On Supporting Small M2M Data Transmissions in LTE/LTE-A Networks

Nitish Rajoria

A Thesis Submitted to

Indian Institute of Technology Hyderabad

In Partial Fulfillment of the Requirements for

The Degree of Master of Technology

भारतीय प्रौद्योगिकी संस्थान हैदराबाद

Indian Institute of Technology Hyderabad

Department of Computer Science & Engineering

June 2014

Declaration

I declare that this written submission represents my ideas in my own words, and where ideas or words of others have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the Institute and can also evoke penal action from the sources that have thus not been properly cited, or from whom proper permission has not been taken when needed.

(Signature)

(Nitish Rajoria)

CS11M01

(Roll No.)

Approval Sheet

This Thesis entitled On Supporting Small M2M Data Transmissions in LTE/LTE-A Networks by Nitish Rajoria is approved for the degree of Master of Technology from IIT Hyderabad

(Dr. Ashudeb Dutta) Examiner
Dept. of Electrical Engineering
IITH

(Dr. Kotaro Kataoka) Examiner
Dept. of Computer Science and Engineering
IITH

(Dr. Bheemarjuna Reddy Tamma) Adviser
Dept. of Computer Science and Engineering
IITH

(Dr. Naveen Sivadasan) Chairman
Dept. of Computer Science and Engineering
IITH

Acknowledgements

First and foremost, I would like to express my sincere gratitude to my adviser Dr. Bheemarjuna Reddy Tamma for his valuable guidance, constant encouragement, motivation, enthusiasm, and immense knowledge. Furthermore I would like to thank Mukesh Giluka (CS11P1002) and Thomas Velerrian Pasca S (CS13P1002) for introducing me to the topic as well as for the valuable guidance and discussion on the way. Many individuals contributed in many different ways to the completion of this thesis. I am deeply grateful for their support, and thankful for the unique chances they offered me.

Finally, I thank my family for supporting me throughout all my studies at the institute. I would like to make a special mention of the excellent facility provided by my institute, IIT Hyderabad.

Dedication

I would like to dedicate my dessertation work to my family and friends who accepted me without ressentment my complete self-isolation during the whole work. Especially thankful to my father Amar Chand Rajoria and my loving mother Chandra Kanta. I also gratitude my elder brothers Himanshu Rajoria and Ashish Rajoria who provide endless support while working on this dessertation. I also dedicate to Mukesh Giluka for his encouragement throughout this process.

Abstract

In Machine-to-Machine (M2M) applications, devices monitor events (e.g., temperature, inventory level), which is relayed through a communication network infrastructure (e.g. Internet, LTE) to an application (software program running on a server connected to the Internet), that translates the monitored event into some meaningful information to be able to take collaborative decisions with limited or no human intervention.

With the availability of IPv6 address, it is possible to interconnect everything in this universe. By using the concept of interconnecting things, several applications can be envisioned to make the world smarter. Internet of Things (IoT) is a paradigm whose aim is to implement the concept of interconnection of everything by using all possible technologies and others means. M2M communication is one of the components of Internet of Things (IoT) whose goal is to make the communication smooth and seamless between any two networking enabled devices. According to the researchers by the end of 2014, 1.5 billion devices and by the end of 2020, 20 billion devices will be part of M2M communication.

Presently, penetration of M2M communications in cellular networks is less. The factors responsible for this observation are: (i) Cellular networks operate in licensed band, hence, costlier in terms of budget to achieve M2M targets. (ii) Cellular networks are optimized for Human-to-Human (H2H) communications, and incorporating M2M may lead to degradation of performance of H2H. (iii) Traffic nature of M2M is different from H2H. Mostly M2M follows infrequent small data transmission (SDT). But, due to large coverage area in comparison to other access technologies, and global connectivity, cellular networks are becoming first choice for companies providing M2M services. Various efforts have been applied by organizations such as 3GPP, ETSI etc. and companies such as Vodafone, Erricson etc. for making cellular networks compatible for M2M communications. In our work, we have tried to optimize 4G LTE systems (LTE and LTE-A) so that M2M can be supported by least affecting H2H services.

Since M2M communications involve infrequent SDT of M2M devices, by incorporating it in LTE systems will raise following issues:(i) Extreme overhead on bandwidth resource scheduler. Since, resource scheduler will have to schedule small amount of resources for large number of M2M devices, it will not only increase the scheduling algorithm complexity but also increase the latency of resource allocation for H2H devices. (ii) Signaling overhead imposed by M2M devices during the procedure of EPS bearer establishment. A device exchanges on an average 25 signaling messages from it is switch on to EPS bearer establishment. In case of H2H devices, this signaling messages exchange is bearable because they are less in number as well as they send mostly large amount of data but in case of M2M devices, condition is completely opposite. In order to resolve above issues, there is a need of separate EPS bearer establishment procedure for M2M devices which not only reduces the number of signaling messages exchange but also reduces overhead on resource scheduler.

Apart from above issues, the LTE systems suffer from problem of contiguous allocation of resource blocks in uplink in order to reduce peak to average (PAPR) power ratio. Because of this, scheduler cannot allocate best set of RBs to users alike downlink scheduling and hence, scheduler allocates an available fixed chunk of contiguous RBs. Since, chunk of RBs to be allocated to users is of fixed size, this scheme of resource allocation for M2M SDTs is very uneconomical. This is because of the fact that, if the chunk size is big then it is a wastage of RBs for SDT but if it is small then it will incur too much overhead on scheduler for larger data transmissions. So, there is a need of variable

size chunk allocation scheme for uplink.

In this thesis, we have attempted to solve above issues by piggybacking M2M data with *RRC connection request message (message 3).* Apart from this, we propose a lightweight EPS bearer establishment procedure (LW-M2M method) for M2M devices sending infrequent SDT. In this LW-M2M method, we have replaced the authentication module of legacy procedure (Legacy method), which authenticates UE and MME, by confidentiality of small M2M data. Because of this, we are able to ignore NAS security keys exchange and RRC security keys exchange and hence, able to ignore signaling messages exchange involved into these security keys exchange. The proposed LW-M2M method reduces the number of signaling messages exchange from 25 to 14. The simulation results from NS3 experiments showed that the end-to-end delay of M2M devices is reduced by 37.5% in LW-M2M method as compared to Legacy method. We have calculated throughput of H2H devices in a setup which has H2H and M2M devices. We observed that H2H throughput increases by 18% in LW-M2M method as compared to Legacy method.

In case of contiguous allocation of resource blocks in uplink, we propose a variable chunk size based algorithm which creates chunks of variable size depending on the requirements sent by the users. The simulation results from NS3 experiments showed that fairness (efficient allocation of RBs among the users) and hence, throughput have been increased in comparison to older schemes. The algorithm performs well as number of users increase.

Contents

Chapter 1

Introduction

1.1 What is M2M?

In Machine-to-Machine communications (M2M) [1, 2, 3], devices monitor events (e.g., temperature, inventory level), which is relayed through a communication network infrastructure to an application (software program running on a server connected to the Internet), that translates the monitored event into meaningful information to be able to take collaborative decisions with limited or no human intervention. The network access technologies used as communication network infrastructure for supporting M2M communication differ from short area coverage such as Wi-Fi, ZigBee, bluetooth to wide area coverage such as wired xDSL or UMTS, LTE, and LTE-A. M2M communications should be able to support following two important features: (i) Large number of low power and low cost devices communicating with each other (ii) Seamless interoperability between different network access technologies.

With the availability of IPv6 address, It is possible to interconnect everything in this universe. By using the concept of interconnecting things, several applications can be designed to make the world smarter. Internet of Things (IoT) [4][5] is a paradigm whose aim is to implement the concept of interconnection of everything by using all possible technologies and others means. M2M communication is one of the components of Internet of Things (IoT) whose goal is to make the communication smooth and seamless between any two networking enabled devices. It is worth mentioning that in some literature M2M and IoT are used as synonyms but in reality they are not.

Because of its capabilities of providing smooth communication between devices, there are several M2M applications have been designed. For example, smart grid, healthcare, asset tracking etc. All such applications are increasing average per person utilization of networking enabled devices by many fold. For example, In case of smart grid application, each electric appliance will also be acting as a networking device. In a common household, if on an average 16 such electric appliances and four people are there then apart from regular useful networking devices (smart phones, laptops etc), a person will be using 4 extra networking devices. Similarly, household may be subscribed for other such applications. So, we can imagine that by the grow of M2M communications, how fast number of networking devices will increase. Table 1.1 shows present and probable future condition of number of networking devices in the world.

Table 1.1: M2M Statistics

Parameters	Values
Ratio of number of connected things and people presently and by 2020 [6] [7]	2:1, 7:1
Number of connected devices by the end of 2012, 2013 and 2020 [6] [7]	8.7 billions, 10.8 billions, 50 billions
Areas in which connected devices will be mostly found	automotive, intelligent building, metering, smart city, healthcare and consumer electronics applications
Number of M2M devices connected to cellular by 2020 [8]	2 billions

1.2 M2M Applications

In [9], based on the present trends, authors have classified all M2M applications into following six categories. Table 1.2 shows the classification and their percentage of penetration in M2M market.

Table 1.2: M2M Applications

Fleet Management	51%
Asset Tracking	18%
Building Security	14%
Modem	9%
Metering	6%
Health care	2%

Figure 1.1 shows M2M Domain and Opportunities related. In this section, we have discussed some applications which have really made M2M more popular.

1.2.1 Smart Grids

An electric grid consists of three units viz., generation, transmission and distribution. Inefficient functioning of any of the unit may affect performance of other units. Smart grid enhances the performance of all these units by establishing communication between them. The main aim of smart grid is to optimize the generation, transmission and distribution of power by collecting and extracting the electricity consumption information from end users.

A typical smart grid architecture facilitates formation of three types of networks of devices and M2M communication between them. First is home area network (HAN), formed by devices consuming electricity in households. For example, television, fridge, bulb, fans, etc. These devices send their power consumption information to a smart meter using a short range wireless network access technology such as ZigBee, Bluetooth, etc. The second type of network is neighborhood area network (NAN), formed by smart meters. After collecting power consumption information from devices, smart meters send the aggregated information to a connector through a medium range wireless network access technology such as Wi-Fi. Now, these connectors form a wide area network (WAN) to send the aggregated information to a centralized control center through a wide range

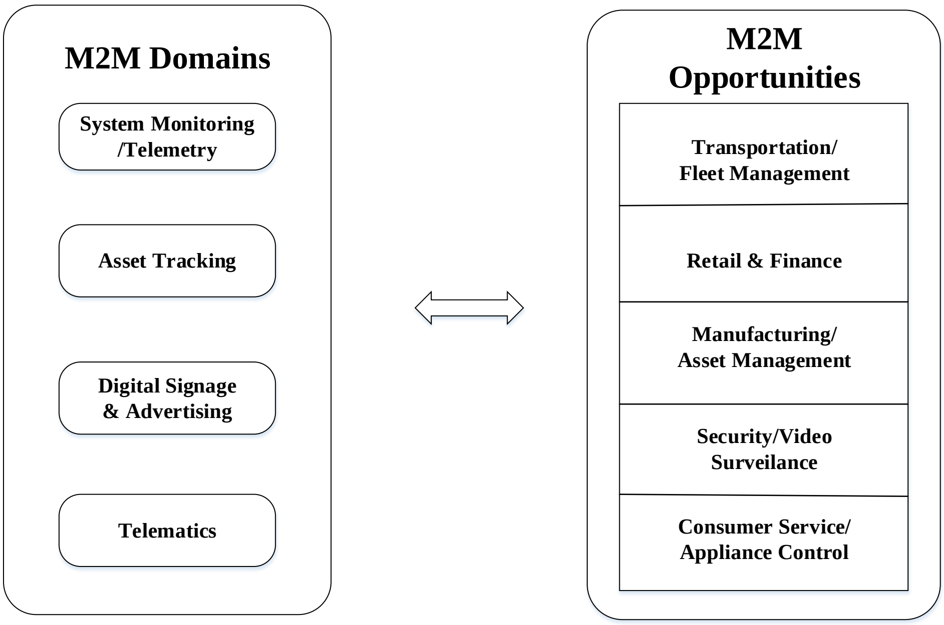

Figure 1.1: M2M Domain

network access technologies such as cellular networks. The role of the control center is to analyze the collected information and take necessary decisions for efficient distribution of power and hence, encouraging accurate generation of power. Figure 1.2 shows a typical architecture of smart grid.

1.2.2 E-Healthcare

Nowadays, M2M communications is playing a big role in healthcare. Healthcare based M2M applications are mainly focused on remote caring of patients. Healthcare based M2M services cover mainly following problems:

- Regular monitoring of patients having severe diseases. For example, wearable monitoring device will send health information to the expert doctor so that the patient will always be under the supervision of doctor and immediate measures can be taken in case of some unpleasant condition.

- To get the instructions for need of check-up or precautions by sending the health information through body sensors. For example, various sensors (blood pressure, heart beat, etc.) implanted in the body will collect information of functioning of body parts and will send the information to some healthcare unit, which will suggest the exact step to be taken after processing.

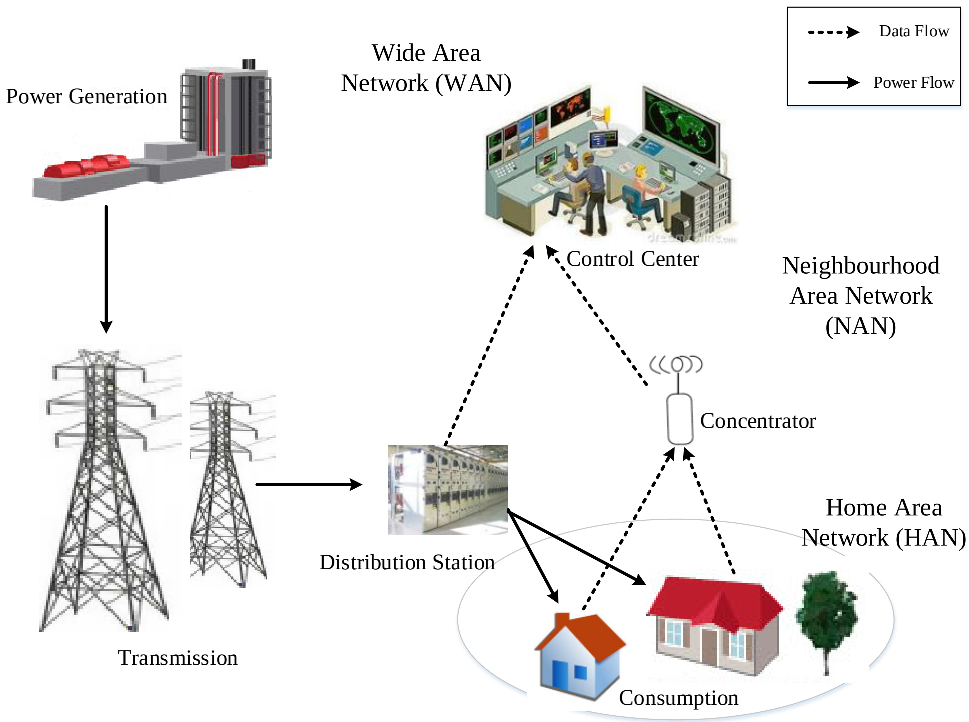

Figure 1.2: An example of Smart Grid architecture [10]

1.3 M2M Requirements

M2M applications cover a diverse field of its applicability. Depending on the application, QoS requirements of M2M communication varies. In this section, we discuss different QoS requirements and how they vary with the application [3].

- Latency: Some applications are delay tolerant in which data packet can bear some amount of delay to reach to destination. For example, environment monitoring applications. But, there are some applications which can not tolerate delay. like, healthcare applications.

- Bandwidth: Some applications send packets of small size. Such applications not require high bandwidth to send their data. For example, environment monitoring applications. But, some applications have to send large amount of data for longer duration. In this case high bandwidth is required. For example, video surveillance applications in which surveillance cameras regularly send the recorded footage to the remote server.

- Reliability: Some applications requires reliable data transmission irrespective of the network conditions. For example, e-healthcare and online payment.

- Priority: Delay intolerant application needs, high priority during allocation of resources.

- Power Consumption: Mostly, M2M devices are less power hungry because in most of the M2M applications, M2M devices experience infrequent human interaction and wake only on demand.

Power consumption by devices are because of activities such as link adaptation, exchange of control signals and uplink power control.

- Mobility: Most of the M2M applications have static M2M devices. For example, environment monitoring, healthcare and smart grids. But some applications are also there where M2M devices are mobile. For example, intelligent transportation system, fleet management and asset tracking.

1.4 M2M Architecture

Figure 1.3 shows a typical M2M architecture. A basic M2M architecture has following components [11]:

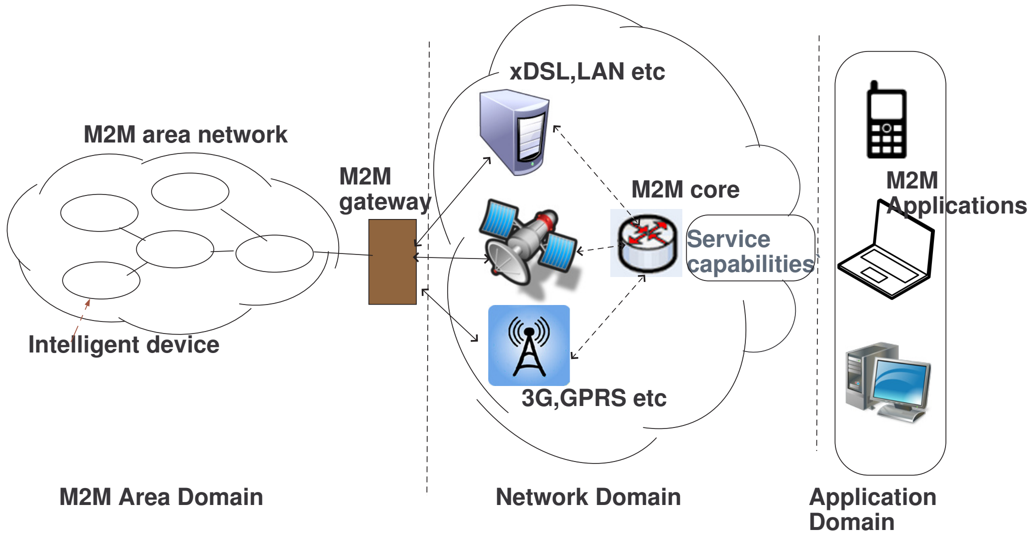

Figure 1.3: M2M Architecture

- Device Domain: M2M devices, deployed in a particular area, send data to application server. Devices either send data directly to the server or through gateway. The gateway is called as M2M gateway.

- Network Domain: M2M devices may form a network to send the data to the gateway. This is a small area network called as M2M area network. Network access technology used in M2M area network is mostly of small range such as bluetooth, zigbee, etc. Devices sending data directly to application server use network access technologies of long range such as cellular networks. Similarly, M2M gateways also use long range access technologies to send aggregated M2M data to the application server.

- Application Domain: After receiving information from M2M devices, the application server does required processing and takes necessary actions. Application server is connected to the users who have subscribed for the M2M services. The M2M app. installed in users machine provides user interface so that services provided by the application server can be used by the service subscriber.

Two approaches have been considered in designing M2M architectures [3]. One is distributed approach and other is centralized approach. Table 1.3 explains characteristics of both types of architectures.

Table 1.3: M2M Architectures

Distributed	**Centralized**
Devices are connected without any infrastructure based network	Infrastructure network is there between two devices
Called as capillary M2M	Called as non-capillary M2M
M2M gateway may use	M2M gateway may use
M2M devices connected to gateway through ad-hoc network	Connected to gateway through cellular or wired network

1.5 M2M Standardization

Overall M2M development is associated with progress in the following fields [3]:

- Device and Network Management
- Device Processing
- Network Architecture and Air Interface
- Applications and Services

Each of the field is covered by different standard development organizations (SDOs). For example, 3GPP is working on issues in cellular networks due to M2M. M2M market is growing rapidly and various SDOs are developing standards and protocols on their own way. In order to make M2M a successful endeavor, interoperability between different standards is required. Table 1.4 [3, 5, 12] shows different SDOs and their work specialty.

1.6 M2M Communication Over LTE/LTE-A Cellular Networks

Presently, penetration of M2M communications in cellular networks is less. There are following factors can be responsible for this:

- Cellular networks operate in licensed band, hence, costly for M2M communications.
- Cellular networks are optimized for H2H communications, and incorporating M2M may lead to degradation of performance of H2H.
- Traffic nature of M2M is different from H2H.

Table 1.4: M2M Standardizations

SDO	M2M Specific Working Area
3GPP (www.3gpp.org)	Works on incorporation of M2M in 3G, 4G cellular networks. Handling issues related to efficient resource allocation, signaling overhead and small data transmissions.
IEEE (www.ieee.org)	Making IEEE 802.16p, 802.11 and 802.15.4 efficient for M2M.
ETSI (www.etsi.org/technologies-clusters/technologies/m2m)	Works on designing M2M architectures and defines functional and behavioral requirements of network elements.
WiMAX Forum (www.wimaxforum.org)	Works for incorporation of M2M in WiMAX networks.
GSMA (www.gsma.com)	Works for incorporation of M2M in GSM networks.
OMA (www.openmobilealliance)	Works for lightweight M2M device management for various networks such as cellular, Wi-Fi, 6LoWPAN, Zigbee.
TIA (www.tiaonline.org)	Works for developing M2M communication framework which can operate over existing underlying networks. The framework can be adapted to the underlying networks through adaptation layer.
OneM2M (www.onem2m.org)	A partnership project formed for cooperating in the creation of access independent M2M service layer specifications which are globally applicable. Partners of this project are CCSA, TTA (Korea), ARIB, TTC, ETSI, ATIS, TIA, OMA.

But, due to large coverage area in comparison to other access technologies, and global connectivity, cellular networks are becoming first choice for companies providing M2M services. Various efforts have been applied by organizations such as 3GPP, ETSI etc. and companies such as Vodafone, Erricson etc. for making cellular networks compatible for M2M communications. In our work, we have tried to optimize 4G LTE systems (LTE and LTE-A) so that M2M can be supported by least affecting H2H services. In this section, we will discuss LTE architecture and its components.

1.6.1 Introduction to LTE/LTE-A Cellular Networks

By introducing the concept of OFDM (Orthogonal Frequency Division Multiplexing) and MIMO (Multiple Input Multiple Output), LTE offers data rate of 100 Mbps for downlink and 50 Mbps for uplink. LtE operates on bandwidth of 1.4 Mhz, 3 Mhz, 5 Mhz, 10 Mhz, 15 Mhz and 20 Mhz. It uses OFDMA for downlink and SC-FDMA for uplink. Figure 1.4 shows the architecture of LTE. The LTE architecture can be divided into two parts, E-UTRAN (Evolved UMTS Terrestrial Radio Access Network) and EPC (Evolved Packet Core). Both parts are combine called as Evolved Packet System (EPS).

- E-UTRAN: Figure 1.5 shows the architecture of LTE E-UTRAN. This is the radio access part

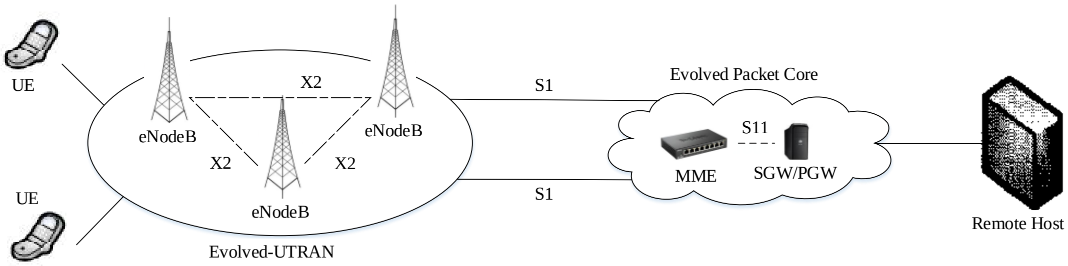

Figure 1.4: LTE Architecture

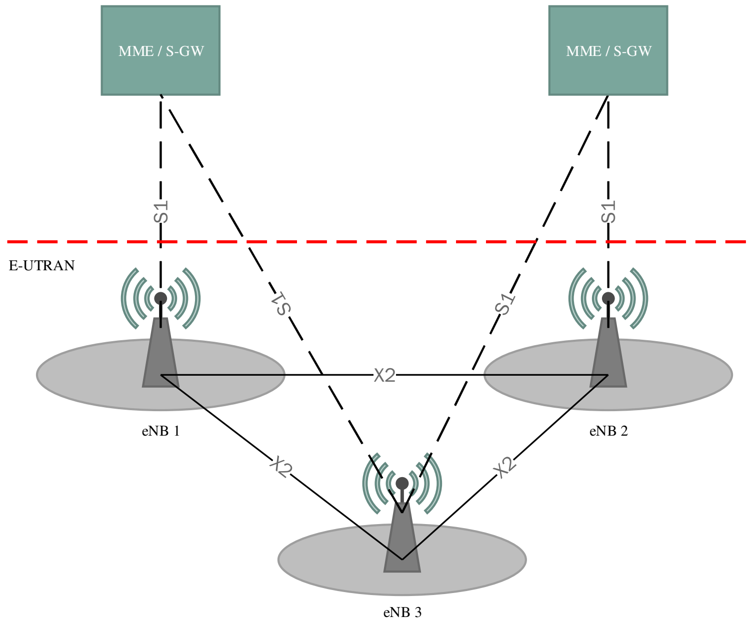

Figure 1.5: Architecture of E-UTRAN

of LTE architecture where communication between device and base station takes place. In LTE, devices are abbreviated as User Equipment (UE) and based stations are abbreviated as eNodeB (eNB).

- EPC: It is the interface between E-UTRAN and core network. There are three components of EPC viz. Mobility Management Entity (MME), Serving Gateway (S-GW) and PDN Gateway (P-GW), Home Subscriber Server (HSS). Figure 1.6 shows an EPC architecture.
  - MME: It takes care of following activities:
    * Authentication of user
    * Management of security keys
    * NAS message exchange with UE
    * Bearer establishment process
    * UE roaming management

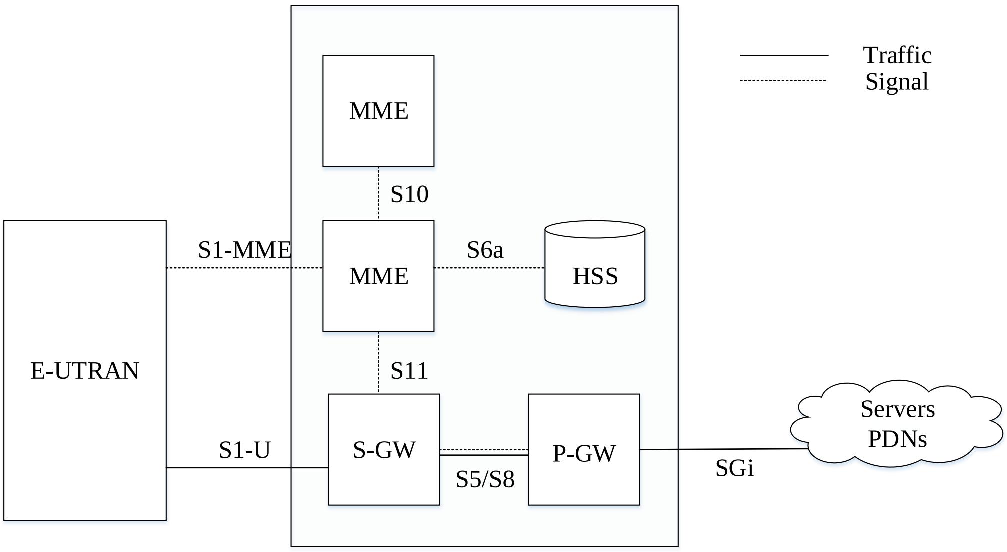

Figure 1.6: LTE Evolved Packet Core

- S-GW: It takes care of following activities:
  * Data packets routing and forwarding.
  * Triggering of paging when downlink data arrives and intended UE is in idle mode.
  * Takes part in bearer establishment.
  * It acts as mobility anchor,in case of UE moves form or to other 3GPP technologies and in case of inter-eNodeB handovers.
- P-GW: It takes care of following activities:
  * It acts as gateway of EPS and core network.
  * Packet filtering and policy enforcement is done at P-GW.
  * It acts as mobility anchor, in case of UE moves form or to other non-3GPP technologies.
- HSS: It is a central database which contains user related information including user subscription profile.

1.6.2 LTE Control Plane

This is used for the exchange of control packets as shown in figure 1.7. The Non-Access Stratum (NAS) protocol is used for control signaling between the UE and MME. The radio sublayers remain the same as in case of the User Plane except for the Radio Resource Control (RRC) sublayer. The RRC layer is responsible for the establishing radio level configuration between the eNB and UE.

1.6.3 LTE Frame Format

In LTE [13], overall system planning is done on the basis of 10 ms, called as frame and resource allocation is done on the basis of 1 ms, called as subframe. There are two types of frame formats

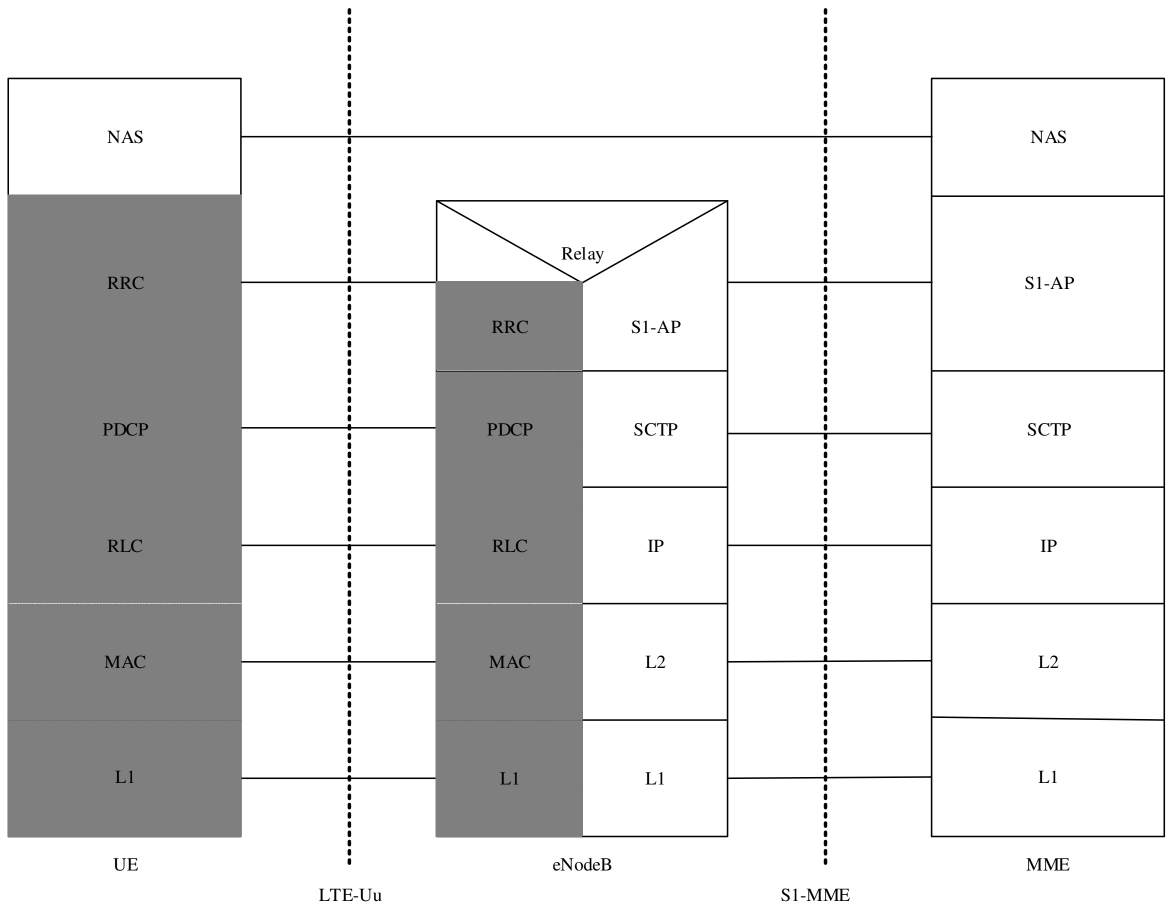

Figure 1.7: LTE control plane protocol stack

proposed in LTE. In first type, resource allocation for uplink (device → base station) and downlink (base station→ device) is done separately. This frame format is called as frequency division duplexing (FDD). In other words, the whole frame is dedicated for either uplink or downlink. In FDD, the whole bandwidth is equally distributed for uplink and downlink transmissions, hence, both transmissions can take place simultaneously. But, it is the capability of the UE that whether it can support full-duplex transmissions (both transmissions simultaneously) or half-duplex transmission (one transmission at a time). If the UE supports half-duplex transmission, and downlink reception is immediately one subframe before uplink transmission then in this case, the UE is allowed to skip receiving the last OFDM symbol of downlink subframe. Figure 1.8 shows frame format for FDD. A subframe is divided into two slots, each of 0.5 ms duration. Therefore, 20 slots per frame will be there. In the second type of frame format, resource allocation for uplink and downlink is done together. This frame format is called as time division duplexing (TDD). In TDD, transmission is done with whole bandwidth. Here, in the same frame, some subframes are dedicated for uplink and rest are dedicated for downlink. Figure 1.9 shows uplink/downlink subframe configurations for TDD. D denotes a subframe for downlink transmission, U denotes a subframe for uplink transmission and S denotes a "special" subframe used for a guard time. For switching from downlink to uplink, the special subframe always takes place because in downlink to uplink switching, control shifts from

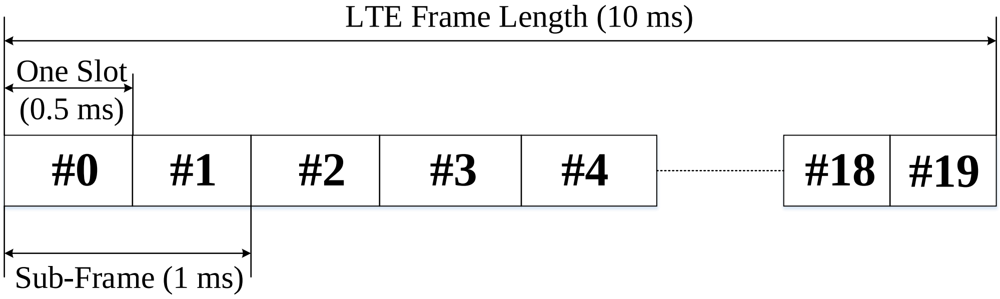

Figure 1.8: LTE Frame Format in FDD mode

UPLINK-DOWNLINK CONFIGURATION	DOWNLINK TO UPLINK SWITCH PERIODICITY	SUBFRAME NUMBER									
		0	1	2	3	4	5	6	7	8	9
0	5 ms	D	S	U	U	U	D	S	U	U	U
1	5 ms	D	S	U	U	D	D	S	U	U	D
2	5 ms	D	S	U	D	D	D	S	U	D	D
3	10 ms	D	S	U	U	U	D	D	D	D	D
4	10 ms	D	S	U	U	D	D	D	D	D	D
5	10 ms	D	S	U	D	D	D	D	D	D	D
6	5 ms	S	S	U	U	U	D	S	U	U	D

Figure 1.9: LTE Frame Format in TDD mode

eNodeB to UE. A special subframe consists of following three fields:

- Downlink Pilot Time Slot (DwPTS): Facilitates downlink synchronization
- Gaurd period (GP): To avoid interference between uplink and downlink. It provides the transceiver sufficient time to switch from reciever mode to transmit mode.
- Uplink Pilot Time Slot (UpPTS): Facilitates uplink synchronization

Except the special subframe, like in FDD, all other subframes are divided into two slots of 0.5 ms duration. In LTE, bandwidth resources are allocated to users in terms of resource blocks (RBs). A resource block (RB) consists of 12 subcarriers in frequency domain and 6-7 OFDM symbols in time domain spanning 0.5 ms. OFDM subcarrier spacing is 15 KHz. Therefore, a RB is of worth 180 KHz. A resource element is the smallest physical resource in LTE. A resource element consists of one subcarrier in the duration of one OFDM symbol. So, a resource block consists of $7 * 12 = 84$ resource elements. Figure 1.10 shows typical structure of a resource block with resource elements.

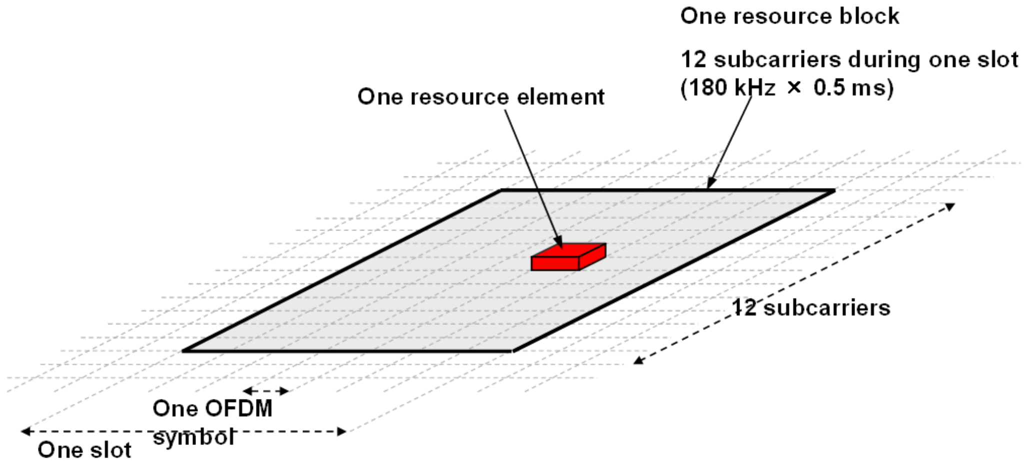

Figure 1.10: Structure of Resource Block (RB) and Resource Elements [13]

1.6.4 LTE Attach Procedure

A device has to be attached with eNB before doing communication (downlink or uplink) in LTE. It should be synchronized with the cell for that it has to do cell search process by that it will gets the cell information.

Cell Search

During the cell search process, a device gets the frame timing of the cell, for that device should synchronize with cell and it needs the cell identity. For this information eNB continuously broadcasts two synchronization signals.
Primary Synchronization Symbol (PSS): From PSS UE can find,

1. Five millisecond timing of the cell
2. Position of Secondary Synchronization Symbol (SSS)
3. Cell identity within a cell identity group

Secondary Synchronization Symbol (SSS): From SSS UE can find,

1. Frame timing
2. Cell identity group

MIB (Master Information Block)

In LTE, MIB carries the following information:

1. Bandwidth
2. Physical Hybrid-ARQ Indicator Channel (PHICH)

3. System Frame Number

MIB is scheduled in Subframe #0 of every radio frame with a periodicity of 40 ms.

SIB (System Information Block)

In LTE, SIB carries the following important information:

1. Tracking Area Code
2. Cell Selection Info
3. Frequency Band Indicator
4. Scheduling Information of other SIBs

Random Access Procedure

After reception of messages PSS, SSS, MIB and SIB, the UE is assumed to be downlink synchronized but uplink synchronization is yet to be done. In the following cases, an UE is suppose to be uplink synchronized:

- When UE is switched on.
- At the time of handover.
- At the time of connection re-establishment.
- Before downlink data arrival from eNB.
- Before uplink data transmission from UE.
- Positioning.

For uplink synchronization, UE follows the Random Access Procedure (RACH) procedure. In RACH procedure, UE sends a preamble (message 1) to eNB. There are 64 such preambles available in LTE in which, approximately 54 preambles are for contention-based RACH procedure and remaining are for contention-free RACH procedure. In case of contention free RACH procedure, eNB itself assigns preambles to UEs while in contention based RACH procedure, UEs choose a preamble randomly. So, contention free RACH procedure is collision less and used mostly for handovers. When eNB receives random access preamble, it sends a random access response message (message 2) to UE. This message contains:

1. T-CRNTI (Temporary-Cell Radio Network Temporary Identifier): The eNB allocates this identity to UE for further communication between them.
2. Timing Advance : In order to adjust the time clock of UE, the eNB calculates the time advance and sends it through message 2 to UE.
3. Number of resource blocks (RBs) allocated for sending message 3 from UE to eNB.
4. Modulation and coding scheme to be used by UE to send message 3.

After receiving message 2, UE sends message 3 to eNB. This step is called as terminal identification. Message 3 contains C-RNTI of the device if it is already having this, and core network terminal identifier if the device is first time connecting to the network. After receiving message 3, eNB sends its response to UE. This step is called as contention resolution step.

1.7 LTE EPS Bearer Establishment Procedure

Radio Resource Control (RRC) layer in LTE is responsible for connection setup between UE and EPC network entity. When UE wants to send data, it has to establish a connection. Figure 1.11 shows the messages exchange during the EPS bearer establishment procedure which has the following components:

1. RACH Procedure
2. RRC Connection Procedure
3. Authentication Procedure
4. RRC Reconfiguration Procedure

- Message-1 : Random Access Request - An UE sents a preamble to eNodeB which is chosen from the group of preambles.
- Message-2 : RACH Response - It gives C-RNTI, which is used as user identity in subsequent communication procedure. Timing advance and uplink resource grant are also added in RACH response.
- Message-3 : RRC Connection Request - It is sent on uplink shared channel (ULSCH) by UE with UE identity and establishment cause for the request.
- Message-4 : RRC Connection Setup - UE is notified with an appropriate response from eNB, creating a signaling radio bearer with all the configuration for Uplink Shared Channel (ULSCH), Power Headroom Report (PHR) and Uplink power control.
- Message-5 : RRC Connection Setup Complete - It contains PLMN Identity and NAS request. The eNB on receiving the message forwards NAS request to MME. The purpose of NAS request is dual authentication i.e., UE authenticates network and MME authenticates UE.
- Message-6 : Authentication Request - MME requests HSS (home subscriber server) for Authentication Vector (AV) in authentication data.
- Message-7 : Authentication Response - HSS looks for corresponding IMSI in the database and retrieves the shared key K. K is available only at HSS and SIM (Subscriber Identification Module). This makes their communication as a security overlaid communication between UE and MME. With key K, HSS generates AV and replies to MME request.
- Message-8 : NAS Authentication Request - AV contains Authentication Token (AUTN), Expected Response (XRES), Random Number (RAND), Ciphering Key (CK), Integrity Key (IK). NAS Authentication Request sent from MME contains AUTN and RAND. UE verifies

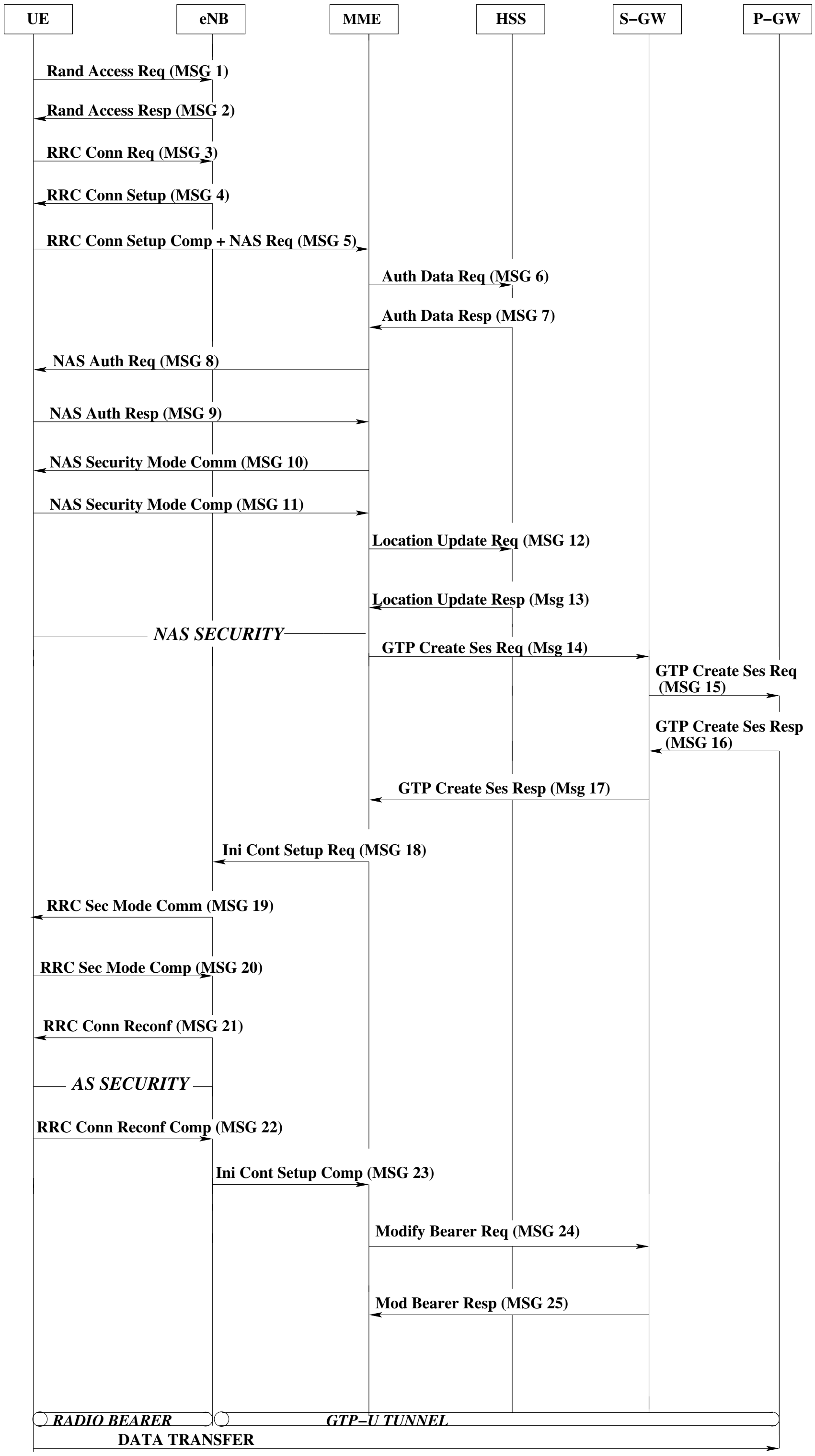

Figure 1.11: EPS bearer establishment procedure in LTE network

the network with AUTN. AUTN has Sequence Number (SQN) Ex-OR with Anonymity Key (AK), Authentication Management Field (AMF) and Message Authentication Code (MAC).

With sequence number UE verifies the network. UE also needs to prove its authenticity, for which it generates Response (RES) from RAND.

- Message-9 : NAS Authentication Response - RES is sent from UE. MME checks RES obtained from UE with XRES obtained from HSS. If they are equal, then UE is authenticated else authentication is void and connection is rejected.
- Message-10 : NAS Security Mode Command - If authentication is successful then ciphering algorithm and integrity algorithm are sent to UE in message 10. After receiving this message, UE calculates the set of keys for NAS encryption ($K_{NAS-enc}$, $K_{NAS-int}$ and K_{eNB}).
- Message-11 : NAS Security Mode Complete - After receiving this message, Location Update request is sent to HSS in Message 12 by MME.
- Message-12 : Location Update Request - It is sent to HSS by MME. HSS updates current PLMN-ID and Radio Access Technology (RAT) of UE.
- Message-13 : Location Update Response - HSS replies back APN Configuration profile, which has detailed information about Packet Data Network (PDN) parameters. At this point, NAS security is done.
- Message-14 : GTP-Create Session Request - MME sends request to S-GW, to create a GTP tunnel.
- Message-15 : S-GW forwards the create session request to P-GW with bearer parameters which has to be supported..
- Message-16 : P-GW replies back, Tunnel Endpoint Identifier (TEID) with which communication has to be made over S5 interface. Similarly a different TEID is used for communication in S1-U interface. P-GW creates dedicated bearers along with default bearer depending on the required QoS. Bearer ID and P-GW TEID are sent to S-GW using which S-GW to P-GW headers are to be defined.
- Message-17 : S-GW TEID and bearer context are forwarded to MME, for MME to S-GW communication.
- Message-18 : Initial context Setup Request - eNB all the details necessary for GTP-U and K_{eNB} for establishing RRC Security between eNB and UE. There is further generation of $K_{RRC-int}$, $K_{RRC-enc}$ and K_{up-enc} at eNB derived from K_{eNB} .
- Message-19 : RRC Security Mode - eNB sends the ciphering and integrity algorithm which has to be used to generate keys for communication between eNB and UE.
- Message-20 : UE generates same keys with the algorithm mentioned by eNB with K_{eNB} which is already been generated by UE in Authentication procedure. UE responds with RRC Security Mode Complete.
- Message-21 : RRC Connection ReConfiguration - It contains EPS bearer ID, DRB ID and Radio configurations.

- Message-22 : RRC Connection ReConfiguration Complete - UE sets RRC Reconfiguration parameters.
- Message-23 : Initial context Setup Complete - To set E-RAB ID, eNB GTP-U TEID, eNB transport address at MME.
- Message-24 : GTP-C-Modify Bearer Request - MME will trigger eNB related information such as EPS bearer IDs, eNB F-TEID to S-GW. S-GW replies a modified bearer response after storing list of eNB IDs.

1.8 Motivation

1.8.1 Small Data Transmission (SDT)

In most of M2M applications, M2M devices send infrequent small data packets. Since, number of M2M devices are increasing rapidly, signaling and scheduling overhead is more in comparison to amount of data sent by these devices. Some of such SDT applications are regular monitoring, IMS signaling, vehicle tracking, emergency alerting, etc.

1.8.2 SDT Issues in LTE

The M2M devices may lead to inefficient use of resources. In LTE, before data transfer, a device requires to finish EPS bearer establishment procedure which establishes a logical connection between the device and P-GW. After finishing this EPS bearer establishment procedure, the devices will be allocated RBs by the scheduler to send data. Because of SDT of large number of M2M devices, following issues will be raised in LTE systems:

1. Extreme overhead on bandwidth resource scheduler. Since, resource scheduler will have to schedule small amount of resources for large number of M2M devices, it will not only increase the scheduling algorithm complexity but also increase the latency of resource allocation for H2H devices.
2. Overhead on RAN due to so many resource allocation requests sent by such devices.
3. Signaling overhead imposed by M2M devices during the procedure of EPS bearer establishment. A device exchanges on an average 25 signaling messages from it is switch on to EPS bearer establishment. In case of H2H devices, this signaling messages exchange is bearable because they are less in number as well as they send mostly large amount of data but in case of M2M devices, condition is completely opposite.

Apart from above issues, the LTE systems suffer from problem of contiguous allocation of resource blocks in uplink in order to reduce peak to average (PAPR) power ratio. In case of downlink scheduling, the eNB can afford the high power but it will be hazardous for users if devices generating high power signals for uplink. PAPR will be controlled if transmission is done in single carrier rather than multiple carrier i.e., SC-FDMA (single carrier- frequency division multiple access) is used in place of OFDMA (orthogonal frequency division multiple access). Because of SC-FDMA based media access scheme, scheduler cannot allocate best set of RBs to users alike downlink scheduling and hence, scheduler allocates an available fixed chunk of contiguous RBs. Since, chunk of RBs to be allocated to users is of fixed size, this scheme of resource allocation for M2M SDTs is very uneconomical. This is because of the fact that, if the chunk size is big then it is a wastage of RBs for SDT but if it is small then it will incur too much overhead on scheduler for larger data transmissions. So, there is a need of variable size chunk allocation scheme for uplink. In this thesis, we are addressing above problems.

1.9 Thesis Outline

The Thesis is structured as follows :

- In Chapter 2, we review the literature survey on solving the issues of signaling congestion, efficient resource scheduling and SDT issues.
- In chapter 3, we address the issue of contiguity constraint in uplink resources allocation with respect to SDTs.
- In Chapter 4, we address the issue of signaling and scheduling overhead with respect to SDTs
- Conclusion and future work are discussed in Chapter 5.

Chapter 2

Related Work

There are lots of effort have been made to address the issue of massive access of M2M devices in LTE network communications. Researchers have been focused on following major issues:

- The issue of signaling congestion due to large number of M2M devices accessing the network at the same time.
- The issue of unnecessary signaling and scheduling to send only a single data packet of approximately 50 Byte by most of the M2M devices
- The issue of resource allocation to M2M requests without affecting or least affecting H2H requests.

In this chapter, we review existing solution to addressing the some of the above issues.

2.1 Approaches for Handling signaling Congestion in LTE

In case of RACH procedure, UE sends a preamble to eNB. There are 64 such preambles available in LTE in which, approximately 54 preambles are for contention-based RACH procedure and remaining are for contention-free RACH procedure. Here, we will discuss only about contention-based RACH procedure. Out of 54 contention-based preambles, if two devices choose same preamble for message 1 then collision occurs and devices back-off. After back-off, devices may choose different preambles and submit. In case of M2M communications, it is highly possible that large number of devices are ready to perform RACH procedure at the same time. Since preambles are limited, so, large number of collisions of preambles can take place which may result into denial of connection of the devices with the network or large delay in connection establishment. Because of this arrival pattern of M2M traffic, both Human to Human (H2H) and M2M devices will suffer. Since, present cellular networks are optimized for H2H communications, they should not be affected by the incorporation of M2M communications in the network. Researchers have proposed algorithms in such a way that H2H users should not be affected or minutely affected and overall success rate should also be enhanced.

In [14], 3GPP have discussed following schemes to solve the above issue:

1. *Long Backoff Based Scheme*: In this scheme, when network is overloaded, all M2M devices go for a longer backoff while H2H devices will be doing normal backoff. A device does backoff in following scenarios: (a) When device does not receive random access response (RAR) message before time-out expires (b) When device receives RAR but it is not intended for that particular device (c) When device does not receive contention resolution message (Message 4) before time-out expires. In case of normal backoff, a device waits for a random amount of time and again accesses the network. 3GPP has kept the backoff indicator value as 20 ms. It means that devices randomly choose a number between 0 to 20 and wait for that much amount of time before accessing the network again. In case of longer backoff, waiting time will be more than that of normal backoff. It can go to several seconds. This scheme works well in case of low congestion in the network.

2. *Access Class Barring Based Schemes*: If number of devices in the network is so large that network is unable to support it, then in this case network starts barring some devices from accessing the network. Two barring technique have been proposed. The first one is access class barring (ACB) and other is extended access barring (EAB). In ACB technique, devices are classified into different access classes. A class will contain both M2M and H2H devices. In case of congestion in the network, eNB starts barring one or more classes, depending on the level of the congestion in the network. But, in this technique, both H2H and M2M devices are being barred. In EAB technique, a device will be barred if it is configured for EAB. Typically, delay tolerant M2M devices will be configured for EAB so that in case of congestion in the network, these devices will stop their access. In this technique, H2H devices may not be barred from accessing the network.

3. *RACH Resource Separation Based Schemes*: In these schemes, RACH resources (preambles) are distributed separately between H2H users and M2M users so that H2H users will not be affected by increasing number of M2M users. In [15], authors have proposed two methods to separate the RACH resources. In the first method, RACH resources are distributed into two groups. H2H and M2M devices are allowed to choose the RACH resources only from that particular group. In the second method, again RACH resources are distributed as first method but now H2H devices are allowed to choose RACH resources from both groups but M2M devices will choose as in the case of the first method. In [15], authors also have distributed M2M devices into various classes depending on the type of M2M applications. These classes are allowed to access in some particular PRACH slot but H2H devices are allowed to access in each PRACH slot. For example, if M2M devices are distributed into five classes then in a particular PRACH slot, may be only 2 classes are allowed to access. These schemes increase the success rate of H2H devices but success rate of M2M devices may badly affected.

4. *Dynamic Allocation of RACH Resources*: In a frame, there can be two to six PRACH slots. In this scheme, depending on the level of congestion in the network, eNB enables number of PRACH slots in a frame. As per 3GPP specifications, typically two PRACH slots per frame are enabled.

2.2 Approaches for Efficient Resource Scheduling of M2M and H2H Traffic

In [16], four classes have been defined in which all applications are divided. An utility function is associated with each class where user utility is a function of achievable data rate. The main aim of this approach is to maximize the aggregate throughput by maximizing the aggregate utility. But, in this approach priority and fairness of a device is ignored. As a result of this, if a device has delay intolerant data but scheduling this device does not increase aggregate throughput then this device may not be scheduled. Similarly, device having weak signal strength may also be not scheduled. Other drawback of this approach is that delay is the only metric for classification of M2M applications while other metrics such as reliability and priority should also be considered.

In [17], two scheduling algorithms are proposed for allocating resources between H2H and M2M. Both the algorithms give first priority to H2H. After the allocation of RBs to the H2H devices, the remaining RBs are allocated to the M2M devices. The first algorithm gives higher priority to the SINR value of a RB with respect to M2M device, in comparison to delay tolerance level during the allocation of RBs to M2M devices. The second algorithm gives higher priority to delay tolerance level than the SINR value. The main drawback of these algorithms is that they do not allocate RBs to M2M devices based on the applications they belong to. It does not differentiate the delay tolerant and delay intolerant M2M devices and there fore efficient allocation of RBs in not done.

In [2], authors proposed a scheduling algorithm which considers delay tolerance and minimum guaranteed bit rate of applications and preference of H2H flows over M2M flows to schedule RBs. Requests are classified based on the delay tolerance time and given preference in resource allocation having minimum delay tolerance. This solution solves the issue of facilitating M2M requests with least affecting H2H requests but it does not improve the performance of M2M users.

2.3 Solutions for SDT in LTE

In M2M communications, most of the applications generate infrequent small data. Since, large number of devices take part in M2M communications, it is very uneconomical to follow legacy methods of signaling and allocating resources to devices. In this section, we have discussed some research papers which have tried to solve this issue.

In [19], authors have proposed some solutions to reduce the signaling overhead due to RRC connection. According to authors, RRC connection is relevant when a device has to send data in bulk amount for longer duration. But in case of SDT, throughput to overhead ratio is very low. In the first solution, in place of first RRC message, MAC PDU has been sent. By doing this, authors have preferred to by-pass whole RRC connection establishment procedure. In this way, RLC/RRC/PDCP entities are not involved in communication and hence, complexity of the system is reduced. In the second solution, in place of sending data in shared channel, data is actually being sent in PRACH itself through some special preambles and hence, further reduced the overhead in MAC layer. The third solution is somewhat different from first and second. In this solution, authors have suggested a Gateway based solution to handle small and infrequent data traffic. In place of sending data directly to eNB, M2M devices send data packets to a gateway. The gateway forwards the data packets to eNB immediately if it is urgent otherwise it stores the data packet in its buffer and sends to eNB by aggregating them. The motivation behind such aggregation of small data is to use the bandwidth efficiently and reduce the overhead on RAN.

In [20], authors proposed a solution where in each subframe or in a periodicity of some subframes, some RBs (at least 4) will be kept reserved to send small data packets. Since, the access is contention based, so it is possible that some devices will try to send their small data packet in the same RB. As a result, collision will occur and devices will back-off (authors have assumed the same backoff policy as PRACH failure). Authors have compared the proposed solution with legacy data access mechanisms in LTE over PUCCH and PRACH. In the proposed approach, resources are explicitly reserved to send small data packets which will affect the performance of H2H users. In the legacy procedure of data transmission, an EPS bearer is establish between UE and P-GW but in this approach, there is no such bearer establishment process has been discussed to send the small data from UE to P-GW. Some mechanism should have exists to send small data beyond eNB.

In Release 12, 3GPP has emphasized to resolve issues raised because of SDT [21] by M2M devices. 3GPP has proposed a different EPS bearer establishment procedure for M2M devices which involve SDT. The idea is to reduce the signaling and scheduling overhead. In the proposed EPS bearer establishment procedure, data packet is piggybacked with RRC connection setup complete message (message 5). Here, in place of creating an EPS bearer and sending data through it, data is sent to P-GW through MME. In our proposed LW-M2M method, SDT is done through message 3 so that extra RBs can optimally be used. Authentication process in between M2M devices and MME is more secure in our method because in the method proposed in [21], *sequence number* and $eKSI$ are sent from UE to MME as unencrypted which may further lead to exposure of the secret key K, if some intruder does brute-force attack. Apart from this, we have done grouping of preambles to ensure minimal effect on the performance of H2H users due to excessive number of M2M devices in the network.

In [22], authors define a cluster of M2M devices based on the parameters: packet arrival rate and maximum tolerable jitter. An M2M device belongs to a cluster if both the device and cluster have identical values of these parameters. A cluster with larger packet arrival rate has high priority. Depending on the traffic rate and priority of cluster, a fixed access grant time interval will be allocated to clusters. The main drawback here is that it considers traffic arrival rate as constant while in reality, M2M traffic can be random in nature. In [23], authors have attempted to remove the drawbacks of [22] but they did not consider the cases when M2M applications should be given more preferences over H2H applications.

Chapter 3

Contiguity Constraint Algorithm For Uplink Resource Allocation

In LTE systems, bandwidth resources are allocated in terms of resource blocks (as discussed in chapter 1). Scheduler located on MAC layer of eNB, schedules these RBs for users so that they can send or receive their data. There are two types of scheduling have been discussed in any cellular network viz. uplink scheduling and downlink scheduling. In uplink scheduling, the scheduler schedules the RBs for users taking part in uplink data transmission while in downlink scheduling, scheduler schedules RBs for downlink data transmissions. The media access technology used in downlink is OFDMA (Orthogonal Frequency Division Multiple Access) and in uplink, it is SC-FDMA (Single-Carrier Frequency Division Multiple Access). In SC-FDMA, resource allocation is done on single carrier i.e.,RBs are assigned contiguously in frequency domain while in case of OFDMA, resource allocation is done on multiple carrier separated orthogonally. Figure 3.1 shows SC-FDMA and OFDMA based resource allocation. In the figure we can see that in OFDMA, resources can be assigned to different users (different colors) in frequency domain as well as time domain but in SC-FDMA, resources can be allocated to different users only in time domain.

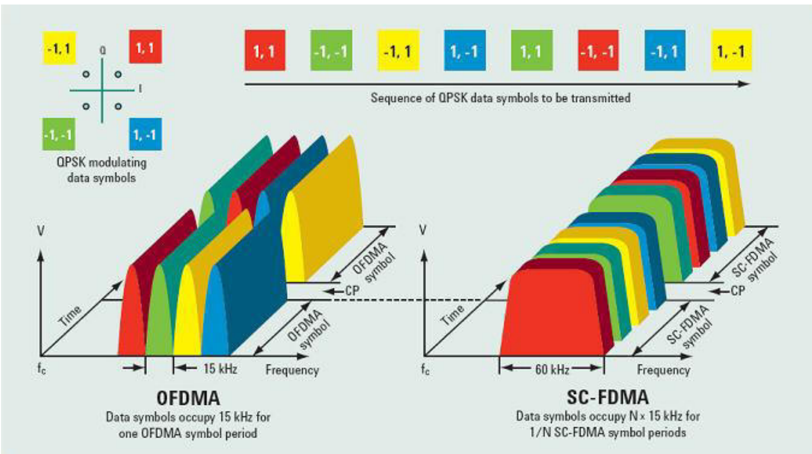

Figure 3.1: OFDMA and SC-FDMA based resource allocation [13]

Peak-to-average power ratio (PAPR) is important factor for the uplink mobile devices. This high PAPR is one of the challenges that face OFDM, because it reduces the efficiency and hence increases the cost of the RF power amplifier, which is one of the most expensive components in the radio. Because of high PAPR in OFDM, LTE use Single-carrier Frequency Division Multiple Access (SC-FDMA) for uplink. The major constraint with LTE uplink resource scheduling is that the number of RBs assigned to a flow must be contiguous because of SC-FDMA [8] scheme for uplink channel access. Maximization of throughput with the constraint of contiguous RB allocation is a NP-Hard problem. From following example, we will try to understand the drawback of contiguous allocation of RBs over non-contiguous allocation of RBs. Table 3.1 shows CQI (channel quality information) values of each devices with respect to each RB. Here, we have taken three devices and 6 RBs. According to OFDMA based assignment, RB1 and RB4 will be allocated to device1, RB2 and RB6 will be allocated to device2, and RB3 and RB5 will be allocated to device3. In case of SC-FDMA based assignment, same scheme cannot be adopted. In this method, RB1 will be allocated to device1. Since, RB3 and RB5 are best for device3 but in order to maintain contiguity, RB4 will also have to be allocated to device3. Therefore, RB3, RB4 and RB5 are allocated to device3. RB6 will be allocated to device2. Since, RB2 is also best for device2 but due to contiguity constraint, it cannot be allocated. So, now RB2 will be allocated to either device1 or device3. But, by assigning RB2 to device3, greater spectral efficiency can be achieved. So, RB2 will be allocated to device3. From the above example, we can understand that how SC-FDMA based media access technique reduces the spectral efficiency in comparison to OFDMA based technique.

Table 3.1: CQI value of different devices with respect to different RBs

Devices/RBS	**RB1**	**RB2**	**RB3**	**RB4**	**RB5**	**RB6**
Device 1	3.5	1.5	1	2	1	2
Device 2	1	2.5	1.8	1	0.8	3
Device 3	2	2	3	1.2	1.5	1

As discussed above, for uplink transmission, resource blocks (RBs) are assigned contiguously to UEs. Presently, methods which ensure contiguous assignment of RBs, allocate a chunk of RBs to an UE at a time. In case of H2H communication, devices send data in bulk, so allocating a chunk of several RBs to a device is correct choice. But, in case of M2M communications, mostly devices follow infrequent small data transmission (SDT) and a request for bandwidth resources by an M2M device can be served by allocating merely two RBs. So, assigning a chunk of RBs is very uneconomical. In order to allocate resources efficiently, there is a need of variable size chunk allocation methods so that depending upon the resource requirement of a device, size of a chunk to be allocated can be varied. In this chapter, we have discussed such a variable chunk size resource allocation method.

Paper [24] proposes some approaches for contiguous allocation of RBs so that RBs can be allocated efficiently. We have discussed following approaches:

- Largest-Metric-Value-RB-First: In this approach, before assigning a RB to an user, neighbor RBs are being checked. If the neighboring RBs are assigned to the same user then the RB will be allocated to the user otherwise last assigned RB to the user will be identified. If the RBs between last assigned RB and current RB are free then all the intervening RBs will be assigned to same user and hence, contiguity will be ensured. The drawback of this approach is that it is possible to be allocated all RBs to same user. It is also possible that some users will be allocated more RBs than required and some users will be getting less number of RBs than required. In order to solve this problem, authors proposes the second approach.

- Riding Peaks: In this approach, authors divide the RBs into chunks and chunks are allocated to users. Before assigning a chunk of RBs to an user, neighbor chunks will be checked. If the neighboring chunks are assigned to the same user then the present chunk will be allocated to the user otherwise second best user will be searched and the chunk will be allocated to it and the process continues. But, in this approach, chunk size is always fixed. So, it is hard to find a optimum size of chunk. Apart from this, another problem is that how many chunks should be assigned to an user. We have attempted to solve these issues in the proposed contiguity constraint algorithm (CCA).

3.1 The Algorithm

Algorithm 1, the Contiguity Constraint Algorithm (CCA), proposes a variable chunk size based uplink resource allocation heuristic scheme where a flow is assigned best available chunk of contiguous RBs to upload its data. Size of a chunk is the number of contiguous RBs required to send the desired amount of data. Size of a chunk, to meet demand of a flow, will be different for different sets of RBs because of change in CQI (channel quality information) with respect to RBs and user location. In CCA, R denotes a set of unallocated, contiguous RBs and $NEED$ denotes a two dimensional matrix where $(NEED)_{ij}$ is the chunk size needed to meet the demand of flow i, if first RB of the chunk is j^{th} RB of the set R. So, row i contains the value of required chunk sizes to send data of flow i with respect to each RB (*i.e.,* as a first RB of the chunk) of set R. Now the algorithm will choose a chunk of minimum size with which the flow i can send its data. If the chosen chunk is already assigned to some request then the algorithm will choose next minimum size chunk and will check its availability. If the chosen chunk is free then it will be assigned to flow i and RBs of the chunk will be marked as *allocated* in the set R. After allocating RBs to flow i, the algorithm will move to schedule $(i+1)^{th}$ flow.

Algorithm 1 Contiguity Constraint Algorithm

Require: $NEED$ matrix
Ensure: Allocation of RBs to requests, Set of unserved H2H requests with updated RTTS

R is the set of not yet assigned RBs { Initially it contains the whole set of RBs in the network}
$NEED$ is a two dimensional matrix where $(NEED)_{ij}$ is number of RBs required by flow i to send its data if RBs are allocated starting from j^{th} RB of set R
while All RBs of R not allocated **do**
  Find minimum value of $(NEED)_{ij}$ for flow i { Minimum value in the i^{th} row}
  Assign all RBs between j^{th} and $(j + (NEED)_{ij} - 1)^{th}$ RBs of set R to flow i
  Mark all RBs between j^{th} and $(j + (NEED)_{ij} - 1)^{th}$ RBs of set R as *allocated*
  Assign ∞ to all elements of columns of $NEED$ matrix from j^{th} to $(j + (NEED)_{ij} - 1)^{th}$ column
  $i \leftarrow i + 1$ {Schedule next flow in the order}
end while

Here, we have taken an example to explain the assignment of RBs in contiguous fashion for both Round-Robin (RR) and Proportional Fair (PF) contiguity method and then we discussed about the CCA scheme to show how it is good as compare to both. Let us consider, there are total five users

U1, U2, U3, U4, U5 and among these two users are SDT Users (U1,U4) who send very small amount of data and the remaining three users have large amount of data or infinite buffer. We have ten RBs to be allocated.

In RR, RBs are equally distributed into all active users. Active users are those who wants to send the data in present TTI. Here we assume, all five users are active users. So now each user will get 2 RBs. In RR contiguity scheme, RBs can be started to assign from either of end that mean either they can be assigned from RB1 or RB10. RR scheme assumes that each users will get the same CQI value on each RBs. Figure 3.2 shows the assigned RBs to active users in RR Scheme.

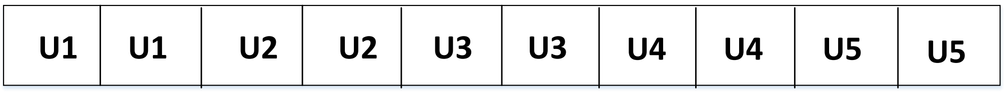

Figure 3.2: Contiguous allocation of RBs in RR scheme

In PF, PF metric is calculated. Based on the PF metric value, RBs are assigned to users. Here, RBs are equally divided into chunks and chunks are assigned to users. Number of chunks is equal to number of active users or number of RBs divided number of active users. If chunk size is less than one then it assumes chunk size as one. Chunks will be assigned to best user based on their PF metric value. Figure 3.3 shows the assigned chunk to users. If we compare RR and PF, we can see in PF, chunks are assigned to best user whereas RBs are assigned in sequence in RR, consequently, overall throughput of PF will increase as compare to RR.

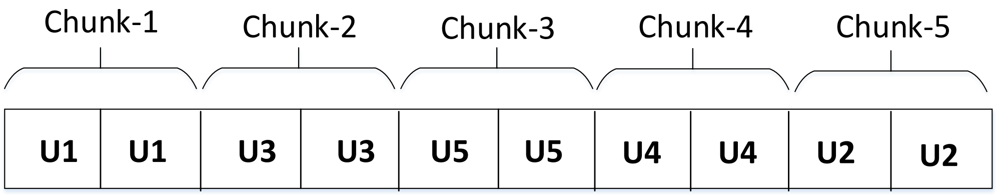

Figure 3.3: Contiguous allocation of RBs in PF scheme

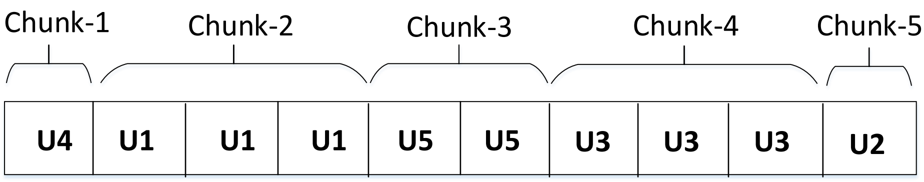

Figure 3.4: Contiguous allocation of RBs in CCA scheme

In CCA, chunk size will depend on the data size which user want to send. In CCA, chunk size is variable and not like PF. First of all, it calculates the $NEED$ matrix explained above. Based on the $NEED$ matrix, it finds the best RB for an user. If 2 RBs are best for the same user than it will check whether they are contiguous or not. If they are contiguous then it will assign the RBs to same user otherwise it will search for the second best user and process continues. At the end, RBs are assigned to users according to their need. As in PF, minimum 1 chunk needs to assign a user even user can send its data in one RB. Figure 3.4 shows, the user 1 and 3 get only 1 RB. So, overall RBs are saved which CCA can allocate to other users. So in comparison to PF, CCA will achieve more throughput.

3.2 Simulation Results and Analysis

In this section, performance of proposed CCA algorithm is evaluated and compared with Round-Robin and Proportional Fair algorithms, using system level simulations in NS-3.16 network simulator [25]. Table 3.2 shows the simulation parameters considered in the simulation. The parameters not mentioned in the table, are assumed as per 3GPP specifications [26]. Devices are located randomly within 1 KM radius using Random Disc Position Allocator Model and they are assumed static.

Table 3.2: Simulation Setup

Simulator	NS-3.16
System Bandwidth	20 MHz
Cellular Layout	Single-Cell with Omni-directional Antenna
Cell Radius	1KM
No. of RBs in a TTI	100
TTI Duration	1 ms
UE-eNodeB Min. Distance	10 m
Number of Flows Per Device	1
Simulation Time	1 sec
Number of Active Users	10, 20, 30, 40, 50, 60

Table 3.3: Simulation Parameters for Flows

Application	**MGBR**	**% of Flows**
IMS Signaling	-	10%
Voice	10kbps	50%
Video	100kbps	20%
Web Browsing	-	20%

Table 3.3 shows simulation parameters for flows running into devices. Here, we have taken three different types of traffic characteristics. IMS signaling is a small data delay intolerant traffic in nature. A device sending such traffic, have a small data packet to send at a time. Voice and video traffic require a minimum data rate to be supported. We have termed this as minimum guranteed bit rate (MGBR). Web browsing is delay tolerant big data traffic in nature. In other word, a device sending web browsing traffic will have several packets of maximum packet size.

In order to evaluate the performance of the proposed algorithm, we have taken aggregate throughput and fairness as metrics. For fairness, we have taken Jain's fairness index [27]. Figure 3.5 shows the fairness of devices for different schedulers. Fairness shows that how fairly resources are distributed to different users. Value of fairness lies between 0 and 1. 0 means distribution of resource blocks is totally unfair and 1 means RBs are distributed fairly i.e., each device got their requested number of RBs. From the plot we can see that fairness is best in proposed CCA algorithm. This is because of the fact that due to variable chunk sizes, maximum number of flows are being served with same number of RBs while in case of fixed chunk size, RBs are getting finished by serving lesser number of flows. Figure 3.6 shows the aggregate throughput of devices for different schedulers.

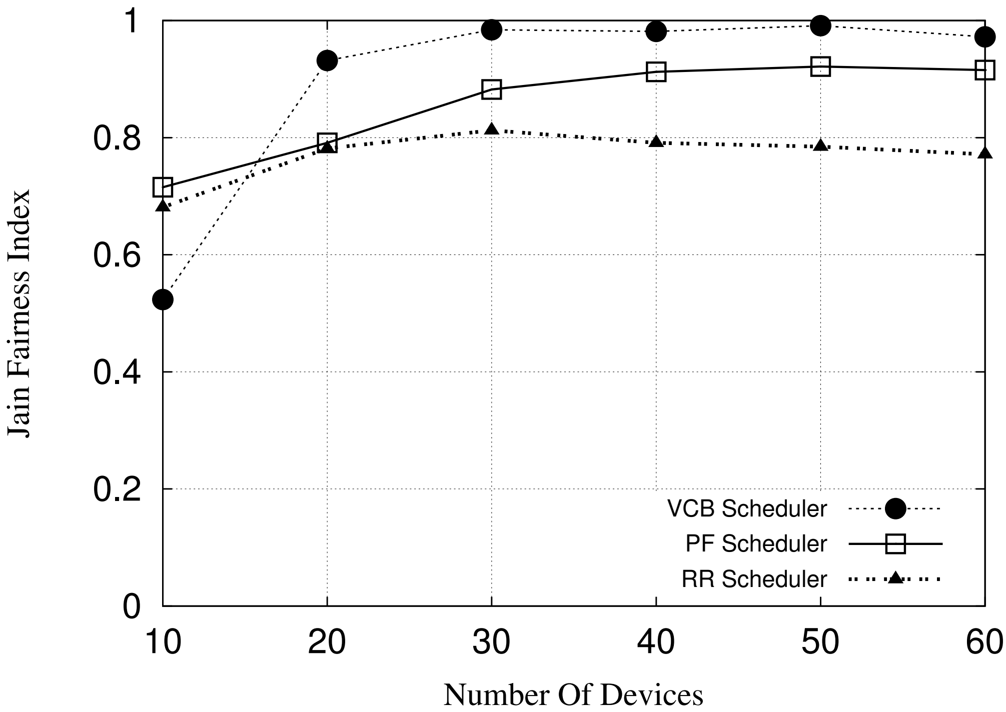

Figure 3.5: Delay comparison for LTE versus LM communication procedure

Performance of the proposed CCA algorithm is best in comparison to other schedulers because due to variable chunk sizes, number of RBs are being optimally utilized, and more number of devices are being served and hence, more data is being transmitted within particular time.

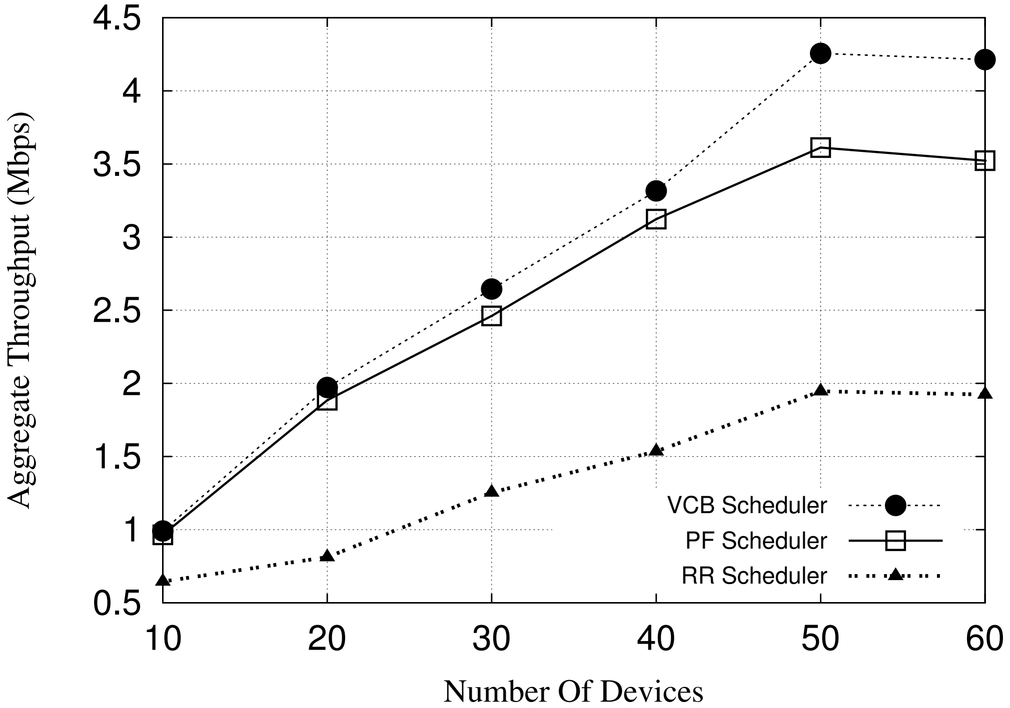

Figure 3.6: Delay comparison for LTE versus LM communication procedure

Chapter 4

Lightweight signaling for SDTs

LTE can support M2M communication, this is possible and good yielding only if H2H does not suffer quality degradation or degraded to a tolerable extent. Since M2M communications involve infrequent SDT of M2M devices, by incorporating it in LTE systems will raise following issues:(i) Extreme overhead on bandwidth resource scheduler. Since, resource scheduler will have to schedule small amount of resources for large number of M2M devices, it will not only increase the scheduling algorithm complexity but also increase the latency of resource allocation for H2H devices. (ii) signaling overhead imposed by M2M devices during the procedure of EPS bearer establishment.
In this chapter, we have attempted to solve above issues by piggybacking M2M data with RRC connection request message (message 3). we also proposed the preamble distribution scheme. Apart from this, we propose a lightweight EPS bearer establishment procedure (LW-M2M method) for M2M devices sending infrequent SDT. In this LW-M2M method, we have replaced the authentication module of legacy procedure (Legacy method), which authenticates UE and MME, by confidentiality of small M2M data. Because of this, we are able to ignore NAS security keys exchange and RRC security keys exchange and hence, able to ignore signaling messages exchange involved into these security keys exchange.

4.1 Classification of Preambles

Preamble distribution scheme proposed in [15], divides preambles into two groups so that collisions of preambles chosen by H2H devices can be reduced. In this work, we are using same scheme with different motivation. Since, information of RBs allocated for sending message 3 is informed to UE by eNB through message 2, the eNB must be able to know about a device (whether it will send a small data packet or not) after receiving message 1 itself. If device has to send only a small data packet then eNB will allocate some extra RBs, so that the device can send its data in message 3 itself, otherwise eNB will not allocate extra RBs. In order to identify small data packet sending devices by eNB after receiving message 1, we distribute all contention-based preambles into two groups. Preambles in first group are chosen only by those devices which send only one small size (40-50 Bytes) data packet. When eNB receives such preamble then it automatically comes to know that UE wants to send a small data packet. Preambles of the second group are chosen by rest of the devices. The other benefit of this distribution of preambles into two groups is, it will reduce the number of preamble collisions for H2H devices because M2M devices (small data packet sending devices) will be confined to limited number of preambles to be chosen and they can not choose any preamble from the group allocated to H2H devices. Figure 4.1 shows that how number of H2H collisions are reduced by distributing the preambles. Results are taken on Network Simulator NS-3.19, where 40 number of H2H devices are constant with M2M devices are keep on increasing. The number of preamble collisions for H2H devices increasing as number of M2M devices are increasing in legacy method. With preamble distribution scheme, collisions of preambles chosen by H2H devices are reduced or it is constant as while increasing M2M devices not affecting on H2H devices.

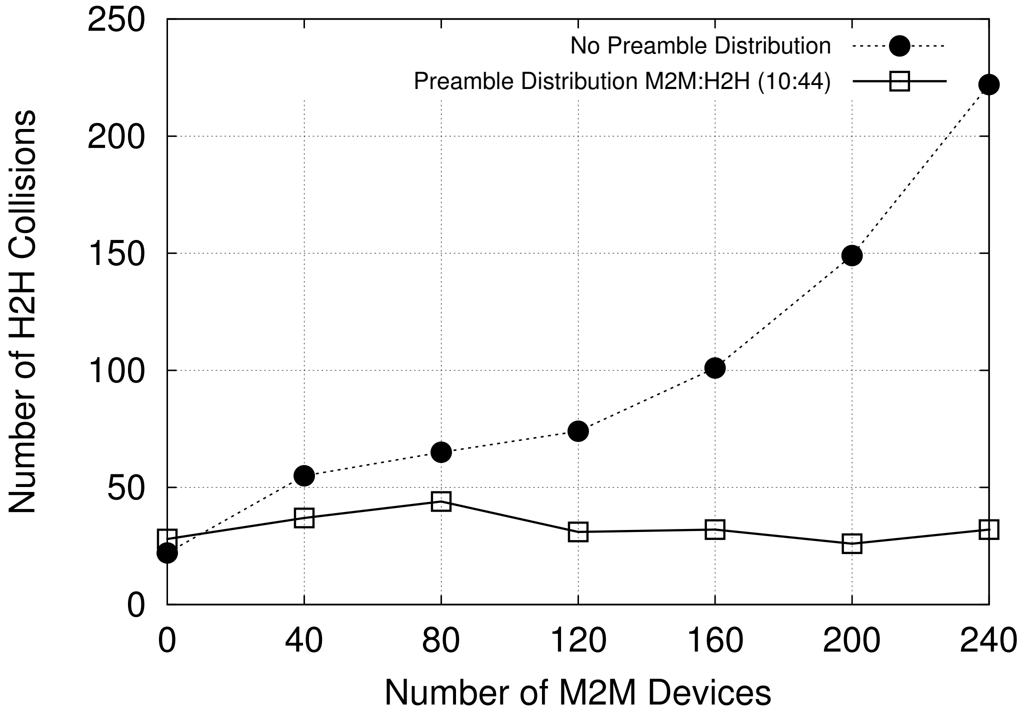

Figure 4.1: Number of H2H Collisions

4.2 LightWeight (LW) M2M Method

In legacy method, EPS bearer establishment process has many issues when large number of M2M device exist in the network. We proposed a LW-M2M Method which is addressing the discussed problems. Figure 4.2 shows the messages exchanges in LW-M2M Method for EPS bearer establishment which are explained as follow:

When eNB receives random access preamble, it sends a random access response message (message 2) to UE. This message contains :

1. Temporary-Cell Radio Network Temporary Identifier (T-CRNTI): The eNB allocates this identity to UE for further communication between network and the UE.

2. Timing Advance : In order to adjust the time clock between eNB and UE, the eNB calculates

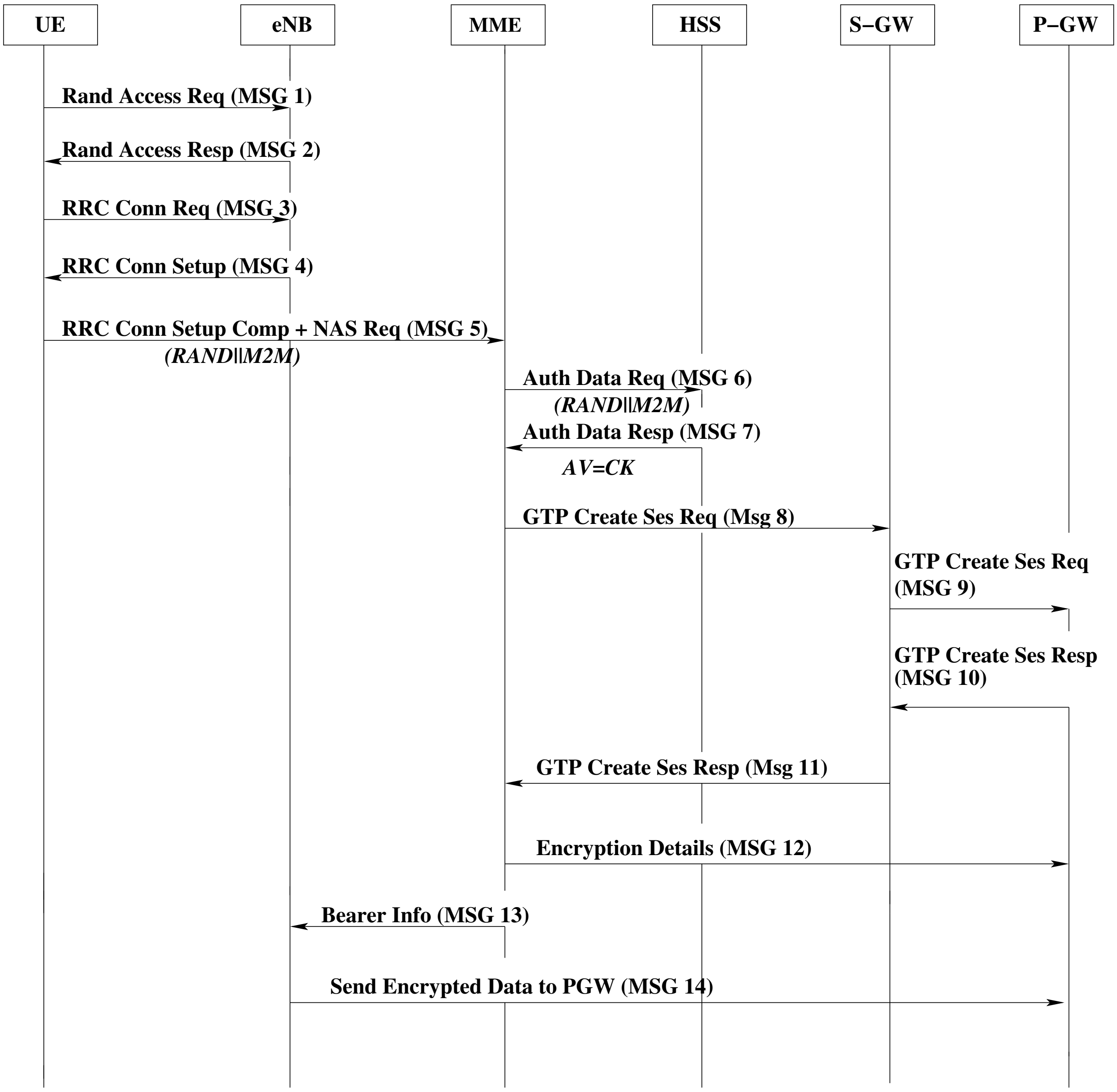

Figure 4.2: Proposed EPS bearer establishment procedure for M2M devices having a small data packet

the time advance and sends it through message 2 to UE.

3. Number of Resource Blocks (RBs) allocated for sending message 3 from UE to eNB.

4. Modulation and coding scheme to be used by UE to send message 3.

In Message-3, along with its content UE piggybacks SDT message also. Rest of the UEs send message 3 as per the conventional method. Since message 3 is sent on PUSCH (Physical up link shared channel), it is also possible to piggyback the data packet with it. In order to send small data packet along with message 3, eNB allocates one or two extra RBs. Here we have kept a threshold on size of the small data packet.

we changed the structure of message-3, so the eNB will get to know this UE has send data in message-3.

4.2.1 Modified MSG-3 Structure

Figure 4.3 shows the modified message 3 packet structure in which one bit M2M flag is introduced to indicate eNB that message 3 contains M2M data also. If M2M flag bit is set to 0 then message 3 does not contain any M2M small data packet. The main motive of sending data packet in message 3 is to avoid scheduling overhead on resource scheduler and reducing signaling overhead on RAN. Large number of M2M devices send SR to the scheduler to get radio resources so that they can send their data. Since, size of the packet is small and number of such devices is huge, it is very uneconomical to follow the conventional process of sending SR and getting scheduled by the scheduler. Because, in this process we not only waste radio resources to send SR and impose extra signaling overhead on RAN but also we make the job of scheduler more complex because it will have to handle both M2M and H2H requests which in turn affect the throughput of H2H requests.

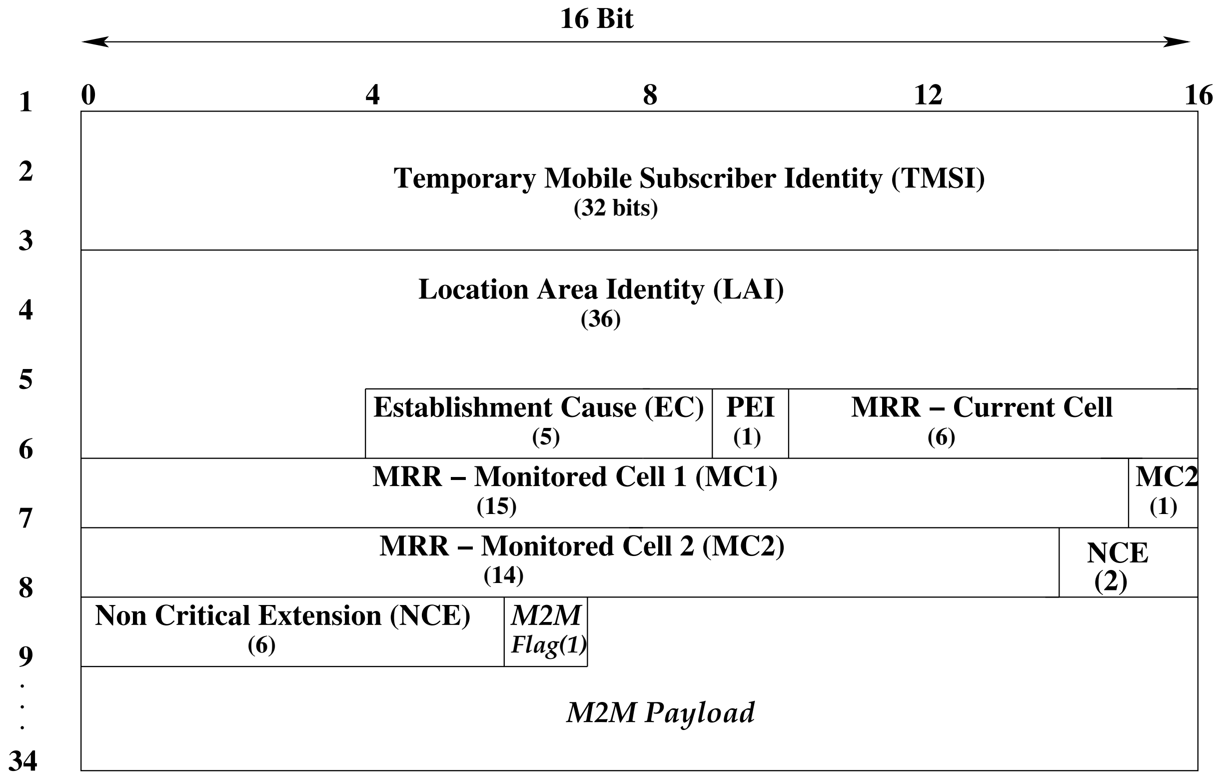

Figure 4.3: Modified Message 3 Frame Format

As discussed in section 1.7, both UE and MME are authenticated and data is encrypted before sending to eNB but the idea of MME and UE authenticating each other makes more signaling. Our approach is to reduce this signaling by removing the authentication module and replacing it with confidentiality. If data is encrypted with a key which is known only to end users (UE and MME), whoever intercepts the data will perceive it as junk bits if they are not the actual authorized ones to receive it. Similarly, UE sends the data encrypted by a key C_K which is generated by RAND and

SIM Key K at UE. RAND is a random number which is generated by the UE. The encrypted data can be deciphered only with the authority having C_K . Encrypted data is sent to eNB in message 3. In RRC connection procedure in Figure 1.11, messages 6, 7, 8 and 9 are used for authentication of UE and MME. Authentication of UE and MME is essential because after the authentication process, they exchange NAS security keys and RRC security keys. Messages 10 and 11 denotes the exchange of NAS security keys while messages 12, 13, 14 and 15 denote the exchange of RRC security keys. NAS security keys are used to encrypt NAS signaling messages and RRC security keys are used to encrypt data packets by the UE. In our proposed RRC connection procedure (Figure 4.2) for devices having a small data packet to send, no NAS signaling message has been used after message 5, so, NAS security keys exchange is not needed. So, messages 10 and 11 can be ignored. Since these devices have only single data packet and this data packet has already been sent in message 3, so, RRC security keys exchange is also not needed and messages 12, 13, 14 and 15 can be ignored. Since, NAS security keys exchange and RRC security keys exchange are not required and if we ensure the confidentiality of the data packet sent in message 3 then we can ignore the authentication process of UE and MME, i.e, messages 6, 7, 8 and 9 can be ignored.

Figure 4.2 shows the proposed RRC connection procedure for the devices sending a small size data packet. As we discussed earlier, the data packet will be encrypted by the key C_K and piggybacked with message 3. Apart from original content of message 5, it contains the parameters RAND and M2M. Here, RAND is the random number generated by UE which is further used to generate C_K . M2M is an one bit information used to indicate the MME that message 5 is sent from an M2M device which have a small data packet to transmit. Along with message 6, MME forwards RAND and M2M to HSS. Since, HSS is having the SIM key, it uses this key and RAND to generate C_K . HSS sends C_K to MME in message 7. After receiving message 7, MME sends the PDN connectivity request to S-GW. Since, the data packet is already been sent to eNB through message 3, so there is no need to create DRB (data radio bearer) between UE and eNB. Only S5 bearer (between S-GW and P-GW) and S1-U bearer (between eNB and S-GW) are created. MME sends C_K to P-GW through message 11. P-GW uses C_K to decrypt the data packet.

4.2.2 Experimental Setup, Results and Performance Analysis

In this section, performance of proposed LW method is evaluated and compared with the legacy LTE/LTE-A connection establishment procedure, using system level simulations in NS-3.19 network simulator [25]. Table 4.1 shows the simulation parameters considered in the simulation. The parameters not mentioned in the table, are assumed as per 3GPP specifications [26]. Devices are located randomly within 1 KM radius using Random Disc Position Allocator Model and they are assumed static. Number of flows per device is taken as 1. We have assumed that M2M devices only send M2M traffic, however proposed solution works even for scenarios where devices carry both M2M and H2H traffic flows.

As discussed earlier, LTE EPS bearer establishment procedure consists of RACH procedure, RRC connection procedure, authentication procedure, and RRC reconfiguration procedure. In NS-3.19, RACH procedure is implemented without back- off mechanism. We implemented the back-off mechanism as per 3GPP specifications. In RACH procedure, a device does back-off in following cases:

Table 4.1: Simulation Setup

Simulator	NS-3.19
System Bandwidth	20 MHz
Cellular Layout	Single-Cell with Omni-directional Antenna
Cell Radius	1KM
No. of RBs in a TTI	100
TTI Duration	1 ms
UE-eNodeB Min. Distance	10 m
Back-off Indicator	20 ms
Number of Flows Per Device	1
Size of M2M Data Packet	45 Byte
Number of Seeds	4
Scheduling Algorithm	Round- Robin
Simulation Time	20 sec

1. When device does not receive random access response (RAR) message before timeout expires.
2. When device receives RAR but it is not intended for that particular device.
3. When device does not receive contention resolution message (Message 4) before timeout expires.

Back-off indicator time is taken as 20 ms as per 3GPP specifications. Out of remaining three procedures, only authentication procedure is not implemented in NS-3.19. Due to this, results like end-to-end delay of M2M devices reported for Legacy Method in NS-3 look better than the real scenario as here in NS-3 delay in exchange of NAS messages for authentication procedure is not counted but in case of proposed LW-M2M method, there is no such authentication module for M2M devices. In other word we can say that delay calculated by the simulator for M2M devices in Legacy method is lower bound of actual delay while in case of Lw-M2M method, it is accurate.

In order to show the comparative performance of proposed LW-M2M method over Legacy method, apart from delay, we have considered throughput as metrics. We have calculated delay by subtracting the time when a device attempts to connect to network (when a device has data to send, it will first connect to the network. The EPS bearer establishment procedure starts with triggering of RACH procedure) and the time when its all data get delivered to the destination. For evaluating the performance of H2H devices, we have kept number of H2H devices constant and taken results with increasing number of M2M devices. We have kept number of H2H devices as 40 and taken results when number of M2M devices are 0, 40, 80, 120, 160, 200 and 240 respectively. All M2M devices are assumed as delay tolerant and sending a small UDP data packet of size 50 Byte in each 2 sec interval. Each time M2M devices are suppose to establish RRC connection before sending a data packet. All H2H devices send TCP traffic using Bulk-Send application in NS-3.19, regularly throughout the simulation. Because of unavailability of other scheduling algorithm for uplink, we used Round-Robin as scheduling algorithm for allocating resources to requests.

The LW-M2M method proposes a Light Weight EPS bearer establishment procedure with the network for M2M devices sending single small data packet. In comparison to Legacy method, this method reduces number of signaling messages exchanged between an M2M device and the network which in turn reduces the time required to establish the connec- tion. Figure 4.4 shows the plot of

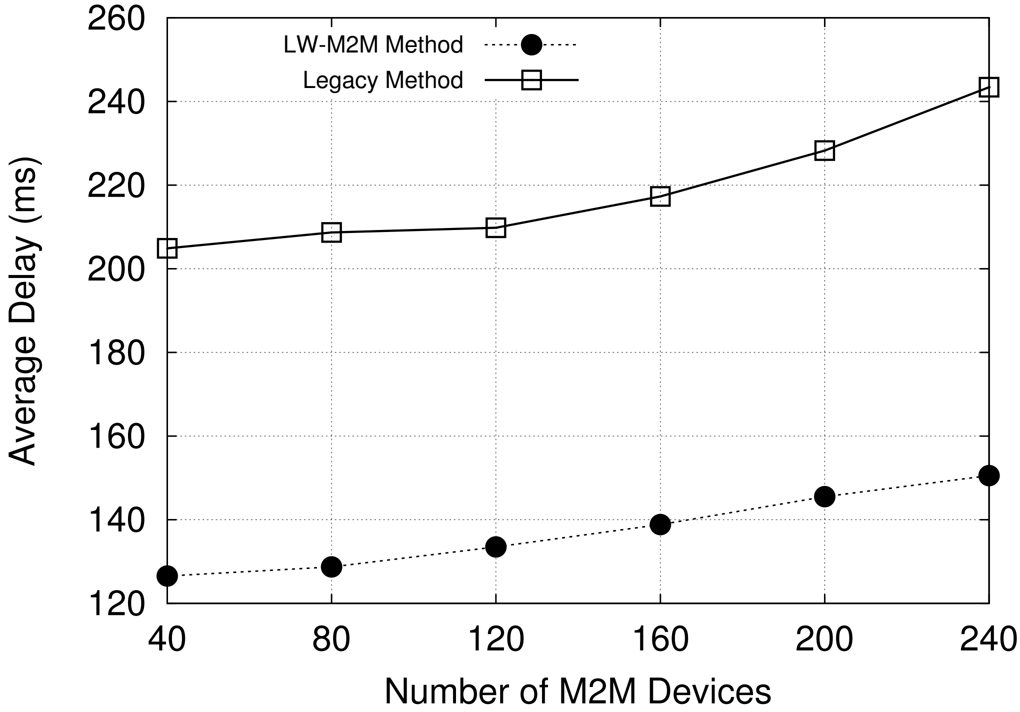

Figure 4.4: Delay comparison for LTE versus LM communication procedure

average end-to-end delay experienced by M2M devices for connection establishment in both methods.

As number of M2M devices increase, average delay of M2M devices in both methods increase. But the average delay experienced by M2M devices in Legacy method is more than that of LW-M2M method because in Legacy method, an M2M device experiences extra delay in terms of scheduling delay and connection establishment delay. In worst case (maximum number of M2M devices) also, average delay in LW-M2M method is reduced by 37.5% in comparison to Legacy method.

In LW-M2M method M2M devices send their data piggybacked with message 3, therefore scheduler has no role in allocating resources to them. Because of this, scheduler can allocate more resources to H2H devices which in turn increases the throughput of H2H devices. Here, we have considered that message 3 has sufficient resources to carry the data packet. Figure 4.5 shows the plot of aggregate throughput of H2H devices in both methods. In case of Legacy method, as number of M2M devices increase, throughput of H2H devices decrease drastically in comparison to LW-M2M method. This is because of the fact that scheduler has to allocate resources to M2M devices also while in case of LW-M2M method, scheduler has to allocate resources to only H2H devices. In worst case, aggregate throughput in LW-M2M method is increased by 18% in comparison to Legacy method.

In order to identify M2M devices by eNB just after receiving message 1, we have divided the set of preambles into two parts. One part is reserved for H2H devices and another is for M2M devices. Figure 4.6 shows the plot of aggregate throughput of H2H devices in both methods for different sizes of set of preambles for H2H and M2M devices.

Throughput of H2H devices without division of preamble set is also compared in the same plot. Here, we have considered two scenarios. In first scenario, number of random access preambles reserved for H2H devices and M2M devices are 44 and 10 respec- tively while in second scenario

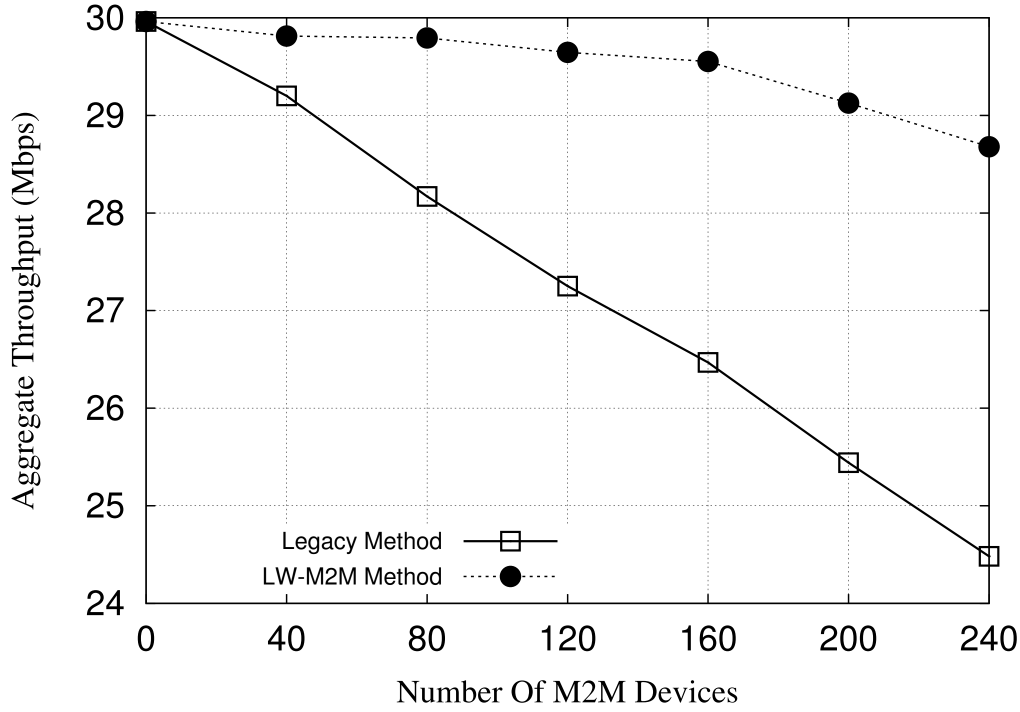

Figure 4.5: Throughput comparison for LTE versus LW communication procedure

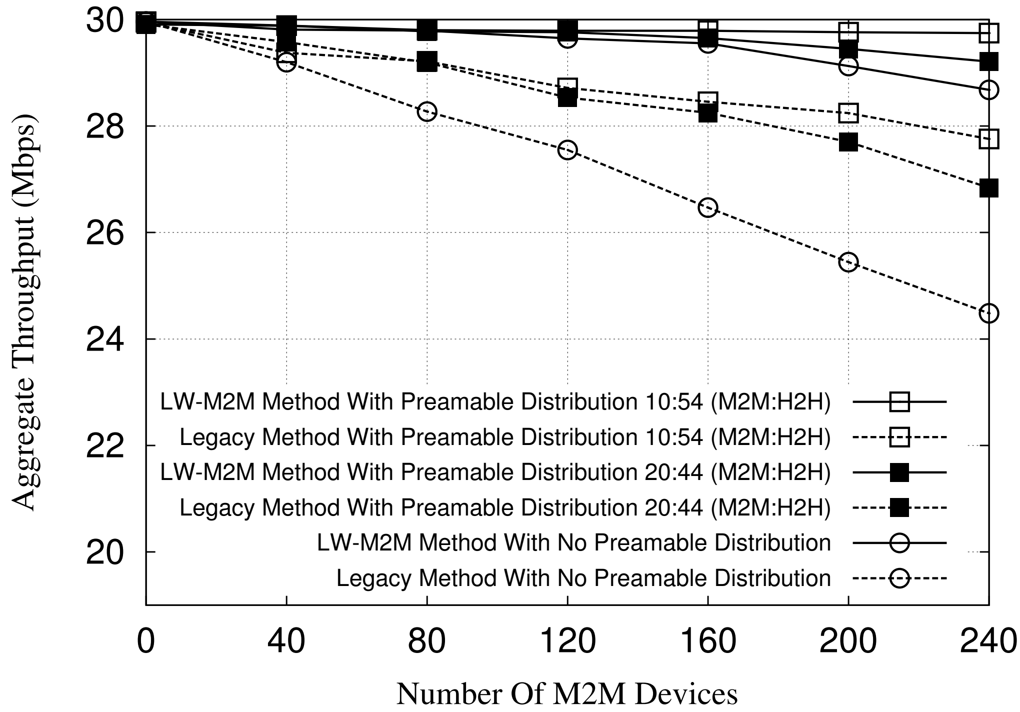

Figure 4.6: Throughput comparison of H2H devices for both methods

the distribution is 34 and 20 respectively. We can observe from the plot that throughput in both methods is more in case of preamble reservation because when there is no preamble reservation, success rate of H2H devices in RACH procedure decrease which in turn decrease the throughput. Upto 80 M2M devices, in both preamble reservation distributions, throughput is almost same but after that throughput starts decreasing because as number of preambles reserved for M2M devices increase, preamble collisions for H2H devices increase and hence, delay in successful transmission of H2H preambles increase which results into decrease in throughput of H2H devices. One of the reasons for decrease in throughput of H2H devices in Legacy method is, reduction in allocation of average number of RBs per TTI to H2H devices with increase in number of M2M devices. In Figure 4.7, we can see that in case of LW-M2M method, average number of RBs per TTI allocated to H2H devices is almost constant because in this method all M2M data has been transmitted to eNB through message 3.

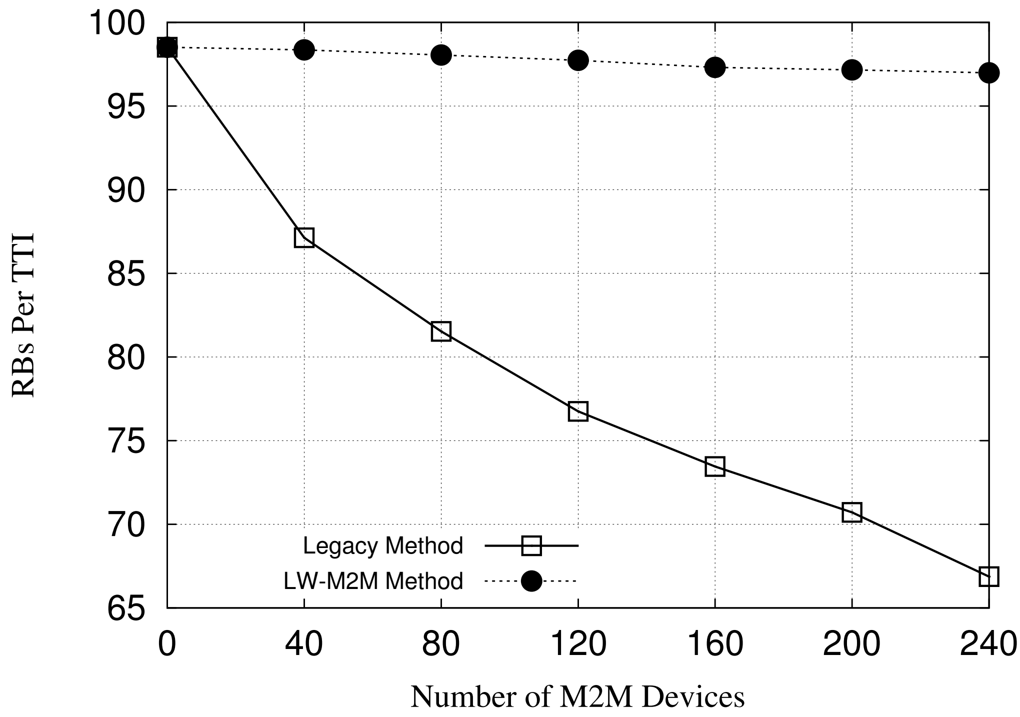

Figure 4.7: Average number of RBs allocated to H2H devices in both methods

Chapter 5

Conclusion & Future Work

Internet of Things (IoT) is fast growing technological paradigm which involves various technical and non-technical areas. M2M communication is one of the component of IoT which deals with networking and communication to implement IoT. In IoT, most of the applications use a small data packet for communication. These data packets are sent by the devices in periodic or event-driven manner.

Present cellular networks are optimized for H2H communication in which each device sends a large amount of data for long time. Using the same system for M2M communication without any modification will make the system inefficient for both H2H and M2M communication. In this work, we proposed a Light Weight EPS bearer establishment procedure for SDT of M2M. This procedure not only reduces signaling overhead by reducing number of signaling messages exchange and hence, delay in connection establishment but also reduces overhead on scheduler which in turn increases throughput of H2H devices. Simulation results are showing how average delay per device in connection establishment of M2M devices is reduced and how throughput of H2H devices improved in LW-M2M method as compared to Legacy method.

Apart from this, we have discussed variable chunk size based resource allocation scheme in uplink for ensuring the constraint of contiguous allocation of RBs. Since, in M2M communications, devices mostly follows infrequent SDT, so, fixed chunk size based resource allocation will be very uneconomical and hence, will result in inefficient resource allocation. We evaluated the performance of proposed algorithm based on the metrics aggregate throughput of devices and fairness achieved in allocation of resources among devices. The results show that how the proposed algorithm performs over Round-Robin and Proportional Fair quantitatively.

As future work, we are planning to propose a resource scheduling algorithm to allocate resources efficiently between M2M and H2H requests. After that, new simulation results will be taken by combining this work with proposed scheduling algorithm.

References

[1] D. S. Watson, M. A. Piette, O. Sezgen, N. Motegi, and L. Ten Hope. Machine to machine (M2M) technology in demand responsive commercial buildings .

[2] S. Dye. Machine-to-machine (M2M) communications. *Article (CrossRef Link)* .

[3] N. Chilamkurti, S. Zeadally, and H. Chaouchi. Next-Generation Wireless Technologies: 4G and Beyond. Springer, 2013.

[4] http://en.wikipedia.org/wiki/Internet of Things .

[5] M. Chen, J. Wan, and F. Li. Machine-to-Machine Communications: Architectures, Standards and Applications. *KSII Transactions on Internet & Information Systems* 6.

[6] A. Metnitzer. The horizontalization of the machine to machine (M2M) world and how to market it. In MIPRO, 2012 Proceedings of the 35th International Convention. IEEE, 2012 603–606.

[7] L. Mainetti, L. Patrono, and A. Vilei. Evolution of wireless sensor networks towards the internet of things: A survey. In Software, Telecommunications and Computer Networks (SoftCOM), 2011 19th International Conference on. IEEE, 2011 1–6.

[8] Machina, The Global M2M Market in 2013 .

[9] M. Z. Shafiq, L. Ji, A. X. Liu, J. Pang, and J. Wang. A first look at cellular machine-to-machine traffic: large scale measurement and characterization. In ACM SIGMETRICS Performance Evaluation Review, volume 40. ACM, 2012 65–76.

[10] D. Niyato, L. Xiao, and P. Wang. Machine-to-machine communications for home energy management system in smart grid. *IEEE Communications Magazine,* 49, (2011) 53–59.

[11] R. Lu, X. Li, X. Liang, X. Shen, and X. Lin. GRS: The green, reliability, and security of emerging machine to machine communications. *Communications Magazine, IEEE* 49, (2011) 28–35.

[12] G. Wu, S. Talwar, K. Johnsson, N. Himayat, and K. D. Johnson. M2M: From mobile to embedded internet. *Communications Magazine, IEEE* 49, (2011) 36–43.

[13] E. Dahlman, S. Parkvall, and J. Skold. 4G: LTE/LTE-advanced for mobile broadband. Academic Press, 2013.

[14] G. T. . V0.5.1. Study on RAN Improvements for MachineType Communications .

[15] K.-D. Lee, S. Kim, and B. Yi. Throughput comparison of random access methods for M2M service over LTE networks. In GLOBECOM Workshops (GC Wkshps), 2011 IEEE. IEEE, 2011 373–377.

[16] K. Zheng, F. Hu, W. Wang, W. Xiang, and M. Dohler. Radio resource allocation in LTE-advanced cellular networks with M2M communications. *Communications Magazine, IEEE* 50, (2012) 184–192.

[17] A. S. Lioumpas and A. Alexiou. Uplink scheduling for machine-to-machine communications in LTE-based cellular systems. In GLOBECOM Workshops (GC Wkshps), 2011 IEEE. IEEE, 2011 353–357.

[18] M. K. Giluka, N. Rajoria, A. C. Kulkarni, V. Sathya, and B. R. Tamma. Class based dynamic priority scheduling for uplink to support M2M communications in LTE. In Internet of Things (WF-IoT), 2014 IEEE World Forum on. IEEE, 2014 313–317.

[19] Y. Chen and W. Wang. Machine-to-Machine communication in LTE-A. In Vehicular Technology Conference Fall (VTC 2010-Fall), 2010 IEEE 72nd. IEEE, 2010 1–4.

[20] S. Andreev, A. Larmo, M. Gerasimenko, V. Petrov, O. Galinina, T. Tirronen, J. Torsner, and Y. Koucheryavy. Efficient small data access for machine-type communications in LTE. In Communications (ICC), 2013 IEEE International Conference on. IEEE, 2013 3569–3574.

[21] T. . V12.0.0. 3GPP - Study on Machine-Type Communications (MTC) and other mobile data applications communications enhancements .

[22] S.-Y. Lien, K.-C. Chen, and Y. Lin. Toward ubiquitous massive accesses in 3GPP machine-to-machine communications. *Communications Magazine, IEEE* 49, (2011) 66–74.

[23] A. G. Gotsis, A. S. Lioumpas, and A. Alexiou. Analytical modelling and performance evaluation of realistic time-controlled M2M scheduling over LTE cellular networks. *Transactions on Emerging Telecommunications Technologies* 24, (2013) 378–388.

[24] S.-B. Lee, I. Pefkianakis, A. Meyerson, S. Xu, and S. Lu. Proportional fair frequency-domain packet scheduling for 3GPP LTE uplink. In INFOCOM 2009, IEEE. IEEE, 2009 2611–2615.

[25] Network Simulator. Available online at:http://www.nsnam.org .

[26] G. T. . V8.7.0. Evolved Universal Terrestrial Radio Access (E-UTRA);Physical Channels and Modulation (Release 8) .

[27] R. Jain, D.-M. Chiu, and W. R. Hawe. A quantitative measure of fairness and discrimination for resource allocation in shared computer system. Eastern Research Laboratory, Digital Equipment Corporation Hudson, MA, 1984.

List of Publications

[1] M. K. Giluka, N. Rajoria, A. C. Kulkarni, V. Sathya, and B. R. Tamma. Class based dynamic priority scheduling for uplink to support M2M communications in LTE. In IEEE World Forum on Internet of Things (WF-IoT). IEEE, 2014 313–317.

[2] M. K. Giluka, N. Sharath, N. Rajoria, and B. R. Tamma. Class based priority scheduling to support Machine to Machine communications in LTE systems. In Communications (NCC), 2014 Twentieth National Conference on. IEEE, 2014 1–6.

[3] N. Rajoria, M. K. Giluka, T. Velerrian, and B. R. Tamma. Lightweight Signalling for Small M2M Data Transmissions in LTE/LTE-A Networks. In the 10th IEEE International Conference on Wireless and Mobile Computing, Networking and Communications WiMob.2014 (Submitted).