied. Radio conditions were measured with physical layer parameters like RSRP, RSRQ, UE reported CQI and SINR. ICMP ping was used to measure the latency of the

Operating Frequency Band	LTE 2600MHz (10M/20M)/1800MHz (15M/20M)/800MHz (5M/10M)
Maximum Transmitter power	Power Class 3, Maximum 23 dBm
Static receiver sensitivity	Compliant with 3GPP TS 36.101(R8/R9)
UE category	Cat 3
Platform	Qualcomm MDM9200TM Chipset (Huawei), Qualcomm Snapdragon 600 (Samsung S4)

Table 6.1: LTE UE technical specification

network. ICMP ping measures the Round Trip Time (RTT) to destination ping server. To maintain consistency of the measurement, Google DNS server was selected as ping server for all measurements. Google automatically uses the closest server located based on the location of user.

To measure random access delays, a script was created in Nemo outdoor to run a loop of events which causes terminal to compete for random access channels. Along with random access delays, random access counts were also recorded for contention based random access procedure to detect if there were high random access delays due to multiple random access attempts. The measurements were done during the day time when congestion have minimum effect. Moreover, multiple measurements were done to ensure the credibility of measurement data.

Operator	**User inactivity Timer (seconds)**
ELISA	20.367
DNA	10.932
SONERA	10.295

Table 6.2: User inactivity timer values for different operators in Finland (measured)

ICMP ping request was sent from mobile terminal (client) to web server for different interval times ranging from 100 ms to 20 seconds to study the effect of irregular/periodic traffic behaviour on the latency of the network. The maximum time interval was selected such that interval period is greater than RRC connection user inactivity timer such that UE enters to RRC_IDLE mode. Different operators optimize user inactivity timer according to their specific needs. It is difficult to get operator specific timer information as they are confidential. A short measurement was conducted to get approximate idea about the user activity timer information. A short script was made which initiates RRC connection, and timestamp was recorded when RRC connection successful message was received. The terminal was kept idle without any data connection used, timestamp is recorded again when RRC release message was received. Therefore, timestamp difference between RRC successful and release message give an idea about the user inactivity timer value used in the network. Every time UE attempted to make RRC connection, RRC connection setup time was recorded. Table 6.2 shows the average user inactivity timer measured for different operators in Finland. The timer value is specifically critical for latency sensitive M2M communication, which sends intermittent small data packets with variable time period.

ICMP ping test was also performed with variable packet size, which emulates the variable packet sizes of GOOSE packets used in smart grid communication.The effects of buffer size of LTE networks and congestion in the network on latency of the network were also studied.

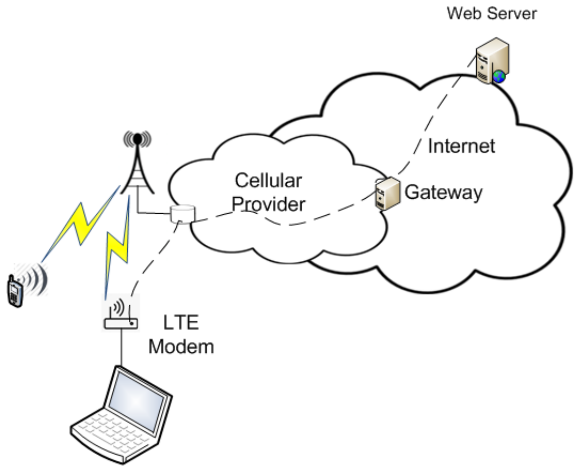


Figure 6.1: Measurement topology.

Figure 6.1 shows the measurement topology and setup of the network. Figure shows all the relevant nodes necessary for the measurement, viz. LTE enabled UE, Web Server etc. In the measurement, LTE client has a static position hence, mobility is not considered. Figure 6.2 shows the step-wise breakdown of measurement procedures followed to measure control and user plane delays.

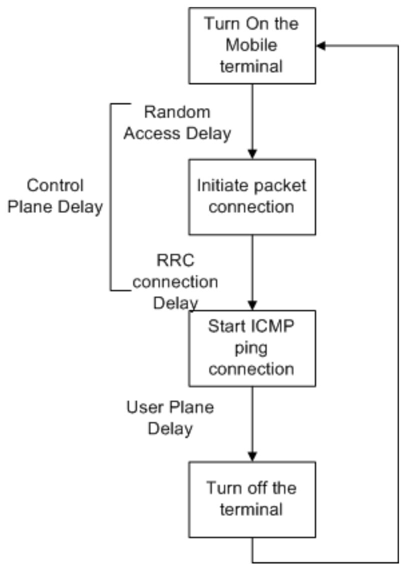


Figure 6.2: Measurement flowchart.

6.3 Data Abstraction

The output of Nemo outdoor is in .nmf format, which contains all information that are exchanged between UE and eNodeB including PHY, RRC and MAC layer messages. Therefore, a parse code was written in C++ to extract the required parameters by choosing the correct Nemo messages. Nemo file format file was referenced to create parser such that the correct messages were parsed for GSM/UMTS/LTE system. RRC messages exchanged between UE and eNodeB were also monitored so that RRC connection setup time could be calculated. Using parser, a csv file was created which included the filtered parameters which were useful for measurement results and analyses. The csv file was easily exported to MS-EXCEL and MATLAB for further statistical analysis and creation of figures. Moreover, it was also possible to export the measurement file to .kml file to visualize the measurement route in Google earth.

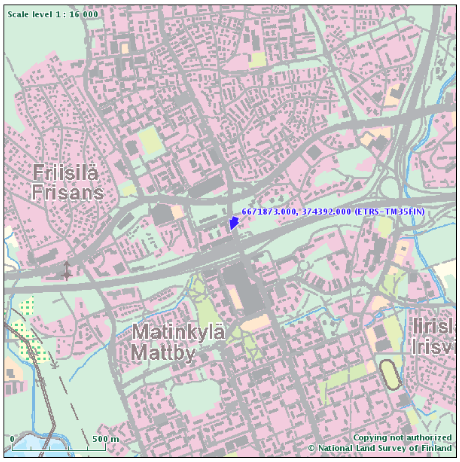
6.4 Site Selection

The LTE-800 measurement sites were selected from Espoo region based on the land terrain, demographic features and location of base station (building mounted or mast mounted). The measurements were conducted in ELISA's LTE 800 network. The base station's locations and parameters were obtained from Elisa. Elisa primarily covers LTE coverage with LTE 800 band and provides hotspot coverage with LTE 1800 and LTE 2600 bands. Table 6.3 shows the radio parameters of the measured sites viz. Piispanportti and Eestinkallio.

Parameters	**Piispanportti 10**	**Eestinkallio 2**
Location	60.16440072, 24.73652457	60.16810836, 24.6854511
Mast Height	Attached to Building 25 m	30 m
Frequency	816.0 (DL)/857.0 (UL) 6400 (EARFCN)	816.0 (DL)/857.0 (UL)
Bandwidth	10 MHz	10 MHz
Physical Cell Identity	101	36
Bandwidth	250	200

Table 6.3: Radio parameters for measured sites

In each measurement site, series of measurements were done to study if there was any effect of radio conditions on the latency and other factors which have effect as well. Measurements included random access delay, RRC connection setup time, User plane delay with varying inter-arrival time and packet sizes. Similar measurements were conducted in another site for the verification of the results.



(a) Location of mast with its surrounding environment

(b) Mast on the top of the building

Figure 6.3: Details of the Piispanportti site

6.5 Measurement Results

6.5.1 Site 1: Piispanportti

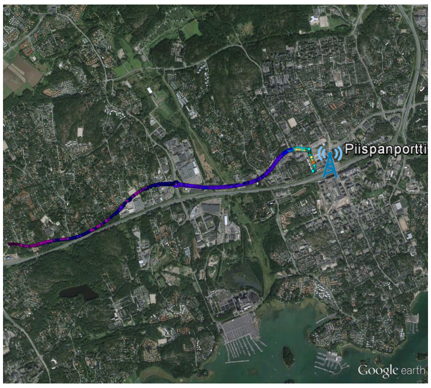
Piispanportti site was located in urban area with numbers of high-rise buildings around the site. LTE 800 network provided coverage to residential area, which was located few kilometers away from the site. LTE 800 was deployed in the area for coverage limited network rather than capacity limited as LTE 1800 cells were also found nearby providing hot-spot coverage. Figure 6.3 shows the location and surroundings of piispanportti site along with the mast.

Initially, a drive test measurement was done to compare the maximum radius of the LTE 800 and LTE 1800 cells. For this purpose, LTE user terminal was locked to particular PCI and the channel of a measured cell, and drive measurement was done towards the direction of the cell's bearing (azimuth). Figure 6.4 shows the measurement routes for LTE 800 and LTE 1800 cells. It's seen from the figures that the coverage radius for LTE 800 cell is almost five times than LTE 1800 cell's radius.

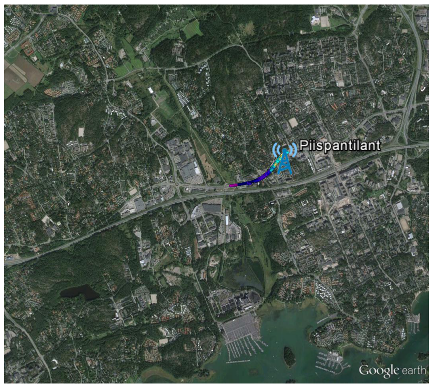
Based on the route measurements, three places were selected as good, average and bad coverage places to do stationary measurement. Table 6.4 shows the measured physical parameters based on which stationary measurement sites were decided.

	RSRP(dBm)	RSRQ(dBm)	CQI
Good	-62.66	-8.01	11
Average	-100.78	-17.8	5
Bad	-114.71	-20.0	3

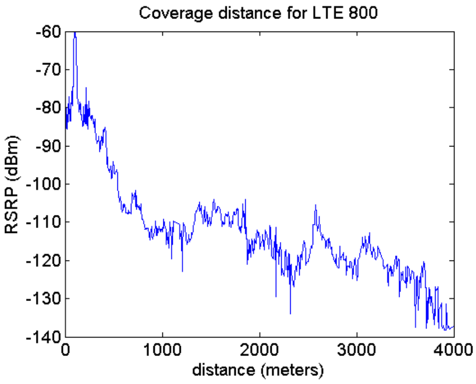
Table 6.4: Stationary Measurement location based on physical parameters



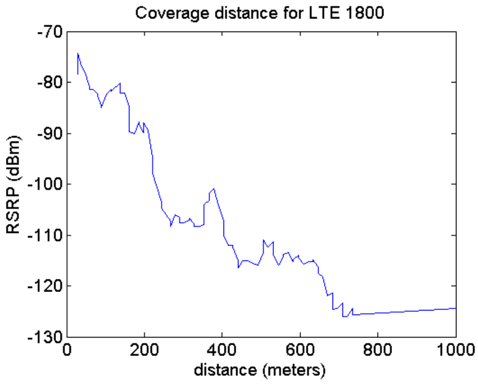
(a) Coverage radius of LTE 800 cell



(b) Coverage radius of LTE 1800 cell



(c) Coverage radius of LTE 1800 cell



(d) Coverage radius of LTE 1800 cell

Figure 6.4: Maximum coverage distance for LTE cell

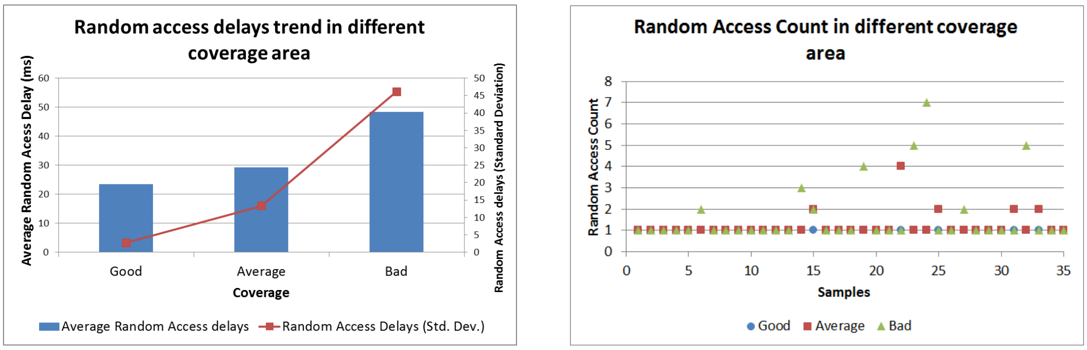
6.5.1.1 Control Plane Delays

In machine type communication, terminal needs to go to sleep or idle mode to save energy consumption and radio resources. Therefore, whenever the terminal is in idle mode and has to receive critical message, it has to either wake up from idle mode or restart the terminal. Waking up from idle mode requires RRC connection re-establishment while in some cases the terminal has to contend for the radio resources using random access channel. Therefore, whenever terminal is switched on, terminal acquires the radio resources through random access procedure which can be contention-based or contention free. Random access delay may range from 10 - 300 ms based on how many times random access procedure has failed. Random access delay is critical in M2M communication where terminals are widely distributed and terminals have to send data less often, and terminals go to idle mode.

To study the effect of coverage conditions on the random access delays, random access delays were measured in all coverage conditions. Table 6.5 shows the measured random access delays in all coverage conditions. In good radio conditions, random access delay is as low as 22 ms, and terminal is able to complete random access procedure at once for all of the random access attempts made. The variation of random access delays is also small in comparison to average and bad coverage measurements shown by deviation value. For average coverage measurement site,

	Average Random Access delays (ms)	Random Access Delays (Std. Dev.)	Random Access Success at once (%)
Good	23.51	2.71	100
Average	29.32	13.28	90.9
Bad	48.44	46.10	81.4

Table 6.5: Random access delays for different radio conditions



(a) Random access delays trend in different coverage area

(b) Random access count in different coverage area

Figure 6.5: Variation of Random access delays for varying coverage

access delay is around 29 ms, and about 91% of random access attempt is completed at once, but rest 9 % of the attempts are completed with two or more retries. In bad coverage site, multiple random access attempts are observed as shown in Figure 6.5b which increase average access delay to around 48 ms,twice as good coverage's random access delays, around 19% of first random access attempts failed, multiple random access count reached up to 7 which is maximum attempts possible defined by operators.

Therefore, from the above observations, it can be concluded that radio condition has a definite effect on the random access delays. The average random access delay doubles when terminals are in bad coverage conditions compared to good one. High random access delay values are due to multiple random access attempts made. As M2M terminals are widely distributed and there are huge amount of the terminals in a same cell, terminals have to contend for getting access to network more often using random access channel. If terminals are intended for mission critical applications where network latency is crucial, it is important to ensure there is good coverage to guarantee required latency requirements. Moreover, most of the future M2M devices are located indoor where radio conditions are challenging, robust random access methods are required to guarantee the ubiquitous network connectivity.

After terminal acquires the random access grant from the base station, terminal still has to get radio resource connection (RRC Connection setup). Additional delay occurs during radio resource control setup procedure. The RRC session is limited if terminal doesn't have any active connection going on. Terminal goes to idle mode as soon as user inactivity timer expires. If terminal has to initiate data connection again, it has to wake up from from idle state i.e. transition from RRC_IDLE mode to RRC_ACTIVE mode which involves additional delay. This delay is termed as RRC connection setup time. In the next measurement, RRC connection setup time was measured for different radio conditions.

	Average RRC connection setup time (ms)	**RRC connection setup time (Std. Dev.)**
Good	44.31	14.31
Average	86.80	14.64
Bad	99.04	56.78

Table 6.6: RRC Connection setup time for different radio conditions

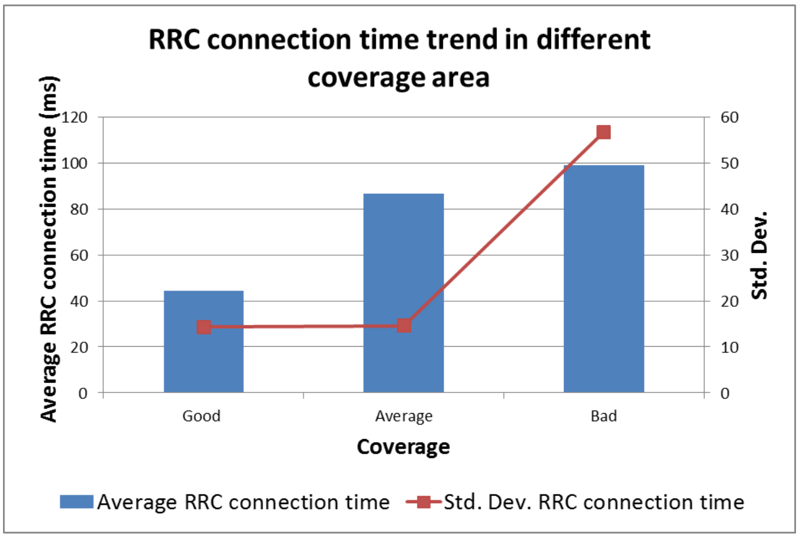


Figure 6.6: RRC connection trend for different coverage area

Figure 6.6 and Table 6.6 show the average RRC connection setup time and randomness of the values measured in different coverage place. The trend of RRC connection setup time also follows similar pattern as random access delays where setup time increases from good to bad radio condition. The average RRC connection setup time in good coverage site was around 45 ms, but it rises to 100 ms in bad coverage conditions. The reasons for higher RRC connection delay in bad coverage area are dropping of RRC connection and re-establishment of RRC connection. Moreover, in most of the cases, RRC connection was dropped in the middle of RRC session, requiring need of RRC connection re-establishment procedures. The purpose of RRC CONNECTION RE-ESTABLISHMENT procedure is to re-establish the RRC connection, which involves the resumption of SRB1 operation and the re-activation of security. The UE initiates the RRC CONNECTION RE-ESTABLISHMENT procedure when one of the following conditions is met:

- Upon detecting radio link failure
- Upon handover failure
- Upon mobility from E-UTRA failure
- Upon integrity check failure indication from lower layers
- Upon an RRC CONNECTION RECONFIGURATION failure

In bad coverage measurement, around 42 % of RRC session were dropped with normal release (timeout of RRC session), while 58 % of RRC session was disconnected due to dropped RRC connection which invokes RRC reestablishment. Among RRC reestablishments attempts, 66% of attempts succeeded whereas 33% of attempts failed. RRC connection retry and failure makes RRC connection setup time to go high in bad radio condition environment. Abnormal RRC disconnections and RRC reestablishments were not seen in good coverage conditions.

Both random access delay and RRC connection setup time constitute the control plane delay. From the above discussion, we saw the variability of delays with the change of coverage. The average control plane delay (RA delay + RRC connection setup time)varies from 67.82 ms (Good) to 147.48 ms (Bad). Change in radio conditions increased the C-plane delay by 80 ms. C-plane latency can be removed if keep alive message is sent all the time irrespective of how often data packets are sent, so that terminal never goes to sleep mode or have to contend for radio resource using random access. However, considering boundless M2M terminal connecting to network at a same time, it will congest the network and required performance is not met by the network. Therefore, it would be viable to use robust random access method and carefully choosing user inactivity timer value to optimize the C-plane delay.

6.5.1.2 User Plane Delays

As discussed in chapter 4, MTC communication differs from Human-Type communication. MTC involves discontinuous transmission of small data packets with higher latency requirements. Therefore, to investigate the performance of LTE network for intermittent traffic, latency was measured for different inter-arrival times in only good radio coverage measurement site to avoid the effects of other unavoidable reasons. In this measurement, specific LTE features like Discontinuous reception with short and long cycles, radio resource control features were studied which affect mostly user-plane delays. Different inter-arrival times were chosen ranging from 10 ms to 25 seconds, such that terminals stay in continuous mode, terminal go to short and long DRX cycle and RRC state transition is made by terminal. The maximum limit of the inter arrival time was decided based on the operator's user inactivity timer, such that RRC state transition happens when timer expires. The minimum limit was defined to have continuous reception without UE going to DRX mode.

During measurement, an ICMP ping message was sent for every interval time period without any other background traffic. Figure 6.7 shows the CDF distribution of RTTs for different inter-arrival times. RTT values are divided into 4 different groups: $<$ 200 ms, $<$2 s, $<$ 20 s and $>$ 20 s. The preliminary measurement revealed that RRC connection user inactivity timer for the measured network i.e. ELISA was about 20 seconds. Therefore, RRC inactivity timer decided the upper limit of our inter-arrival RTT measurement. Very short inter-arrival times were also required to make sure that LTE terminal stays in continuous reception mode without going to discontinuous reception mode. Within 200 ms inter-packet interval, terminal stays in "continuous reception" mode. Therefore, RTTs for inter-arrival time less than 200 ms is minimum compared to other curves as terminal doesn't go to idle states. For inter-arrival time between 200 ms and 2 seconds, terminal enters into short DRX cycle, so, latency increases as terminal has to gain reception mode from short DRX cycle, wait for short DRX cycle to complete before terminal can send data. For inter-arrival time, 2 seconds to 20 seconds, there is enough inactivity in terminal to push it to long DRX cycle, and when terminal tries to send ICMP packet in each interval, terminal should wait long DRX cycle to complete. But, if inter-arrival time is greater than RRC connection inactivity timer i.e. 20 seconds in our case, then terminal enters into RRC idle mode from RRC active mode. After 20 seconds, when a terminal attempts to initiate packet session for ICMP ping, it requires RRC connection setup procedure. RRC connection setup time varies from 60 ms to 100 ms which adds to latency. Figure 6.8 shows how RTT values increase with increasing inter arrival times. The randomness of RTT values also increases likewise. There are more consistent RTT values when a terminal is in continuous mode. When DRX mode is used, however, values are fluctuating shown by standard deviation values. When terminal goes to sleep in DRX mode, the time taken by terminal to be in continuous mode again depends on how long should it wait for DRX cycle to be completed. As a result, the RTT values have more deviation values.

The above observation shows that the choice of short or long DRX cycle period, user inactivity timer and application refresh interval have strong influence on the perceived latency as well as battery life time of the terminal. RRC connection process (transition from RRC_IDLE to RRC_CONNECTED) involves series of exchange of signalling messages. So, application refresh intervals above the user inactivity timer introduces excessive loads on the core network which would have impact on overall network performance. Moreover, it also can be concluded that perceived latency is varying based on the user activity or how often terminal interacts with LTE network. Idle time between the transmission of data packet may affect the latency by more than 100 ms. In above measurements, although ping messages are sent to common server, the measured latency (RTT) ranges from 20 ms to 200 ms while varying only inter-arrival periods. Therefore, user inactivity timer and DRX cycle period should be optimized such a way that it will meet latency requirements of M2M applications.

Along with latency measurements for various inter-arrival periods, more measurements were also performed with variable packet sizes to see if there is any effect of packet sizes on latency. Figure 6.9 shows the latency measured for variable packet sizes where latency increases with packet sizes which depends on packet queuing and network buffer size, set by network operators. Constant inter-arrival period i.e. 1

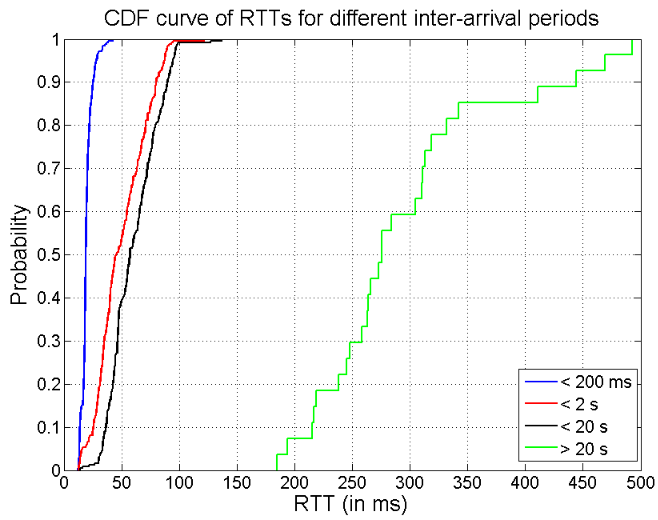


Figure 6.7: CDF curve of RTTs for different inter-arrival periods

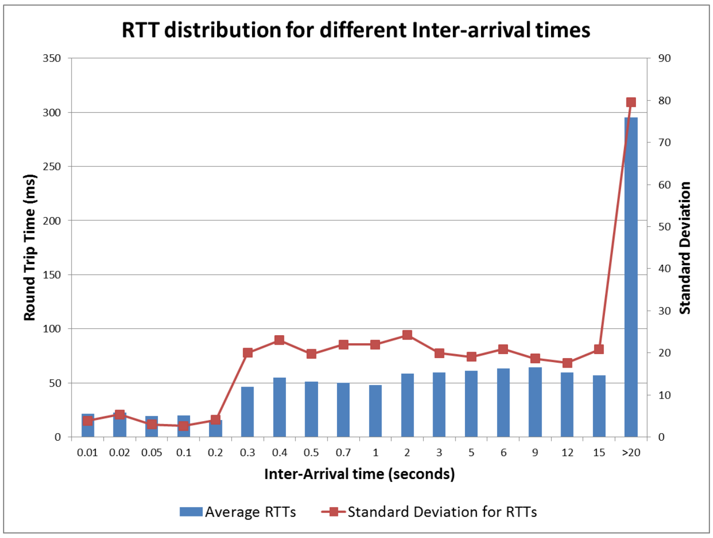


Figure 6.8: RTT distribution for different inter-arrival times

second was used for RTT measurement for variable packet sizes from 60 bytes upto 900 bytes. Marginal increase in latency of around 15 ms is observed when packet size increases from 60 bytes to 900 bytes which is comparatively less than variation of latency based on variable inter-arrival time. Nevertheless, wide range of traffics are used in M2M communication ranging from few bytes to Megabytes, therefore, it is necessary to consider the effect of packet size on latency as well.

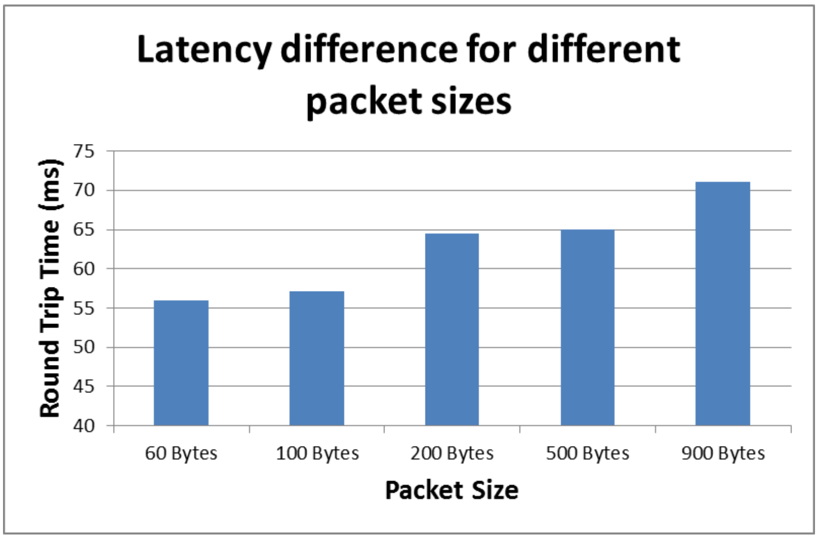


Figure 6.9: Variation of RTTs for different packet sizes

6.5.2 Site 2: Eestinkallio

Similar measurements as done in Piispanportti site were performed in Eestinkallio, located in different kind of terrain environment. Eestinkallio was located at the hill top, antennas were mounted on the typical telecommunication masts. There weren't any high buildings or other obstructions around the mast unlike to site 1. The site was meant to provide LTE coverage over big residential area. The terrain was flat and coverage was expected to be larger than the previous site. Figure 6.10 shows the location of site and coverage route for site 2.

	RSRP(dBm)	RSRQ(dBm)	CQI
Good	-69	-12	11
Average	-105	-15	6
Bad	-115	-22	2

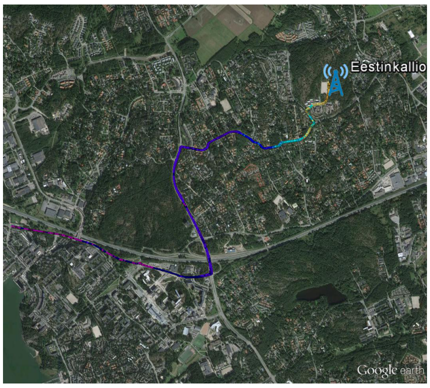
Table 6.7: Stationary Measurement location based on physical parameters

The route drive measurement was done to measure the maximum coverage distance for LTE 800 cell. The coverage extended to nearly 5000 m, which is higher comparison to other LTE network operating on higher frequency band. Based on the route measurement, three measurement locations were defined as good, average and bad coverage according to measured RSRP, RSRQ, and CQIs as shown in Table 6.7.

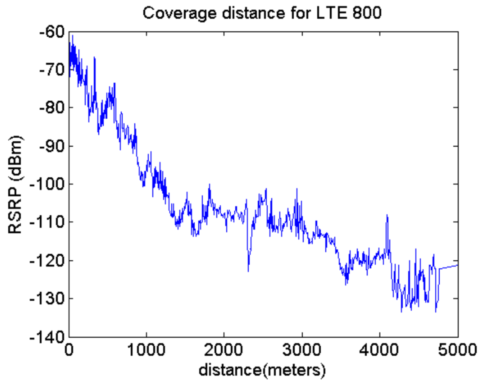
Random access delays were measured, which followed similar trend as the site 1 measurement results. Average delay and randomness of random access delay values in both sites matched each other in varying coverage measurement locations shown in tables 6.5 and 6.8. Assuming the network is with similar load (both measurements done at the same time during day time), random access delays behave in a similar way in similar coverage conditions. Multiple random access attempts cause higher

(a) Mast location of site 2

(b) Site location of site 2



(c) Coverage route



(d) Coverage radius of LTE cell for site

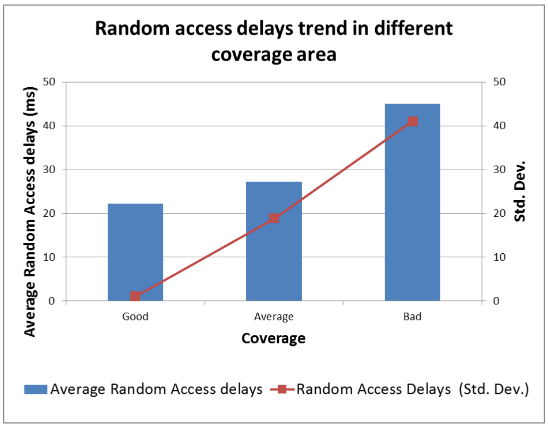
Figure 6.10: Details of the Eestinkallio site

random access delays in bad coverage location, which increases the average values and randomness as well. In good coverage location, all random access attempts were completed on single attempt while the single attempt success rate decreases on moving to poor radio conditions. The delay trends as well as standard deviation of delays are shown in Figure 6.11.

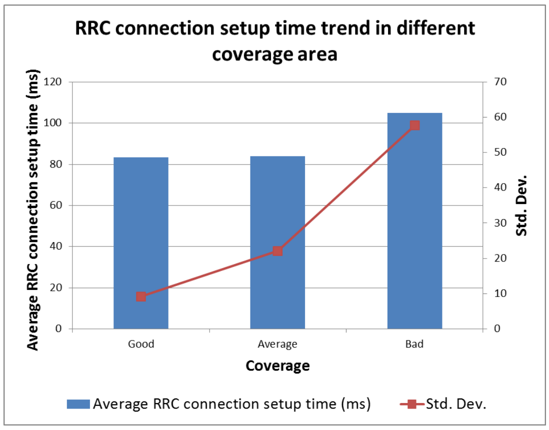
	Average Random Access delays (ms)	**Random Access Delays (Std. Dev.)**	**Random Access Success at once (%)**
Good	22.25	1.06	100
Average	27.31	18.85	95.45
Bad	45.08	41.04	74.4

Table 6.8: Random access delays for different radio conditions

RRC connection setup time was also measured for different coverage locations which were found to have similar trend like site 1 measurement results. Poor radio conditions affect the RRC connection setup time, which increases average RRC connection setup time by 20 ms from good to bad coverage area. Moreover, the fluctuation of delays indicated by the deviation also shows that deviation or randomness



(a) Random access delays trend



(b) RRC connection setup time trend

Figure 6.11: Random access delays and RRC connection setup time trend in Eestinkallio site

in delays is more in the bad radio condition places due to RRC CONNECTION RE-ESTABLISHMENTs and RRC connection failures. Longer RRC connection setup time can also be attributed to more RRC connected users. As the measurements were done during the afternoon period when the capacity of the network is relaxed and there are less active LTE users, the effects of congestion are minimum.

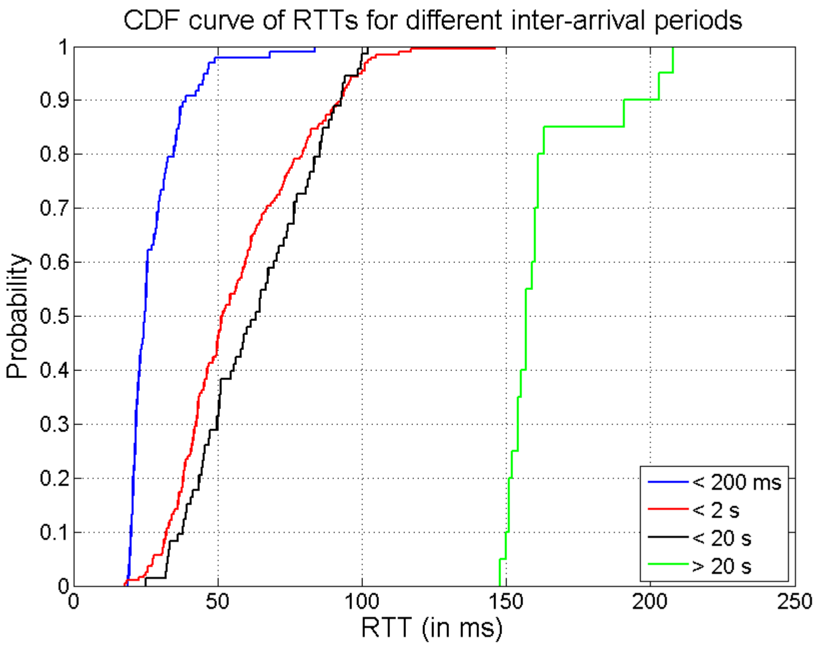


Figure 6.12: CDF curve of RTTs for different inter-arrival periods

Different inter-arrival periods were used to send ping messages to find how user inactivity timer, RRC connection setup time, and long and short DRX cycle affect user plane latency. The ping RTT time were split into 4 different groups, viz, $<$200 ms, < 2s, >20 s and >20 s. In Figure 6.12, CDF curves of RTTs for four different inter-arrival period groups are shown. The blue curve shows the RTT time when terminal is in continuous transmitting phase where terminal continuously send or receive data such that it does not go to sleep. While red and black curves show that the terminal is in short and long DRX cycle, where it has to wait for DRX cycle to complete before it is ready to send the packet which causes additional delays. The effect of user inactivity timer is reflected from green curve where terminal goes to RRC idle as inter-arrival period is greater than user inactivity timer.

6.5.3 Comparison of latency in different LTE systems

Latency measurements were also performed in other LTE networks operating in different frequency bands i.e. LTE 1800, LTE 2600 as well as LTE 800 to find if there are any differences between the systems in terms of latency. A location was selected based on the availability of all LTE networks with similar radio conditions. Table 6.9 shows the basic radio parameters measured for three different networks. 500 RTT samples were recorded for each network simultaneously. RTT was measured as ICMP ping request to www.google.com. Ideally, the RTT values should be same as all LTE networks are using common core network, only differences are delays on radio access side of the network.

	RSRP(dBm)	**RSRQ**	**SINR**	**CQI**
LTE 800	-103	-11	5	7
LTE 1800	-106	-10	7	8
LTE 2600	-86	-6	29	14

Table 6.9: Radio conditions for LTE measurement for different systems

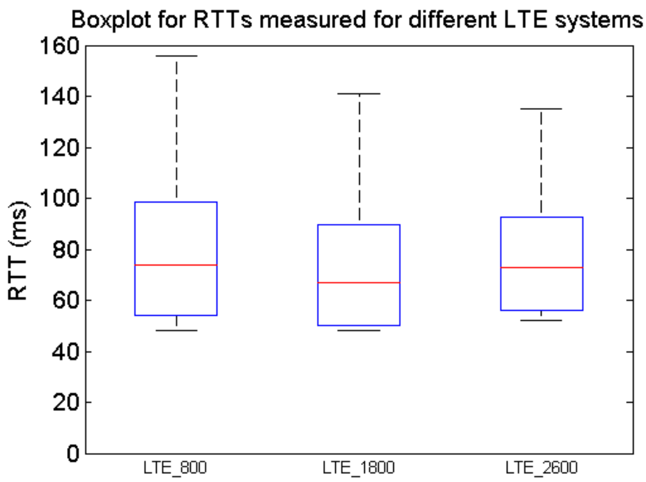


Figure 6.13: Boxplot for RTTs measured for different LTE systems

As seen from figure 6.13, LTE 800 performs as good as its other counterparts working in 1800 and 2600 band. LTE 800 measurements include some outliers which have higher latency values, but median values were comparable among different systems. One of the reasons behind the outliers for LTE 800 might be larger path loss due to larger coverage area and multi-path effects may cause dropping of packets and re-transmissions.

6.5.4 Measurement with Arctic Gateway (RTU)

The latency measurements were also performed with Arctic LTE Gateway [45] which is commercially used in grid applications. Arctic LTE Gateway is used as ideal solution for monitoring and controlling of field devices when high data bandwidth and low latency are required for smart grid applications. It is equipped with external antenna which makes it suitable to be used in challenging coverage conditions. In this measurement, an attempt was made to find how much gain is obtained on the latency using external radio antenna. Latency measurements were done with Arctic as well as mobile device (Samsung S4) simultaneously at same place in good coverage and bad coverage places. Both terminals were connected to same LTE cell, and ICMP ping is sent to same server.

1. **Good Coverage:** Table 6.10 shows the RSRP and RSRQ measured with arctic and Samsung S4. Arctic with external antenna has about 14 dB gain over Samsung phone in received signal as the height and gain of receiver antenna increases the receiver sensitivity of the device. As Samsung phone was inside the car, it causes additional attenuation compared to Arctic with external antennas.

	Samsung S4	**Arctic**
RSRP (dBm)	-74	-60
RSRQ (dB)	-12	-8

Table 6.10: Radio conditions for Good coverage for Arctic and Samsung phone

   Figure 6.10 shows the RTTs values measured from two terminals for different inter-arrival periods. From the figure, it is seen that RTT values are almost similar to each other for both terminals irrespective of differences in the received signal strength and signal quality for all the inter-arrival periods.

2. **Bad Coverage:** Similar measurement as above was repeated in bad coverage place defined by measured RSRP and RSRQ as shown in Table 6.11.

   Figure 6.15 shows the measured RTT values for both terminals for different inter-arrival periods. In contrast to measurement results in good coverage, however, RTT values measured in bad coverage area for mobile phone was higher in comparison to Arctic. In bad coverage site, received signal

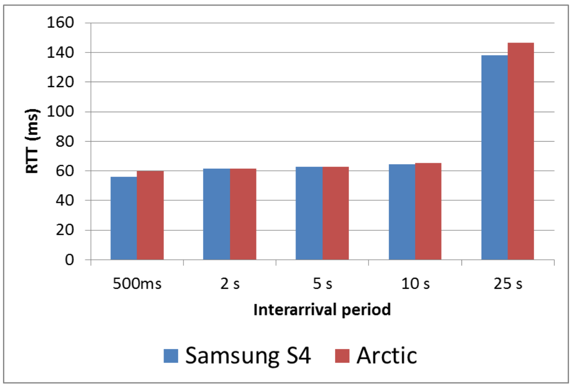


Figure 6.14: Comparison of RTTs Measured by Arctic And Samsung S4

	Samsung S4	Arctic
RSRP (dBm)	-114	-100
RSRQ (dB)	-20	-15

Table 6.11: Radio conditions for Bad coverage for Arctic and Samsung phone

strength and signal quality was poor enough for Samsung phone causing retransmissions and therefore, RTT values are higher for Samsung phone. But, received signal for Arctic RTU was higher enough to have RTT values as high as good coverage area. Therefore,it is essential to provide proper coverage to guarantee the required latency for M2M applications in challenging radio conditions. Use of external antenna to boost the signal strength helps to assure the required latency for the applications.

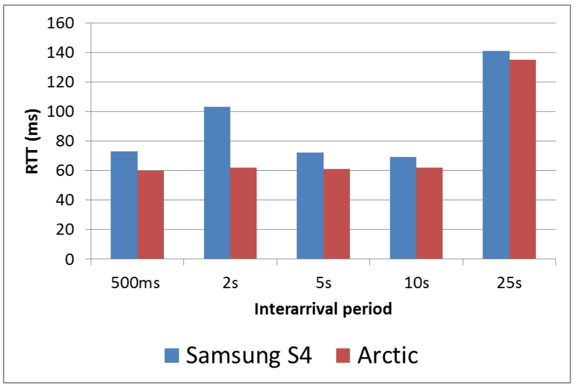


Figure 6.15: Comparison of RTTs Measured by Arctic And Samsung S4

6.6 One-way delay (OWD) measurement

One-way delay measurements are becoming increasingly important to ensure QoS of real-time applications for both wireline as well as wireless backhaul networks like UMTS, LTE. In all the above measurements, latency is measured in terms of round trip time, which doesn't take into account the bottlenecks in uplink or downlink directions. Service providers are taking interest in one way measurements as round trip delay fails to identify QoS issues in asymmetrical access networks. One-way delay measurements can quickly identify and troubleshoot unidirectional QoS issues, provided that it is conducted with sufficient precision and accuracy. Moreover, M2M applications are either downlink traffic dominant (remote automation) or uplink dominant (monitoring), so, round-trip time cannot provide realistic picture of delays involved in each direction. Making one-way delay measurement looks straightforward, sending node sends a probe packet with timestamp on it and receiver end receives the packet and calculates the difference of its own timestamp with probe's timestamp to give one-way delay. But, one way delay is accurate only if the clocks of both nodes are synchronized in the order of microseconds or clock offset (variable for jitter prone network) between the nodes is known. Network Time Protocol (NTP) is the standard for time synchronization in the internet. Synchronization is affected by the delay between the NTP server and measurement device, where NTP tries to overcome the problem measuring round trip delays to estimate clock offsets. Nevertheless, delay is asymmetric for most of the times. Global Positioning Systems (GPS) provide accurate time synchronization between network nodes. GPS satellites include atomic clocks that are monitored and controlled to be highly synchronized with standard UTC time. Using GPS receiver to create stratum 1 (number of hops between time server and accurate time source) time source is the only possible way to reach an accuracy within a number of microseconds.

The most expensive and accurate way to do GPS time synchronization is using GPS receiver in local PCI slot of the computer which reduces transfer delay of GPS's internal clock to local computer via cable. However, these cards are expensive and not widely available. In this measurement, Garmin GPS 18x LVC is used as GPS receiver. The rising or falling pulse generated inside the GPS receiver is used for the synchronization of the computer time. But, the available GPS device had only USB connection, USB interface is not able to transfer pulse signal to the host computer. However, it's possible to transfer the pulses using RS-232 ports. The pulses are sent once every second(GPS with PPS, for pulse per second). Therefore, changes were made in USB connector such that PPS pulse are sent through RS-232 port while NMEA messages are sent through normal USB connection. The measurement was done in linux computer where ntpd and gpsd were installed. NTPD is the daemon which synchronizes the internal computer clock and time source (in this case GPS receiver). GPSD daemon acts as interface between ntpd and GPS device, daemon is needed for GPS communication. Once the GPSD and NTPD daemons are linked together, setup is ready for measurements. The GPS receiver is always kept under open sky which makes synchronization faster and as accurate as possible.

For one-way end-to-end delay measurement, Qosmet [46] tool is used which is a real-time passive measurement tool measuring key QoS parameters from the existing traffic in the network. Qosmet is VTT's in-house built QoS measurement tool able to perform measurements in real-time over any kind of network topology as long as IP (Internet Protocol) is supported. For this measurement, no external traffic was used; only existing the control traffic enough for latency measurement was exchanged

Figure 6.16: Garmin GPS with USB and serial cables

between Qosmet server and client, unlike active probing used in active measurement tools. The time synchronization was done using GPS receiver which provided the accuracy difference of few microseconds. The measurement arrangement is shown in figure 6.17. It consists of Qosmet server and client, clocks in both ends are synchronized using GPS receiver. Qosmet client is installed in laptop which is connected to a USB modem able to access the internet. Qosmet client initiates the bi-directional data transfer with remote Qosmet server.

Delay measurements were carried out during December 2014. OWD measurements were done in publicly available HSPA and LTE networks for two different mobile operators to find if there are any differences in measurement for different operators as well as different technologies (LTE and HSPA). HSPA network was using DC (Dual cell) FDD (Frequency Division Duplex) mode, resulting in bandwidth of 10 MHz in 2100MHz band whereas LTE network was using FDD as well with bandwidth of 20 MHz in 1800 MHz band. One way delay measurement includes both radio access and core network delay in one direction. It is assumed that LTE network has comparatively lower loads than HSPA network with more number of users with considerable traffic. Moreover, three measurement runs were conducted in different times of the day and for evaluation only one data set out of three were selected which seem to have less effect of load in the network as done in [47]. The modem used for measurement was kept fixed during all measurements and was connected to the common masts where the base stations of both the operators were located.

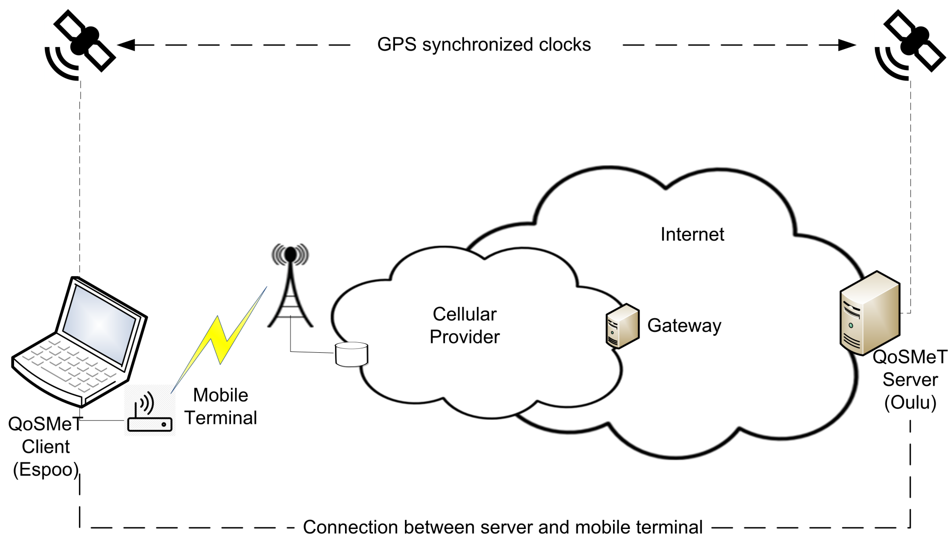


Figure 6.17: Measurement setup OWD measurement

6.6.1 OWD Results

In the measurement, OWD measurement refers to one way user-plane latency. The uplink and downlink delays are compared for two operators' LTE and HSPA network. The differences in uplink and downlink delays are accounted to different resource allocation policies used in LTE and HSPA network as well as network planning strategies used by operators to optimize performance of the network. Measurements were repeated 3 times to remove disparities in the measurement likely to happen due to network load.

Figure 6.18 shows uplink and downlink delays measured in LTE network for two

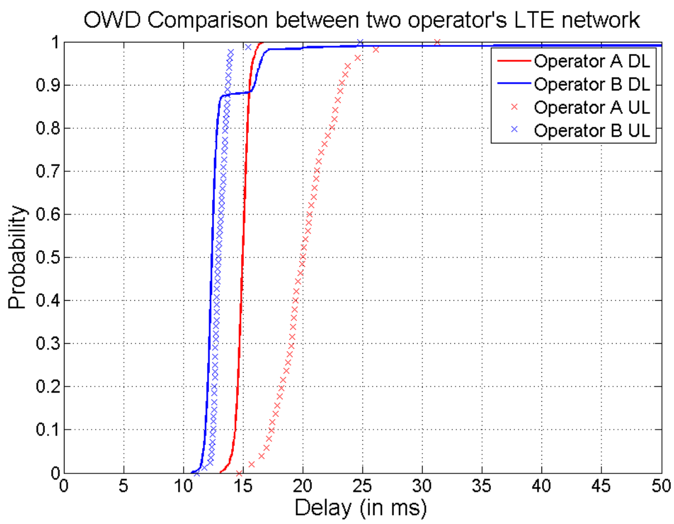


Figure 6.18: OWD comparison between two operator's LTE network

operators. In both operator networks, downlink delays are lower than uplink delays, but the difference is more in operator B than in operator A. Both measurements were measuring downlink delay to the common Qosmet server. As radio link delay is almost similar for both networks, 2 ms difference in downlink delays might be due to core network delay arising from different network equipments or difference in number of hops to reach target server. However, uplink delays for both operators differ by nearly 10 ms which is due to scheduling differences between operators.

As mentioned in section 3.2.3, dynamic scheduling is used in LTE for efficient utilization of radio resources. The downlink scheduling depends on the immediate request of resources, where proper amount of resources are allocated when requested. Downlink scheduling decisions are done in the eNodeB which is the reason behind the low downlink delay. LTE uplink, on the other hand, requires handshake procedure between UE and eNodeB for scheduling of request message from UE and scheduling grant from the eNodeB. A handshake requires messages to be exchanged twice a communication over the air interface, which causes notable delay in uplink direction. The average delay for sending the scheduling request is 2.5 ms and scheduling grant is 4 ms, so, delay with dynamic scheduling adds 7 ms to the uplink delay [25].

In dynamic scheduling, UE get scheduling assignments for every sub-frame providing network full flexibility of assigning resources to the UE but at the cost of transmission of resource allocation information in every sub-frame based on reported channel conditions. Moreover, dynamic scheduling increases control signalling overhead to support more users. For M2M applications, packet size is small, inter-arrival time is constant, and terminal is stationary (no dynamic changes in radio condition). Therefore, optimal solution would be to allocate resources only once and let UE use resources periodically without need of scheduling periodically. This type of pre-allocation of resources is called semi-persistent scheduling (SPS).

From the Figure 6.18, it can be seen that UL delay for Operator A is about 10 ms less than that for Operator B, which is equivalent time required for exchange of resource allocation request and grant messages. From the results, it is seen that Operator A uses SPS scheduling over dynamic scheduling, used in operator B. This difference in optimization strategy used by different operators has significant effect on the UL latency in LTE network.

In HSPA, there is no extra negotiation cycle between UE and NodeB as scheduler in HSPA allocates code-power for average data rate, which makes uplink delay less than downlink delay. When the overall rate changes, the UE requests for additional resources by swapping happy bit. Figure 6.19 shows that uplink delay is less than downlink delay for both operators. Therefore, HSPA is more optimized for small packets and performance is good in small packets than large packets which is typical traffic types for M2M applications.

Latency measured with round trip time measures the cumulative delays in both uplink and downlink directions. However, latency requirements for most of M2M applications are mostly in one way direction, either uplink and downlink. As observed from the measurement results, uplink and downlink delays are asymmetric and are dependent on the radio access technology used (LTE or HSPA) and operator strategies used for network optimization. Therefore, if LTE network is used for M2M application requiring strict latency requirement, it is necessary to have preliminary study on the design of the network used to support applications as well as latency

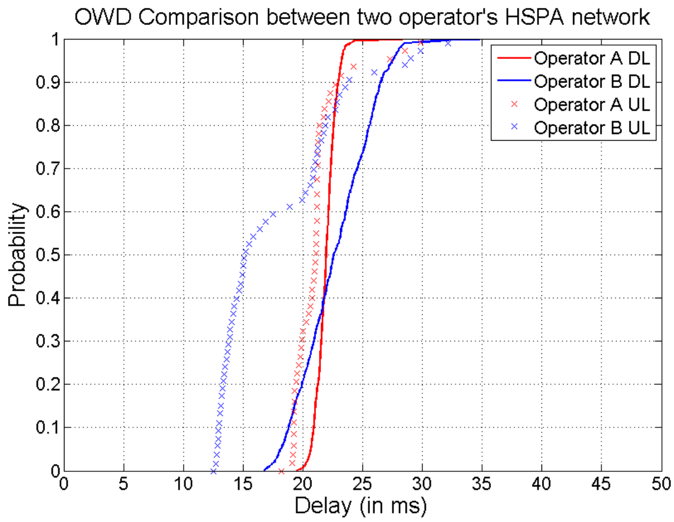
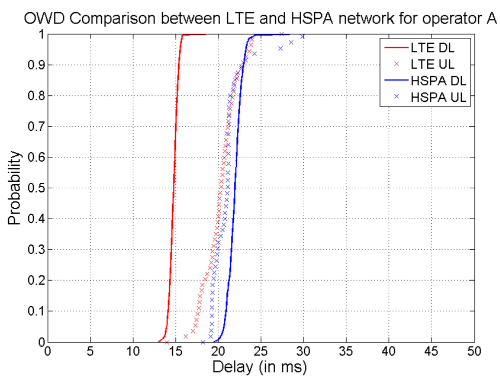


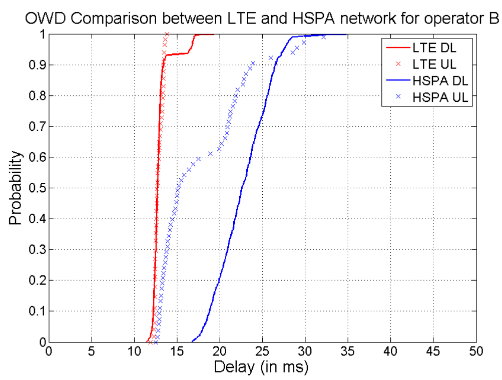
Figure 6.19: OWD comparison between two operators' HSPA network

requirements in both directions

In Figure 6.20, OWD for LTE and HSPA for each operators are compared. For both operators, downlink delay for LTE outperforms the downlink delay for HSPA. However, for uplink delay, operator A, which doesn't use the semi persistent scheduling allocation for LTE, both LTE and HSPA have comparable uplink delay. On the other hand, operator B, which uses semi persistent scheduling, uplink delay is reduced in LTE. The median values for LTE downlink delays of both operators are below 15 ms whereas it is around 22 ms for HSPA. Tables 6.12 and 6.13 show the statistics of the uplink and downlink delays for LTE and HSPA for both operators. The delays are also dependent on the scheduling function used in the network, priority based scheduling for mission critical message decreases the queuing delay in LTE network and hence, reduces the overall latency.



(a) Operator A



(b) Operator B

Figure 6.20: OWD comparison for LTE and HSPA for Operators

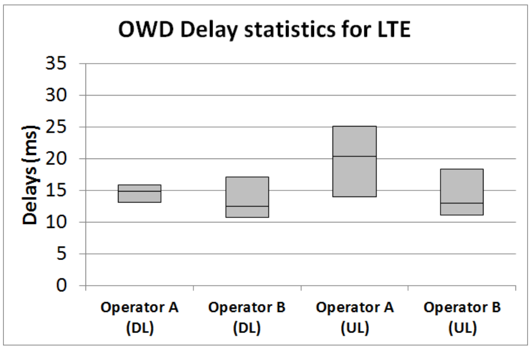
From the above observations, it is clear that one-way delays are asymmetric

	LTE delays (ms)			HSPA delays (ms)		
	Maximum	Minimum	Median	Maximum	Minimum	Median
Operator A	25.01	13.95	20.30	29.74	18.21	21.09
Operator B	18.36	11.11	12.93	32.20	12.54	15.14

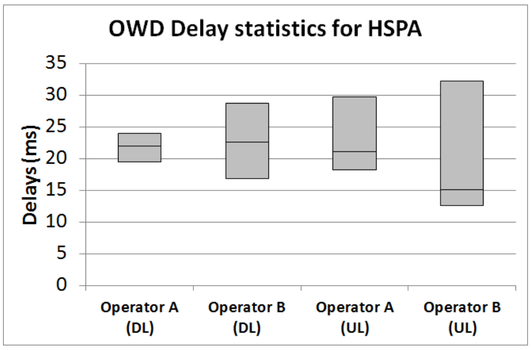
Table 6.12: Uplink Delays in LTE and HSPA for two operators

	LTE delays (ms)			HSPA delays (ms)		
	Maximum	Minimum	Median	Maximum	Minimum	Median
Operator A	15.78	13.10	14.78	23.98	19.50	21.96
Operator B	17.03	10.72	12.40	28.72	16.80	22.58

Table 6.13: Downlink Delays in LTE and HSPA for two operators



(a) LTE



(b) HSPA

Figure 6.21: OWD stats for LTE and HSPA

depending on the type of radio access system used and operator's optimization strategy. In Chapter 5, we discussed about the delay requirements for different smart grid applications. Figure 5.2 showed various performance classes for smart grid applications based on transfer time requirements. LTE as well as HSPA are capable of handling P4 performance class functions with high reliability as both OWD delays for uplink and downlink are less than 100 ms. However, P3 class which requires transfer time of 20 ms can be handled only by LTE but not HSPA. Even though LTE network reduces the latency of network by manifolds in comparison to conventional GPRS & UMTS, LTE is still unable to handle P1 and P2 performance classes which requires transfer time of less than 10 ms. For the strict requirements of latency, a priority class can be defined by the operators to apply different scheduling scheme for this kind of functions in LTE network which can reduce latency.

7 Conclusion and Discussions

In this thesis, the feasibility study of LTE network is done in terms of latency which is a critical parameter for M2M applications, and smart grid is taken as use case example of M2M application. Most of the outdoor measurement were done in LTE 800 network as LTE 800 will be used as primary LTE network providing nationwide coverage. Moreover, LTE 800 has less penetration loss, which makes it ideal network to provide wide indoor coverage. The preliminary study found that network delay or latency is critical in most of the smart grid applications which need real-time services with high precision of delay requirements. This thesis was motivated to find answers how reliable is the latency in commercially available LTE network, how viable will be solutions for utility companies to use LTE network for their services. The key parameters which have significant effect on latency of network were identified like LTE RRC states transition, Discontinuous Reception (DRX) cycle, Random Access delays, packet size variation and, Inter-arrival time of packets. Moreover, One way delay measurement were also done, as network links are asymmetric and RTT (Round Trip Time) which is conventional way of measuring latency, may not be able to identify the problems in uplink or downlink direction. Moreover, the measurements were done in different sites and radio conditions to simulate the environments that M2M terminals have to face during their operations.

As M2M terminal has to transfer data intermittently and receive mission critical messages quite often, terminal has to wake up from sleep mode as soon as possible and make sure latency is guaranteed such that messages are delivered with high time precision as required. In the measurements, random access delay and RRC connection setup times were measured to emulate above scenario, and delays were measured in different coverage conditions. It was found out that the contention based random access is used, where multiple random access can occur if RA procedure fails. In bad radio condition, multiple random access attempts occurred which increase random access delay and consequently, transfer delay as well. Similar trend was seen in RRC connection setup time as well.

The important conclusion was drawn out from the latency measurement done for variable packet inter arrival rates. The latency is dependent on packet inter-arrival period, DRX short and long cycle has effect on end-to-end latency which increases latency by 30-40 ms. If the the arrival interval is greater than user inactivity timer, the situation is even worse, latency is nearly 10 folds than the continuous reception of packets as UE requires additional time for re-establishment of RRC connection. User inactivity timer is used by operators to save radio resources and save battery consumption in the terminal. The single value of latency as promoted by operators gives incomplete information about variation of latency which can happen due to above reasons, and utility companies who are ready to adopt LTE should be aware of the above facts. Latency measurements were also done in all variants of the LTE network viz., LTE 800, LTE 1800 and LTE 2600.It was concluded that the latency measured in all the networks were similar, there were no compromise of latency in any of networks, as they are using similar core network. The only possible variation in latency might be due to radio access transmission delays which are quite negligible.

The measurement performed with Arctic RTU with an external antenna proved that the use of external antennas with proper gain boost the chances of reliable latency values in challenging radio conditions. In one way delay measurement, detailed study was made by breaking latency values into uplink and downlink delays, and finding the reasons behind the asymmetric delays in LTE network. Measurement results also revealed the different strategies used by operators which might have significant effect on the uplink and downlink latency of the network.

The background study and thesis work have been published in following conference proceedings:

1. Horsmanheimo, S.; Maskey, N.; Tuomimäki, L.; "Interdependency Between Mobile and Electricity Distribution Networks: Outlook and Prospects" Smart Device to Smart Device Communication, 281-308, 2014, Springer International Publishing

2. Maskey, N.; Horsmanheimo, S.; Tuomimäki, L., "Analysis of latency for cellular networks for smart grid in suburban area," Innovative Smart Grid Technologies Conference Europe (ISGT-Europe), 2014 IEEE PES , pp.1,4, 12-15 Oct. 2014 doi: 10.1109/ISGTEurope.2014.7028750

3. Maskey, N.; Horsmanheimo, S.; Tuomimäki, L., "Latency analysis of LTE network for M2M applications" The 13th International Conference on Telecommunications (ConTEL 2015) (Status:Submitted)

8 Future Works

The future 5G network is aimed to create networks with capabilities far beyond today's networks which acts as an agile platform for new use cases, new services and new players in a sustainable and cost-efficient way. To meet above goals, 5G has to meet wide range of requirements. 5G is not about the new technology, but the existing network will evolve complementing with new technologies to meet all above requirements for different business use cases. In the future, there will be no longer purpose-built networks for each service within 5G, but instead it will support wide range of new services still using one common network and a common pool of resources and networks will be highly relevant to the new services and execute functions with right performance. Therefore, the use of LTE network is inevitable for M2M applications as the number of M2M terminals are rising exponentially. Morever, LTE with new releases has introduced new features to support MTC applications effectively. In this thesis, emulation of M2M traffic was done to study the latency behaviour based on that traffic from smart grid perspective. In the next research, we are motivated to use real-time GOOSE traffic and study its performance in LTE network. Closer collaboration with operators and utility companies will help to synergize the operations, which will be helpful to both parties. The reliability and security aspects of using cellular networks in smart grid are the main obstacles hindering the use of cellular networks. More researches are needed to define the use cases with their specific requirements as well as develop cyber security scheme of real-time exchange of information. On the other hand, the advanced features introduced in LTE-A like self-organizing networks (SON)can be utilized to self-heal the distribution network during network outage which benefits both mobile communication as well electricity distribution networks. The inter-dependencies between two networks will be studied in detail in future. Next measurement is planned to figure out more KPIs in LTE network which are critical for M2M applications and hence, assisting operators to optimize their network for M2M solutions, without affecting the user experience in H2H communications.

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