MASTER

Capacity study for LTE release 13 eMTC with coverage enhanced RACH

Khan, S.H.

Award date:
2016

Disclaimer
This document contains a student thesis (bachelor's or master's), as authored by a student at Eindhoven University of Technology. Student theses are made available in the TU/e repository upon obtaining the required degree. The grade received is not published on the document as presented in the repository. The required complexity or quality of research of student theses may vary by program, and the required minimum study period may vary in duration.

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain.
Capacity study for LTE Release 13 eMTC with coverage enhanced RACH

Master’s Thesis

Shoaib H Khan
Master of Science in Embedded Systems
Computer Science and Engineering

Supervisors:
Dr. C. H. van Berkel,
Sofia Lindmark (Ericsson),
Dr. David Eriksson (Ericsson),
Dr. Sander Stuijk

Eindhoven, 31\textsuperscript{st} August 2016
Abstract

The recent surge and growth in Internet of Things (IoT) has increased the number of connected devices which has motivated the need to identify the capacity constraints of the existing network. In this thesis we study the impact of increased number of devices to the cellular network, which conforms to the new 3GPP LTE Release 13 eMTC (enhanced Machine Type Communication) specifications. The investigation aims to implement the specifications related to coverage enhancement of Random Access Channel (RACH) and conduct simulations for different scenarios such that the capacity limit of the system can be ascertained. Appropriate simulation setup including propagation and deployment model based on GERAN Scenario 2 is used, with a realistic IoT traffic model covering common IoT use-cases.

When a network does not support devices in very poor coverage, a certain percentage of users are left out from being able to use the network service. Therefore, simulations are conducted for different coverage support levels and results are obtained to understand how these poor coverage devices affect the network capacity. Additionally, coverage enhanced RACH, which is responsible for the connection setup, is needed before the data transfer and therefore it is developed in the simulator and modelled as per the specifications for its capacity analysis.

The results thus obtained suggests that substantial resources are used to accommodate all the devices, i.e. even those in very poor coverage. Therefore, the capacity of the system can be significantly improved if the devices in poor coverage (3 - 4% of the total users) are not supported by the network, suggesting a trade-off scenario. It is found that these devices nearly double the resource consumption and also cause bottleneck in the system. However, the coverage enhancement mechanism allows the network to also accommodate these very poor coverage devices. Hence, different coverage support can be targeted for different zones of an area based on the application requirements and network load.
Acknowledgement

This research was conducted in the WAN Radio Network Algorithm department of Ericsson Research, Kista, Sweden.

I would first like to thank my thesis supervisors- Dr. C.H. van Berkel of Eindhoven University of Technology, Sofia Lindmark and Dr. David Eriksson of Ericsson Research, Sweden. Their constant guidance and support helped me to focus my study and to progress further. Sofia had been highly instrumental in resolving my queries and she was also a source of constant encouragement. She along with Dr. Berkel allowed this thesis to be my own work, while ensuring that I was moving in the right direction. Valuable inputs from David on the implementation of the model also helped me during the development phase.

I would also like to thank the experts at Ericsson, who attended the internal presentations and enthusiastically participated in providing essential input and feedback to the work.

Additionally, I would also like to acknowledge Dr. Johan Söder of Ericsson Research, for his valuable comments, which helped me to improve the quality of the work.

Finally, I must express my gratitude to my family for providing me with unfailing support and continuous encouragement throughout the process of research and study. This accomplishment would not have been possible without them.
## Contents

Abbreviations ............................................................................................................................. vi

1 Introduction ............................................................................................................................... 7

1.1 Motivation .......................................................................................................................... 7

1.2 Problem Definition ............................................................................................................ 8

1.3 Example Scenario ............................................................................................................. 9

1.4 Related Work .................................................................................................................... 9

1.5 Outline and Methodology ............................................................................................... 11

2 Background ............................................................................................................................. 12

2.1 Brief Introduction to LTE ............................................................................................... 12

2.2 LTE Protocol Stack ......................................................................................................... 14

2.3 Physical Channels ............................................................................................................ 14

2.3.1 Downlink Channel ..................................................................................................... 15

2.3.2 Uplink Channel ......................................................................................................... 16

2.4 MTC (Machine Type Communication) ........................................................................... 17

2.4.1 Salient features ......................................................................................................... 17

2.4.2 UE Categories ........................................................................................................... 19

3 Random Access Procedure ................................................................................................. 20

3.1 Random Access ............................................................................................................... 20

3.2 LTE Release 13 eMTC PRACH Specifications ............................................................... 22

4 Simulation Model and Assumptions ..................................................................................... 26

4.1 LTE System Simulator .................................................................................................... 26

4.2 Traffic Model ................................................................................................................... 26

4.3 Deployment and Propagation Model ............................................................................... 28

4.4 PRACH model ................................................................................................................ 30

4.5 Simulation Setup ............................................................................................................ 33

4.6 Other Assumptions ......................................................................................................... 37

5 Results and Analysis ............................................................................................................ 39

5.1 System Capacity .............................................................................................................. 39

5.2 RACH Capacity ............................................................................................................... 41

5.2.1 CE Level 0 ............................................................................................................... 41
5.2.2 CE Level 1........................................................................................................42
5.2.3 CE Level 2........................................................................................................44
5.2.4 CE Level 3........................................................................................................44
5.3 Performance........................................................................................................46
5.4 Reflection............................................................................................................48
6 Future Work .........................................................................................................50
7 Conclusions..........................................................................................................51
References...............................................................................................................52
Appendix A ............................................................................................................54
Appendix B............................................................................................................55
### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>3G</td>
<td>Third Generation</td>
</tr>
<tr>
<td>3GPP</td>
<td>Third Generation Partnership Project</td>
</tr>
<tr>
<td>ACK</td>
<td>Acknowledgement</td>
</tr>
<tr>
<td>AM</td>
<td>Acknowledgement Mode</td>
</tr>
<tr>
<td>ARIB</td>
<td>Association of Radio Industries and Businesses</td>
</tr>
<tr>
<td>ARQ</td>
<td>Automatic Repeat Request</td>
</tr>
<tr>
<td>ATIS</td>
<td>Alliance for Telecommunications Solutions</td>
</tr>
<tr>
<td>BCH</td>
<td>Broadcast Channel</td>
</tr>
<tr>
<td>BLEP</td>
<td>Block Error Probability</td>
</tr>
<tr>
<td>BPSK</td>
<td>Binary Phase Shift Keying</td>
</tr>
<tr>
<td>CAT M1</td>
<td>Category M1</td>
</tr>
<tr>
<td>CCSA</td>
<td>China Communications Standards Association</td>
</tr>
<tr>
<td>CDMA</td>
<td>Code Division Multiple Access</td>
</tr>
<tr>
<td>CE</td>
<td>Coverage Enhancement</td>
</tr>
<tr>
<td>CoAP</td>
<td>Constrained Application Protocol</td>
</tr>
<tr>
<td>CoMP</td>
<td>Coordinated Multipoint</td>
</tr>
<tr>
<td>C-RNTI</td>
<td>Cell Radio Network Temporary Identifier</td>
</tr>
<tr>
<td>DCI</td>
<td>Downlink Control Information</td>
</tr>
<tr>
<td>DFT</td>
<td>Discrete Fourier Transform</td>
</tr>
<tr>
<td>DL</td>
<td>Downlink</td>
</tr>
<tr>
<td>DL-SCH</td>
<td>Downlink Shared Channel</td>
</tr>
<tr>
<td>DTLS</td>
<td>Datagram Transport Layer Security</td>
</tr>
<tr>
<td>EDGE</td>
<td>Enhanced Data Rates for GSM Evolution</td>
</tr>
<tr>
<td>eMTC</td>
<td>enhanced Machine Type Communication</td>
</tr>
<tr>
<td>eNB</td>
<td>eNodeB</td>
</tr>
<tr>
<td>EPDCCH</td>
<td>Enhanced Physical Downlink Control Channel</td>
</tr>
<tr>
<td>EPS</td>
<td>Evolved Packet System</td>
</tr>
<tr>
<td>ETSI</td>
<td>European Telecommunications Standards Institute</td>
</tr>
<tr>
<td>E-UTRA</td>
<td>Evolved Universal Terrestrial Access</td>
</tr>
<tr>
<td>FDD</td>
<td>Frequency Division Duplexing</td>
</tr>
<tr>
<td>FTP</td>
<td>File Transfer Protocol</td>
</tr>
<tr>
<td>GERAN</td>
<td>GSM EDGE Radio Access Network</td>
</tr>
<tr>
<td>GPRS</td>
<td>General Packet Radio Service</td>
</tr>
<tr>
<td>GSM</td>
<td>Global System for Mobile Communication</td>
</tr>
<tr>
<td>H2H</td>
<td>Human to Human</td>
</tr>
<tr>
<td>HARQ</td>
<td>Hybrid Automatic Repeat Request</td>
</tr>
<tr>
<td>HetNets</td>
<td>Heterogeneous networks</td>
</tr>
<tr>
<td>HSPA</td>
<td>High Speed Packet Access</td>
</tr>
<tr>
<td>IoT</td>
<td>Internet of Things</td>
</tr>
<tr>
<td>IP</td>
<td>Internet Protocol</td>
</tr>
<tr>
<td>ISD</td>
<td>Inter-Site Distance</td>
</tr>
<tr>
<td>LTE</td>
<td>Long-Term Evolution</td>
</tr>
<tr>
<td>M2M</td>
<td>Machine to Machine</td>
</tr>
<tr>
<td>MAC</td>
<td>Medium Access Control</td>
</tr>
<tr>
<td>MAR</td>
<td>Mobile Autonomous Reporting</td>
</tr>
<tr>
<td>MCL</td>
<td>Maximum Coupling Loss</td>
</tr>
<tr>
<td>MIB</td>
<td>Master Information Block</td>
</tr>
<tr>
<td>MIMO</td>
<td>Multiple Input Multiple Output</td>
</tr>
<tr>
<td>M-PDCCH</td>
<td>MTC-Physical Downlink Control Channel</td>
</tr>
<tr>
<td>MTC</td>
<td>Machine Type Communication</td>
</tr>
<tr>
<td>NACK</td>
<td>Non-Acknowledgement</td>
</tr>
<tr>
<td>NC</td>
<td>Network Command</td>
</tr>
<tr>
<td>OFDMA</td>
<td>Orthogonal Frequency Division Multiple Access</td>
</tr>
<tr>
<td>OSI</td>
<td>Open Systems Interconnection</td>
</tr>
<tr>
<td>PBCH</td>
<td>Physical Broadcast Channel</td>
</tr>
<tr>
<td>PDCCH</td>
<td>Physical Downlink Control Channel</td>
</tr>
<tr>
<td>PDCP</td>
<td>Packet Data Convergence Protocol</td>
</tr>
<tr>
<td>PDSCH</td>
<td>Physical Downlink Shared Channel</td>
</tr>
<tr>
<td>PDU</td>
<td>Protocol Data Unit</td>
</tr>
<tr>
<td>PHY</td>
<td>Physical</td>
</tr>
<tr>
<td>PLMN</td>
<td>Public Land Mobile Network</td>
</tr>
<tr>
<td>PRACH</td>
<td>Physical Random Access Channel</td>
</tr>
<tr>
<td>PRB</td>
<td>Physical Resource Block</td>
</tr>
<tr>
<td>PUCCH</td>
<td>Physical Uplink Control Channel</td>
</tr>
<tr>
<td>PUSCH</td>
<td>Physical Uplink Shared Channel</td>
</tr>
<tr>
<td>QAM</td>
<td>Quadrature Amplitude Modulation</td>
</tr>
<tr>
<td>QoS</td>
<td>Quality of Service</td>
</tr>
<tr>
<td>QPSK</td>
<td>Quadrature Phase Shift Keying</td>
</tr>
<tr>
<td>RA</td>
<td>Random Access</td>
</tr>
<tr>
<td>RACH</td>
<td>Random Access Channel</td>
</tr>
<tr>
<td>RAN</td>
<td>Radio Access Network</td>
</tr>
<tr>
<td>RAO</td>
<td>Random Access Opportunity</td>
</tr>
<tr>
<td>RAR</td>
<td>Random Access Response</td>
</tr>
<tr>
<td>RE</td>
<td>Resource Element</td>
</tr>
<tr>
<td>RLC</td>
<td>Radio Link Control</td>
</tr>
<tr>
<td>RRC</td>
<td>Radio Resource Control</td>
</tr>
<tr>
<td>RSRP</td>
<td>Reference Signal Received Power</td>
</tr>
<tr>
<td>SC-FDMA</td>
<td>Single Carrier- Frequency Division Multiple Access</td>
</tr>
<tr>
<td>SDU</td>
<td>Service Data Unit</td>
</tr>
<tr>
<td>SIB</td>
<td>System Information Block</td>
</tr>
<tr>
<td>SIB1-BR</td>
<td>System Information Block 1- Bandwidth Reduced</td>
</tr>
<tr>
<td>SINR</td>
<td>Signal to Interference plus Noise Ratio</td>
</tr>
<tr>
<td>SON</td>
<td>Self-Organizing Networks</td>
</tr>
<tr>
<td>TBS</td>
<td>Transport Block Size</td>
</tr>
<tr>
<td>TC-RNTI</td>
<td>Temporary Cell Radio Network Temporary Identifier</td>
</tr>
<tr>
<td>TDD</td>
<td>Time Division Duplexing</td>
</tr>
<tr>
<td>TDMA</td>
<td>Time Division Multiple Access</td>
</tr>
<tr>
<td>TTA</td>
<td>Telecommunications Technology Association</td>
</tr>
<tr>
<td>TTC</td>
<td>Telecommunication Technology Committee</td>
</tr>
<tr>
<td>UCI</td>
<td>Uplink Control Information</td>
</tr>
<tr>
<td>UDP</td>
<td>User Datagram Protocol</td>
</tr>
<tr>
<td>UE</td>
<td>User Equipment</td>
</tr>
<tr>
<td>UL</td>
<td>Uplink</td>
</tr>
<tr>
<td>UMTS</td>
<td>Universal Mobile Terrestrial System</td>
</tr>
<tr>
<td>UTRA</td>
<td>Universal Terrestrial Access Network</td>
</tr>
<tr>
<td>WCDMA</td>
<td>Wideband Code Division Multiple Access</td>
</tr>
<tr>
<td>WoT</td>
<td>Web of Things</td>
</tr>
</tbody>
</table>
Chapter 1

1 Introduction

1.1 Motivation

The world is evolving towards a networked society, where concepts like Internet of Things (IoT) and Web of Things (WoT) are becoming popular. IoT and WoT mainly refer to a core concept that promotes the interconnection of all types of devices, allowing them to send and receive data to exchange information autonomously i.e. without any human intervention. It has been estimated from various researches that the number of IoT enabled devices will grow exponentially, and by 2020 it is expected to reach around 40 billion devices [1, 2]. Various machine type communication services and application are expected to be introduced in the coming years, thereby increasing the demand for such devices. Some of the examples for such machine services are smart meters, wearables, fleet management, tracking devices, vehicle networks, access controls and consumer electronics. With this gradual increase in demand for IoT, and its surge in growth, the load on the communication networks and expectation from various supporting technologies has also increased. Different applications and innovative designs have created new demands and performance requirements. Many of these services do not require a wide area connectivity and can be locally connected through other technologies such as IEEE 802.15.4, IEEE 802.11 and Bluetooth, but with concepts of smart cities, smart grid, connected vehicle network, tactile internet [3] etc., many new services and applications now require a wider area coverage to accommodate more devices. This has given rise to new technologies and methods to provide support and adequate infrastructure for reliable connection and high performance data communication. Given these critical requirements, the existing network of cellular communication is expected to take advantage of this growth and also help in propelling the vision of connected IoT world. However, it is interesting to note, that since the numbers of connected devices are expected to be in billions, a new challenge is to support this many devices without affecting the performance of the network. This thesis, aims to study the impact of increased number of devices to the cellular network having the 3GPP LTE Release 13 communication standards for eMTC (enhanced Machine Type Communications) devices, with the help of an IoT based traffic model.

The result of this study will also be a valuable input for network operators in decision making regarding the extent of network support that they should deploy in regions of variable load. Since, the work in this thesis considers multiple scenarios to emulate different extent of coverage reach supported by a network, the result of this thesis would be a relevant starting point for the operators who might prefer a more economically balanced solution from a business standpoint. The coverage reach supported by the network is based on the specifications with which the hardware and software of the network have been upgraded. From Release 13 eMTC specifications, the coverage that the network should ideally support is expected to be the Maximum Coupling Loss (MCL) of 155.7 dB, which requires additional coverage enhancements compared to the traditional LTE devices and network. However, it may be possible that in some areas of the network such extreme coverage support
may not be required or a trade-off may be needed based on certain performance requirement. In such cases a viable business decision needs to be taken such that there is a sustainable growth of IoT in cellular domain.

1.2 Problem Definition

The following research can be broadly classified as a design-driven research approach with the objective to conduct a study on capacity and performance for LTE based eMTC devices in the existing cellular network infrastructure with the coverage enhanced RACH (Random Access Channel).

Problem statement: How is the capacity of an LTE system affected when more users in poor coverage zones are allowed into the network, by supporting the maximum coverage enhancement for 3GPP Release 13 eMTC devices?

Description: The investigation in this thesis is performed as a system level simulation in an existing state-of-the-art LTE simulator at Ericsson Research. The traffic model and device distribution are according to the GERAN specification (3GPP TR45.820 v13.1.0 Annex E [4]) and the coverage enhancement is varied between 0 dB and the current maximum support of 15 dB as per the specification. By limiting the maximum supported coverage, some fractional percentage of users will not be served. It is interesting to see how much system resources these edge users utilize under full coverage support scenario, and if the trade-off for not supporting few percentages of users would be compensated by increased performance and better utilization of resources. Since these devices or user-equipments (UEs) need to initially establish a connection to the network, it is essential that the new LTE Release-13 specifications for eMTC concerning random access procedure is implemented (currently absent) in the existing LTE simulator, for more accurate modelling of these UEs, before the simulations can be performed.

Details of the relevant concepts is discussed in Chapter 2, 3 and 4; however, to provide an initial context to the problem some of the concepts are discussed in brief below:

- The MTC UE (Release 13) has been specified for limited and reduced functionality to cater the requirements for IoT based machine type communication devices where the power consumption needs to be small, the price of the device is a main concern and the location of the device may be underground or far away from a base station. Therefore, a coverage enhancement mechanism has been introduced to compensate for the limitations in the device as well as to support devices in bad coverage area. With different served coverage levels supported by the network, the capacity and resource utilization will get affected.
- The GERAN (GSM EDGE Radio Access Network) traffic model covers the typical use-cases of such MTC devices and the exact specifications are derived from the study conducted in GERAN by 3GPP (Third Generation Partnership Project).
- The random access channel (RACH) is used by the MTC UE to initiate request for the initial connection setup with the base station and subsequently request for allocation of resources for data transmission to take place. For an
increased number of MTC UEs the impact of these requests to the system is anticipated to be significant and may affect the capacity of the LTE system.

- **Coverage enhancement** is a mechanism through which the system reaches required path-gain to overcome the maximum coupling loss supported by the system. The maximum coupling loss is a difference between the transmission power and the receiver sensitivity which includes the losses due to outdoor path loss and building penetration loss of radio propagation.

- The capacity is measured on two fronts, system capacity and RACH capacity. The system capacity measures the number of served users that the system can accommodate simultaneously. Additionally, it also suggests the spectral efficiency of the communication channels by measuring the utilization percentage of the physical channel resources. The number of non-MTC users served per cell is within the range of 50K - 200K users, but for MTC users this figure is expected to reach much higher because of very small traffic load for each device. The RACH capacity is a measure of the number of simultaneous connection attempts by the UEs that the system can accommodate within tolerable limit of failures as estimated by the network from the capacity equation in [5]. RACH capacity is observed by its collision probabilities for each RACH attempt, access success rates, average connection attempts for a successful attempt, and average delay for initial connection and data transmission etc. [5] Some of the performance metric that are also evaluated are the cell and user throughput. These analyses will be carried out for different coverage levels, wherever applicable.

### 1.3 Example Scenario

Consider an example scenario, which illustrates the use of an MTC type devices. In a town, which also houses a smart grid network, several sensors and actuating devices are used for the purpose of monitoring, reporting and to receive commands and controls from various systems. There can be millions of such devices/sensors within a square kilometre radius some of which could be present deep inside buildings or basements. These devices would need to send periodic reports and sensor data to the central monitoring system and also require reception of actuating commands. Although, each device would mostly require few bytes of data traffic and would largely remain in an idle state, the sheer magnitude in number of devices and also poor coverage for some of the devices can impact the capacity and performance of the network overall. Further, before any data transfer can take place, a cellular network based device requires a connection setup phase. The devices initiate this phase by obtaining the connection setup parameters which are periodically broadcasted by the network to all devices which are within its coverage range. The connection setup itself, requires certain exchange of data and control information before validating the device and establishing the connection. This step also requires additional coverage enhancement and optimization of the protocols such that all the devices are able to seamlessly connect, which is covered in the new specifications.

### 1.4 Related Work

One of the important technical document summarizing the output for the study on RAN (radio access network) improvements for MTC in 3GPP is TR 37.868 [5]. The purpose of the study item of RAN overload control was to avoid high collision
during random-access when massive number of MTC devices are connected in the network, and are simultaneously attempting to connect through random-access channel. The study proposes a number of solution to mitigate the problem, and most of them have already been standardized in the subsequent releases. The calculation and the arguments mentioned in the report provides a valuable starting point for the capacity analysis and for the calculation of the collision probabilities during random-access attempts.

Rapeepat et al. [6], provided a detailed analysis of the different techniques through which the required coverage enhancements could be achieved. They conducted simulations for different downlink and uplink channels with coverage enhancement techniques such as frequency hopping, longer transmission times (repetition), and multi-subframe channel estimation. In addition, their study on capacity with the same traffic model as used in this thesis also gives valuable insight on the channel utilization. Since the exact specification by 3GPP was not available by then, their simulations did not consider the impact on capacity for configurations with different coverage enhancement levels of PRACH (Physical random access channel). However, the results obtained in their research gives some estimation on the repetition values one could expect to reach the desired coverage enhancement.

In [7], Gerasimenko et.al. performed energy and delay analysis of RACH performance under MTC overload conditions. Although, the focus was to formulate the analytical model for delay and energy, the idea was also to investigate the performance of MTC devices, and impact of random access procedure under high network load in terms of metrics such as access success probability, and medium access delay. The simulation conditions and the chosen metric presented a good comparison opportunity, however, the RACH was not modelled as per Release 13 eMTC specification and hence the results are not tenable according to the current specifications.

In 2012, 3GPP conducted a study on the provision of low-cost MTC UEs conforming to Release 12 specifications. The result of the study is detailed in [8], which focusses on the coverage enhancements, power consumptions, impact on specifications, spectral efficiency and cost analysis for the new category of UEs (i.e. Cat 0). Although, the results are outdated from Release-13 perspective, it provides a good insight on the various considerations and simulation configurations that are used for the research. The traffic model used in [8] is slightly more simplistic and different from the one used in this thesis, and the 3GPP case 1 deployment model has been used instead of a GERAN scenario.

Borodakiy et al. in [9], modelled the RACH procedure for M2M traffic in an LTE cell in the form of discrete Markov chain, based on the number of retransmissions of signalling message between the user equipment and eNodeB. The simulation model was based on Monte-Carlo, with the probability of collision calculated as per [10]. The results gave a good approximation for the mean access delay, which was useful in comparison for this work.

In [11], Cheng et al. provides a clear differentiation of the different algorithm for calculation of collision probability and suggests the one which should be used by the
researchers. The analytical model presented in this paper provides a distinction between the two definitions of collision probability, and helps in selecting the formula which has been used for the calculation in this work.

Apart from the above, there are several studies and researches conducted internally at Ericsson for the new LTE release 13 specification for MTC. One of the earlier simulations using the 3GPP case 3 deployment model, and periodic MTC traffic data suggested that downlink data channels can create a bottleneck to the capacity and the utilization of the resources in the presence of normal mobile broadband UEs. In addition, coverage enhancement mechanisms for other channels were implemented and simulated, to estimate its effect in supporting the coverage enhancement requirement of around 15dB which is required for most channels. It is worthwhile to note that during these simulations the PRACH model based on Release 13 specification for MTC devices was not used.

1.5 Outline and Methodology
The remaining thesis is structured as below. The Chapter 2 presents the discussion on the most relevant background to understand this thesis work, including discussions on various channels and protocol stack. In Chapter 3, the random access procedure is discussed, which outlines the various steps and mechanisms involved for the same. The eMTC Rel-13 specification perspective is also presented here.

Chapter 4 presents the implementation details, core simulation models adopted for this work, and discusses the rationale behind the choices. The assumptions and the chosen simulation parameters are also discussed in this section. Chapter 5 shows the results and discusses the analysis simultaneously with it. This is followed by reflection on the overall results.

In Chapter 6 a discussion on the scope of future work is done and the advantages of the current work is discussed. Chapter 7 presents the conclusion and summary of the thesis followed by references and appendix.

The nature of this study is influenced by a positivist research paradigm which is widely adopted within information and communication technology community [12]. A quantitative research methodology with a deductive approach for reasoning has been adopted in this study to investigate the research question for this thesis. Experimental research strategy and design methods were used to investigate the relationship and behaviour of the LTE Release 13 specifications in a given scenario. The data is collected after conducting several sets of experiments with a system simulator, which is afterwards statistically analysed for drawing conclusions and inferences. The performance and capacity constraints are studied, and the results are verified and validated by comparing it with other already verified results and also by conducting controlled experiments for ideal and simpler scenarios. Repeated simulations for several iterations ensures reliability of the results, and the configuration steps detailed in this report would allow replicability of experiments. Ethical practices for conducting experiments and result reporting is used, with the applicability of other quality assurance properties such as dependability, transferability and confirmability of the research [12].
Chapter 2

2 Background

2.1 Brief Introduction to LTE

Long-Term Evolution (LTE) or E-UTRA (Evolved Universal Terrestrial Access) is a communication standard for wireless cellular networks, and governs the access part of the Evolved Packet System (EPS). It is based on the existing infrastructure of the GSM/EDGE and UMTS/HSPA networks and focusses on high-speed data communication and also tries to solve other problems of performance and reliability faced by the existing technologies for voice and data communications.

The traditional system of GSM (Global System for Mobile Communication) or UMTS (Universal Mobile Terrestrial System), were either TDMA based or CDMA, and had bandwidth limitation, data-rate and performance issues. Although, GPRS (General Packet Radio Service) was introduced which enabled packet-switched based data communication, it had its own limitations on data-rate, and the real-time services still heavily relied on the circuit-switched networks as shown in Figure 2.1. With the advent of 3G and higher-bandwidth radio interfaces of UTRA (Universal Terrestrial Radio Access), it was evident that the stage was set for the next generation of cellular communication.

3G evolved into HSPA and eventually a new technology of LTE/LTE Advanced evolved. The driving force behind the continuous evolution of cellular communication can be attributed to improvement of mainly three aspects of quality of service (QoS) i.e. data rate, latency, and capacity. [13] The peak data rate and the communication delay parameters played an important role, but the spectral efficiency and the total data rate that can be provided on average to each user also played a crucial role in performance evaluation. The Evolved Packets System which is the core network developed to support HSPA and LTE/ LTE Advanced, focusses on these concerns and is purely IP based on the packet-switched domain. The evolution of cellular communication can be broadly illustrated from Figure 2.2. LTE which forms the access solution of this core, is based on OFDMA (Orthogonal Frequency Division Multiple Access), and relies on higher modulation schemes like 64QAM and 16QAM etc. One of the striking aspects of LTE (Rel 8) was its increased bandwidth of 20 MHz and provides the theoretical peak data rate of 75Mbps and 300Mbps, uplink and downlink respectively. [14]

The standardization of LTE is done through 3GPP (Third Generation Partnership Project), which is a standard-developing body that specifies for the LTE/LTE Advanced, 3G UTRA and 2G GSM technologies. The partnership project is formed by the various standards bodies ETSI, ARIB, TTC, TTA, CCSA and ATIS. [13] (see Abbreviation chart)
The 3GPP details the specification in documents and presents it as releases. The first LTE main feature and specifications were released in Release 8, December 2008. Subsequent releases were introduced to address various QoS parameters and in 2011, Release 10 was released which brought a major overhaul to enhance the performance and was quipped as LTE Advanced. It was Release 11, that first targeted the IoT market and machine type communication requirements. Release 13, which has recently been announced in March 2016, has been considered to address multiple usability requirements of the IoT domain and introduce enhanced Machine Type Communication standards. The summary for the few recent releases are given below:

Release 10, March 2011 – Improvements in capacity, spectral efficiency, coverage and throughput with data rate up to 3Gbps downlink and 1.5Gbps uplink, introduction of Carrier Aggregation which allowed five separate carriers to enable bandwidth of 100MHz, frequency hopping for uplink channels, increased Multiple Input Multiple Output (MIMO) antenna configurations (8x8 downlink and 4x4 uplink), relay nodes to support Heterogeneous networks (HetNets) and some improvements in Self Organizing Networks (SON).

Release 11, September 2012 – Some major enhancements and minor refinements to Release 10 features, including carrier aggregation, relay, MIMO and introduction to Coordinated multipoint transmission and reception (CoMP). New features such as enhanced PDCCH (ePDCCH), network based positioning, network managed overload control for MTC devices, and means to save battery power of devices.

Release 12, June 2014 – Further enhancement were made to LTE advanced, with improvements in support for HetNets, carrier aggregation, inter-networking with LTE and Wi-Fi, and introduction to a new UE category (Cat 0) for MTC operations.

Release 13, March 2016 – Major overhaul to the existing specifications to improve bandwidth, spectral efficiency and other QoS parameters. Enhancement towards carrier aggregation to enable support of 32 component carriers instead of 5 as in Release 10, improvements for higher order MIMO and introduction of a new category of UE for MTC operations targeting low power consumption and complexity, with further enhancement in MTC standards, apart from improvements in existing indoor positioning techniques and downlink multiuser transmission.
2.2 LTE Protocol Stack

Like other cellular networks, LTE provides coverage to large operational areas which are divided into multiple cells, where each cell is served by a base station also known as eNodeB (eNB). The cells contain many UE nodes or devices such as cellular phones, wireless sensors, personal computers, other mobile devices etc. This thesis work discusses only the communication between the UE and the immediate base station (eNB), and does not focus on the inter-network communications.

The LTE stack for radio communication consists of five layers as shown in Figure 2.3, where the lower four layers denotes the Data link (L2) and Physical layer (L1) of the OSI (Open Systems Interconnection) model. The RRC (Radio Resource Control) layer handles the control plane signalling of L3 between the UE and Radio Access Network. The PDCP (Packet Data Convergence Protocol) layer is responsible for ciphering of data, IP header compression and transfer of user-plane or control-plane data. The RLC (Radio Link Control) layer handles packet concatenation, segmentation and reassembly of RLC SDUs (Service Data Units – inward data units to the protocol stack), and also re-segmentation in Acknowledgement Mode (AM) for RLC PDUs (Protocol Data units – outward data unit to the protocol stack). It is also responsible for re-transmission and error correction through ARQ (Automatic Repeat Request). The MAC (Medium Access Control) layer in cellular network is responsible for scheduling of the packets and setting up appropriate priorities. It is also responsible for using a re-transmission scheme known as HARQ (Hybrid ARQ). HARQ with Soft-Combining (i.e. different re-encoding of re-transmissions) uses ACK/NACK responses to indicate whether a sent packet is received correctly or a re-transmission is necessary. The PHY layer handles the radio related modulation and encoding schemes and also validates the packet integrity using checksum. The above mentioned layers append their own headers to the PDU when transmitting, and also remove them from the SDU when receiving.

2.3 Physical Channels

The downlink and uplink support different physical channels that exchange information from higher layers in the LTE stack and the physical signals used in the PHY layers. These physical channels map to transport layers which acts as a service access points for layer 2/3 of the protocol stack. Each physical channel has a defined
algorithm for bit scrambling, modulation, layer mapping and precoding. An operator is typically allocated a frequency band where the communication signals are transmitted. An LTE based operator uses the band by dividing it into a number of sub-bands using the technique called Orthogonal Frequency Division Multiplexing (OFDM). In this case the frequency band is divided into a number of carrier sub-bands such that no carrier bands interfere with each other i.e. they are orthogonal to each other. Hence, by using OFDM, many devices can communicate with the base station at the same time and frequency resource without interfering with each other.

The capabilities of a UE and an eNodeB are quite different, and therefore, the PHY layer of downlink and uplink have different channels and have different modulation schemes. OFDM is the basic transmission scheme for downlink and SC-OFDM is used for uplink transmissions, which uses a wider single carrier sub-band. The reason for using SC-OFDM in uplink is because OFDM shows large variation in transmission power and power-amplifier efficiency, which is critical for uplink transmission since the power consumption and cost is of importance for the terminal devices. The uplink transmission applies DFT (Discreet Fourier Transform) precoding before OFDM modulation, called DFT spread OFDM.

The time aspect of the LTE physical resource-grid is such that each frame consists of ten sub-frames which in turn consists of two slots (0.5ms) each of which contains seven OFDM symbols (when short cyclic prefix is used), as shown in Figure 2.4. The LTE specification defines both duplexing modes i.e. FDD (Frequency division duplexing) and TDD (Time division duplexing). The work done in this thesis deals exclusively in FDD duplex mode, and hence TDD related specifications are not discussed.

The different channel encoding schemes available for downlink and uplink are BPSK, QPSK, 16QAM or 64QAM which allows symbol resolution of 1, 2, 4 or 6 bits per transmitted symbol respectively.

### 2.3.1 Downlink Channel

The downlink physical channel corresponds to the set of time-frequency resources used for downlink transmission of a particular transport channel where each transport channel is mapped to a corresponding physical channel as shown in Figure 2.5. There are also some channels which does not have a corresponding transport channel, known as layer 1 or layer 2 control channels and they are used for Downlink Control Information (DCI). Although, there are many downlink physical channels as shown in the figure, only the relevant ones are discussed here.
2.3.1.1 PDSCH

The Physical Downlink Shared Channel (PDSCH) is used for unicast data transmission, and also for transmission of paging messages (network triggered connection setup for UEs in idle state). The resources for this channel are allocated on a sub-frame basis by the downlink scheduler. It is designed for very high data rates, with three modulation options: QPSK, 16QAM, and 64QAM. Spatial multiplexing is used for this channel.

2.3.1.2 PDCCH

The Physical Downlink Control Channel (PDCCH) is used to transmit downlink control information. The data rate is not the chief consideration for this channel, instead reliability and robustness is considered critical. The information transmitted could be scheduling decision for reception on the PDSCH or scheduling grant on the PUSCH. QPSK is the only available modulation format. The PDCCH is mapped to resource elements up to the first three OFDM symbols in the first slot of a sub-frame which is mapped to the entire system bandwidth. In case of MTC devices, PDCCH is not used, since they only monitor 6 PRB (Physical Resource Block), i.e. 1.08 MHz of the entire system bandwidth at a time, and hence an alternate channel called M-PDCCH is used, which is located in the narrow bandwidth of 6 PRB of the downlink data channel.

2.3.2 Uplink Channel

The uplink physical channel, like the downlink channel, also corresponds to a set of time-frequency resources for uplink transmission of a particular transport channel as shown in Figure 2.6 [13]. There are some channels which do not have a corresponding transport channel, which are used for Uplink Control Information (UCI). The three uplink physical channels are discussed here.
2.3.2.1 PUSCH

The Physical Uplink Shared Channel (PUSCH) is similar to PDSCH, but is used for uplink data transmissions. The resources for this channel are allocated on a sub-frame basis by the uplink scheduler. The modulation format that may be employed by PUSCH are QPSK, 16QAM or 64QAM. However, the new category of MTC devices (CAT M1) do not support 64QAM.

2.3.2.2 PUCCH

The Physical Uplink Control Channel (PUCCH), carries the uplink control information, and is used by terminals to provide status information such as channel quality indications (CQI). It is never transmitted simultaneously with uplink data, and is used for ACK/NACK, HARQ and to request scheduling for uplink transmission. The PUCCH transmission is frequency hopped at the slot boundary which means it occupies a variable number of resource blocks at the top and bottom frequency of the uplink system bandwidth as shown in Figure 2.7.

![Figure 2.7: Uplink physical channel resources in the frequency-time grid](image)

2.3.2.3 PRACH

The Physical Random Access Channel (PRACH) is used for establishing connection to the network, and requesting grants from the network to transmit uplink data. This allows the UEs to perform their first transmission for initial access when establishing a radio link, to re-establish a radio link after failure and is used during handover when uplink synchronization is needed when moving to a new cell. The first message which is sent to initiate a random access procedure is transmitted on PRACH, as shown in Figure 2.7. More details in Chapter 3.

2.4 MTC (Machine Type Communication)

2.4.1 Salient features

Machine type communication or machine-to-machine communications (M2M) is a form of automated data communication which involves one or more entities
Capacity Study for LTE Release 13 eMTC

Figure 2.8: Typical MTC device positioning scenario in a network and its relationship with different entities [15]

Figure 2.9: Current cellular based network architecture (EPS) for supporting MTC services [6]

that do not necessarily need human interaction to use the underlying data transport infrastructure. Therefore, an MTC device is a UE which communicates through a PLMN (public land mobile network) with MTC server(s) and/or other MTC device(s). An MTC server is a server which communicates to the PLMN itself, and also to other MTC devices through the PLMN. The MTC server can also have an interface which can be accessed by an MTC user who is subscribed to the services exposed by the MTC server. [15] The Figure 2.8 and 2.9, illustrates the relationships between these entities and the network architecture for MTC, respectively.

The services offered to or demanded by these type of communication significantly differ from regular human to human interaction based services. Some of the salient properties of these services are: less traffic per terminal, low bandwidth and data rate, delay-tolerance and potentially very large number of terminals. Some of its service requirements are low cost and complexity, high coverage requirements and power efficiency [16]. Having identified these service requirements, it is also important to note that most of the service properties are dependent on the type of application they are used for, and therefore, some of the MTC devices may also have service requirements similar to current mobile network communications. Some of the example MTC applications can be categorized under the following use-cases: metering, control system and monitoring, tracking, payment, security and public safety [15]. This implies that not all MTC applications have the same characteristics. Therefore, not every system optimization is suitable for every MTC application, and considering this the 3GPP has specified features which can be provided to these devices from the network. Some of these features are: low mobility, time controlled network
access, small data transmissions, less frequent mobility management, MTC monitoring, secure connection etc. [15] The rationale behind these features can be understood based on the traffic model and the deployment scenarios that have been identified for these devices, which we shall discuss in the later sections.

2.4.2 UE Categories

A new category of UE has been introduced in Release 13 that has distinct features tailored for MTC use cases. It differs in complexity from the previous ‘simplest’ MTC device category - Category 0 UE, which was specified in Release 12. The uplink and downlink bandwidth have been reduced to 1.4 MHz as oppose to 20MHz for the ‘normal’ LTE categories type. The max Transport Block Size (TBS) is 1000 bits for both downlink and uplink. The duplex scheme can be either Full or Half with FDD or TDD, and a single receiver chain is supported which results in a major reduction in complexity and power consumption. Further reduction in the maximum transmission power to 20dB (optional) and support for only QPSK and 16-QAM modulation schemes would also help in reducing power requirement for the UE, thereby, increasing its battery life. However, by reducing the complexity and transmission power, some coverage loss is anticipated apart from the additional loss that these UEs may incur if some of them would be placed in basement and underground scenarios. Therefore, to compensate for the loss, coverage enhancement (CE) of 15dB compared to Category 0 UE has been standardized. The coverage enhancement can be achieved through repetitions, frequency hopping, relaxed requirements for miss probability or false detection etc. The different categories of UE and their properties are listed in Table 2.1.

Table 2.1: UE categories and its specifications [17, 18]

<table>
<thead>
<tr>
<th>UE Category</th>
<th>Downlink bitrate (Mbps)</th>
<th>Uplink bitrate (Mbps)</th>
<th>Max No. of spatial layers in DL</th>
<th>Rx Antennas</th>
<th>Support for 64QAM in UL</th>
<th>Max Tx Power (dBm)</th>
<th>Duplex Mode</th>
<th>Bandwidth (MHz)</th>
<th>Modem Complexity (with Cat1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>0.3</td>
<td>0.375</td>
<td>1</td>
<td>1</td>
<td>No</td>
<td>20 or 23</td>
<td>Full or Half</td>
<td>1.4</td>
<td>25%</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1.16</td>
<td>1</td>
<td>1</td>
<td>No</td>
<td>23</td>
<td>Full or Half</td>
<td>20</td>
<td>50%</td>
</tr>
<tr>
<td>1</td>
<td>10.296</td>
<td>5.16</td>
<td>1</td>
<td>2</td>
<td>No</td>
<td>23</td>
<td>Full</td>
<td>20</td>
<td>100%</td>
</tr>
<tr>
<td>2</td>
<td>51.024</td>
<td>25.456</td>
<td>2</td>
<td>2</td>
<td>No</td>
<td>23</td>
<td>Full</td>
<td>20</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>102,048</td>
<td>51.024</td>
<td>2</td>
<td>2</td>
<td>No</td>
<td>23</td>
<td>Full</td>
<td>20</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>150.752</td>
<td>51.024</td>
<td>2</td>
<td>2</td>
<td>No</td>
<td>23</td>
<td>Full</td>
<td>20</td>
<td>125%</td>
</tr>
</tbody>
</table>
3 Random Access Procedure

3.1 Random Access

Random access is the mechanism through which a UE establishes connection with a network inside a cell. The eNB or base station provides access to the UE to its network after establishing its validity and also grants it with channel resources for data transmission. Either a contention-based or contention-free random access can be used. The contention based scenario happens when two or more UEs use the same random access opportunity to transmit the same preamble. A contention-free scenario happens when the eNB signals an already connected UE (e.g. during handover) to use a dedicated preamble which will not been used by any other UE during the same occasion. A contention based random access process typically involves four message exchanges between eNB and the UE terminal. A non-connected terminal, needs to complete the connection setup before transmitting or receiving data as shown in Figure 3.1, which includes the random access procedure (i.e. the first four messages exchanges between the UE and eNB), as discussed below.

![Random Access Procedure Diagram]

Figure 3.1: Connection setup steps including random access procedure (Msg1 to Msg4), before data transmission can initiate, followed by connection release by network.
1. The UE transmits a random access preamble in a predefined random access preamble slot on PRACH.
2. The network transmits a response with the timing advance command based on the timing estimate obtained from the first step. It also sends the temporary identity and a scheduling grant for uplink resource to be used in the next step. This message is sent on downlink data channels indicated by PDCCH (or M-PDCCH in case of MTC UEs).
3. The UE responds using the uplink grant resource with its own identity based on its current state, on the uplink data channel.
4. The final step consists of transmission of contention resolution message from the network to the UE on a downlink data channel.

PRACH resources are periodically configured in the uplink data channel on a pre-defined number of the frequency bands in the uplink system bandwidth. Each single contiguous PRACH resource is referred to as RACH opportunity, as shown in Figure 2.7. The RACH opportunities are differentiated by both time and frequency. Several UEs can use the same RACH opportunity to transmit a preamble which can cause collision. This risk can be reduced by using different preamble coding thereby increasing the total effective RACH opportunity. There are a total of 64 different preambles defined for an LTE cell, out of which some are dedicated preamble which can only be used by the UEs if the network commands, for example in cases of handover. The remaining preambles are free to be chosen by the UEs for the initial preamble transmission. All 64 preambles are orthogonal and therefore do not interfere with other requests. Since a single UE does not have knowledge of the preamble chosen by other UEs, there is still a possibility that two or more UEs use the same preamble in the same RACH opportunity thereby creating a scenario for RACH collision. In such a case, the step 4 of the random access procedure resolves the contention by allocating only one of the UEs with the Radio identity and gives permission to transmit further messages, and the rest of the UEs will try again after the contention resolution timer expires for them. More details regarding the steps involved in random access procedure are discussed below.

The random access starts with the first message (Msg1) of ‘preamble’ signalling to the network, from the list of available preambles allowed. This list and other system information parameters are broadcasted by the eNB in the Master Information Block (MIB) and System Information Blocks (SIBs) esp. SIB1 and SIB2. The UE selects the appropriate preamble based on its coverage requirements, and signals the same to eNB at a defined frequency and time resource slot of the uplink PRACH [19]. The eNB responds with a Random Access Response (RAR) in the downlink data channel, which contains the temporary-identifier (TC-RNTI) for the UE and a grant for resource of uplink data channel where it would send Msg3 (i.e. RRC Connection Request). [13] If it is the contention-free random access, Msg3 is the last step and the UEs use the already existing connected-identifier (C-RNTI) for further communication. For the contention-based access, two or more UEs may have used the same preamble value where only one of which was decoded by the eNB. Therefore, all these UEs will receive the RAR with the same TC-RNTI identifier from the network, and hence the next two messages (Msg3 and Msg4) are extremely important for
contention resolution. The UEs will send Msg3, with their terminal identifier (a random value) in the allocated uplink resource, as an acknowledgement and request for connection. However, the eNB will only be able to read Msg3 from the UE for whom it had sent the RAR message. To resolve the contention eNB sends the response Msg4 (i.e. RRC Connection Setup) which contains the same terminal identifier which it had received in the previous message. The UEs detect this message and consider the contention to be resolved if the received terminal identifier matches with the previously transmitted value and then promotes the TC-RNTI to C-RNTI for further communication. [13] Other UEs, which do not find a match or are unable to detect this message would consider the random access procedure as a failure and will retry from Msg1 after a fixed waiting period and varying back-off time expires.

With the Release-13 MTC UE requirement, it is required for PRACH channel to be able to connect to the eNB at a maximum coupling loss of 155.7 dB. To achieve this value, additional 15 dB of coverage enhancement are required as compared to the Cat-0 UE defined in Release 12. In the legacy PRACH channel, after not receiving RAR response from eNB, the UE increases its transmission power to overcome the coupling loss. In case no response is received for an increase in transmission power, the UE keeps attempting preamble transmission after the expiry of the RAR window until the maximum preamble attempts are reached [19]. This would result in wastage of power for UEs in bad coverage and can also affect the network load when several UEs are attempting to connect at the same time in a small area. Therefore, in the Release-13 eMTC specifications, such situations are dealt by using a repetition mechanism together with additional new coverage levels for PRACH. The UE will then select a coverage level based on its current coverage condition. This allows the possibility of pre-selecting the necessary repetition values before attempting connection setup.

### 3.2 LTE Release 13 eMTC PRACH Specifications

Additional coverage enhancement is required for the connection setup of these new Release 13 MTC UE types. A UE in a bad coverage may require high coverage enhancement to overcome the coupling loss. The maximum coupling loss for Release 13 low complexity UE is targeted to be 155.7 dB for both FDD and TDD [20], and therefore the coverage enhancement required for Category M1 UE as compared to Category 0 UE is about 15 dB for PRACH channel [20, 21, 16]. To overcome the requirement of coverage enhancement for the MTC UEs during connection setup, the Release 13 eMTC specifications consists of additional connection configuration parameters and also specific mechanism at the MAC layer which these UEs should follow. The details of these new parameters and the protocols are presented below.

Before the UE can initiate a random access procedure, it receives the configuration parameters from the MIB and SIB1-BR (a new System Information Block for low complexity UE types). These configurations and others are received through the BCH (Broadcast channel) and DL-SCH (Downlink Shared channel) channels respectively. One important decision that the UE needs to take, based on the RSRP (Reference Signal Received Power)\(^1\) threshold value, is to select the appropriate initial coverage level. Three values of RSRP thresholds are broadcasted in the system.

\(^1\)Reference Signal Received Power (RSRP), is defined as the linear average over the power contributions (in [W]) of the resource elements (REs) that carry cell-specific reference signals within the considered measurement frequency bandwidth. [25]
information block for each cell, which helps the UEs to select its Coverage enhancement level. This allows the UE to avoid unnecessary interference with other cells, avoid using extra system resources, and prevents it from using excessive power if it is already in a strong coverage zone. The UE initiates the random access procedure by selecting the appropriate CE level, by comparing its measured RSRP value with each of the three RSRP threshold values. If the measured RSRP value is less than the RSRP threshold for the CE level 3, then the UE is configured with the parameter values of CE level 3 as defined above. If the measured value is greater than RSRP threshold of CE level 3, and less than RSRP threshold value for CE level 2, then the UE is configured with the parameter values of CE level 2. Similarly, it checks for other levels, until the UE is assigned with an appropriate CE level. After this the UE proceeds to select the random access resources defined by the parameters for each CE level. It is to be noted that there is only one random access procedure ongoing at any given instance in a MAC. Therefore, if a random access is ongoing, and a UE receives a request for another random access, it is up to the UE implementation to continue with the existing procedure or with the new one [19].

For each PRACH coverage enhancement level the following parameter are configured [22]:
- PRACH config index – **Provides information on the periodicity of RACH opportunity and also its time-offset.**
- Frequency offset – **Provides mapping of 6 PRBs in the resource grid of the frequency domain.**
- Preamble Group – **The set of preambles allocated to each level.**
- Number of repetition per preamble attempt – **The repetition value per attempt**
- Starting sub-frame – **The relative sub-frame value at which a fresh attempt can be made.**
- Number of preamble attempts – **The maximum attempt that can be made.**
- Frequency hopping config (if available) – **The configuration required to set frequency hopping feature e.g. activation/deactivation, frequency hopping offset etc.**
- RA Response window time – **The number of sub-frames within which the RAR is expected.**
- Contention resolution window time – **The number of sub-frames within which the contention resolution message is expected.**

In addition to these, there are other parameters such as the number of narrowbands to monitor for RAR and the maximum number of repetition for M-PDCCH transmission specified for each level. The selection of random access preamble resource is not different for low complexity UE type with the normal UE types, except that the resources are chosen as per the preamble-group allocated to the particular CE level, and therefore one preamble is randomly chosen from among the group of preambles. Each random access preamble occupies a bandwidth corresponding to 6 consecutive resource blocks, and there is no change for MTC UE types in the sequence generation mechanism (i.e. from Zadoff-Chu sequences) for the preambles. [23] Once the resource is selected, the UE waits for the appropriate sub-frame number where it is permitted for preamble transmission which is based on the PRACH config index value and starting sub-frame value. Every new preamble
attempt comprises of the number of repetition as per the configuration for a CE level, which needs to be transmitted before a fresh attempt can be made. The illustration in Figure 3.2 provides more clarity on the new solution.

![Figure 3.2: Rel-13 eMTC PRACH requirements, includes the repetition per attempt and maximum attempt for each CE level.](image)

An example configuration for the different PRACH CE Levels is shown in Figure 3.3

![Figure 3.3: PRACH configuration in Uplink channel resources for different CE Levels](image)

If it is not a repetition but a fresh attempt, the UE waits for the permitted sub-frame number based on the starting sub-frame value and PRACH config index value. If it is a repetition of the same preamble attempt then the next available sub-frame which qualifies as a PRACH sub-frame is eligible for transmission. The UE then transmits the preamble with the transmission power similar to the normal UEs and with the power ramping factors as assigned for each cell. However, if the UE is in its Maximum CE level (i.e. CE level 3), it transmits with maximum power for each attempt.

Once the last repetition is transmitted, the UE waits for the RAR to be received by
MPDCCH scheduled PDSCH from the eNB. The UE knows the narrowband (i.e. 6 PRB) it needs to monitor and the corresponding sub-frames for the possible RAR message from its PRACH CE level resource. If a RAR is received, then the UE transmits a RRC Connection request message (Msg3) in PUSCH at the narrowband which was explicitly indicated in the uplink grant of RAR. After transmitting Msg3 it initiates the contention resolution timer. It monitors M-PDCCH for RRC Connection setup message (Msg4) until it receives a message or the contention resolution timer expires. If the contention resolution time expires (i.e. Msg4 is not received), the UE re-attempts preamble transmission retaining its current PRACH CE level. If RRC Connection setup message (Msg4) is received by the UE, the random access procedure is considered a success.

If the UE does not receive the RAR message from the eNodeB within the RAR Window time or if none of the received RAR contains a random access preamble identifier corresponding to the transmitted random access preamble, the attempt is considered a failure. In such a case, the UE re-attempts a new preamble attempt with the same number of transmission repetitions as configured for that particular level. This continues, till the UE exhausts all its attempt of a particular CE level or establishes a successful random access procedure. If the UE exhausts all its attempts, it ‘jumps’ to the next CE level i.e. it assigns itself with the configurations of the next CE level, if there exists any, otherwise it stays in the current CE level and restarts attempting again with a certain back-off period as configured. [19]

Similar to the PRACH CE levels, there are two coverage enhancement modes or levels defined for other channels; CE mode A and CE mode B, which provides up to 15dB of enhancement for other channels by using different enhancement techniques. The CE mode A is considered for lower coverage enhancement requirements, and CE mode B is used when high enhancement is desired for a particular channel. Based on the success of the preamble phase (i.e. Msg1) of the random access procedure, the CE modes are decided for other messages (Msg2 to Msg4) as illustrated in Figure 3.2. If the PRACH CE level is either 0 or 1, then CE Mode A is selected otherwise CE mode B for further communication.
Chapter 4

4 Simulation Model and Assumptions

4.1 LTE System Simulator

The simulation of the system is carried out using a java-based software developed at Ericsson Research. This software is capable of simulating LTE, WCDMA, EDGE and other radio access technologies, and allows for easy integration of different deployment, propagation and network models. It is equipped to provide integration of the entire communication stack with accurate simulation of the PHY, MAC and RLC layers. Different application traffic models can be implemented with this software, and the modular nature of the simulator allows an easy integration of these into the system. The high level block diagram of the simulator structure is represented in Figure 4.1. The data retrieved after the simulation is processed using MATLAB to give the results. The details of the software are beyond the scope of this report.

![High-level block diagram of LTE simulator, and its data flow](image)

Figure 4.1: High-level block diagram of LTE simulator, and its data flow

4.2 Traffic Model

The traffic pattern for the devices is chosen as per GERAN IoT traffic model [4]. The chosen traffic model is well defined and reflects a typical IoT device’s traffic behaviour. Although, there are other types of traffic patterns, the chosen model cover many of the common IoT use-cases. As per GERAN traffic model, there are four different application traffic types to reflect the different traffic behaviour expected for M2M type of communications.

1. Mobile Autonomous Reporting (MAR)- Exception Reports
   As the name suggests these types of UEs will only send reports when an exception event is triggered which they have been programmed to observe. Such events are expected to be rare and may typically occur every few months or even years. These are mainly monitoring type sensors which are event-driven. One of the most important performance requirement for such traffic is its latency which is expected to be within 10s. The uplink payload for such a report is estimated to
be around 20 bytes. An ACK in the downlink will be sent for every such report, and its size is zero bytes at the application layer.

2. Mobile Autonomous Reporting (MAR)- Periodic Reports

Periodic reports are expected to be common where a sensor shall send reports to the server periodically, informing about its current state or the value of its sensor variable. Example of such devices come in the category of monitoring and metering. These reports are self-triggered by the devices based on its configurations and are therefore frequent in number. The model assumes that the server responds with ACK to 50% of the reports. The communication pattern is illustrated in Figure 4.2. The frequency and distribution of the packets sent is defined as per the Table 4.1. The distribution for the sizes of the uplink reports is based on Pareto distribution having minimum size of 20 bytes and the alpha (shape parameter) being 2.5. Any payload size above 200 bytes is considered as 200 bytes. With the above distribution, the mean size of the report is 35 bytes.

![Figure 4.2: MAR- Periodic Reports traffic type](image)

<table>
<thead>
<tr>
<th>Periodicity</th>
<th>%age of UL report</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 day</td>
<td>40</td>
</tr>
<tr>
<td>2 hr</td>
<td>40</td>
</tr>
<tr>
<td>1 hr</td>
<td>15</td>
</tr>
<tr>
<td>30 min</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 4.1: Frequency and distribution of packets sent traffic type

3. Network Command (NC)

The Network Command traffic type is used to model application servers which initiate reporting triggers for the UEs or give commands for some sort of actuation at the UE end. Such traffic is triggered by the network or server, and its frequency is similar to the MAR periodic reporting i.e. Table 4.1. The downlink packet size for such commands is considered to be 20 bytes. For the uplink there are two possibilities, one of which is to respond with reports to 50% of the total NCs, and the remaining 50% response is the ACK with zero bytes as shown in Figure 4.3. The distribution of the report sizes is based on Pareto with the same parameters as for the MAR periodic reports described earlier.

![Figure 4.3: NC traffic type](image)
4. Software update/reconfiguration
It is assumed that the UEs may require some software updates periodically which can be sent as downlink traffic by the network. The frequency of such traffic is estimated to be 180 days, and can also be a planned event. The network will then be loaded with a larger downlink packet whose distribution is based on Pareto distribution having minimum size of 200 bytes and alpha (shape parameter) as 1.5, the maximum cut-off size is 2000 bytes.

The sizes mentioned above does not include the header size of the higher layers, assumed to be CoAP/DTLS/UDP/IP, which is estimated to be 65 bytes in case of uncompressed header, and 29 bytes in case of compressed header. The traffic type 1 is not used for simulation since the traffic load is less and the frequency of occurrence is rare; further, traffic type 4 is not used since the periodicity of occurrence is very rare and it may be a planned event unlike the other traffic types and hence the traffic load is less. Hence, for the sake of simplicity and optimistic assumption, we have used traffic type 2 and 3, i.e. MAR-Periodic Reports and NC, for simulation setup, which will have a significant impact on the system. The distribution of these two types of traffic is considered to be 80%-20% respectively [4], and the distribution of the packet sizes, including the 65 bytes of uncompressed headers (not including PDCP/RLC/MAC overheads- although modelled), is shown in Figure 4.4.

4.3 Deployment and Propagation Model
For the system level simulation, the deployment and propagation model of GERAN scenario 2 [4] is used which is regarded as more challenging than scenario 1 because of higher building penetration loss for higher number of UEs. The building penetration loss is a component of overall path loss, where the devices are kept in deep indoor or in the basement. The relation between the two is given below. 

\[ \text{Path loss} = \text{Outdoor path loss} + \text{Building Penetration Loss} \]

For an enthusiastic reader the building penetration loss model is detailed in Appendix B.
The outdoor path loss model chosen is as per GERAN specification [4]
\[ \text{Pathloss (L)} = l + 37.6 \times \log_{10} R, \]
Where \( R \) is in kilometers, and \( l \) is 120.9 for 900 MHz band.

Other options for the choice of propagation model are 3GPP Case 1 (urban scenario) or Case 3 (rural scenario), which were not selected for simulation since GERAN scenario 2 propagation is typically chosen as a comparison scale for different technologies having similar applications. Further, it is more challenging from coverage perspective since it includes additional indoor losses. In GERAN scenario 2, both external wall loss and internal wall loss are part of the model, and the path loss curve has a longer tail of users in bad coverage area compared to 3GPP Case 3. The distribution of the UEs for the average path gain is shown in Figure 4.5. As can be observed from the figure, this model has a long tail and there are UEs below -155.7 dB.

![Figure 4.5: Distribution of UEs for average path gain in GERAN scenario 2. The long tail beyond -140 dB shows around 9% of the total UEs are in poor coverage.](image)

The deployment of these UEs in a cell are based on the typical hexagonal cell deployment model as shown in Figure 4.6, where,
Therefore, the average number of devices per cell site sector (Nc)
= Area of cell site sector × Household density per Sq km
* number of devices per household

Hence, 

\[ Nc = 52547 \]

This value of Nc is incremented for simulations to estimate the capacity which the system can support. We can assume that the household density per Sq.km increases at a slower rate but the number of devices within a household increases at a much higher rate given the current paradigm of networked society.

### 4.4 PRACH model

The model implemented in the simulator for RACH is based on the specification details as mentioned in the LTE Release 13 eMTC documents [23, 19, 22, 20, 24, 25]. The MAC layer of the channel, is responsible for the control and decision logic of the channel behaviour, whereas the PHY layer controls and satisfies the transmission and reception conditions.

As already mentioned in Chapter 3, the decision on the appropriate CE level will be chosen based on the RSRP value. The measured RSRP takes into account the effects of fading. The decision is made at the MAC layer and subsequently appropriate configuration parameters is selected for the preamble transmission attempt. The parameters such as repetition number, starting sub-frame number, maximum number of attempts, preamble resource values, frequency and time multiplexing locations etc. are configured before the actual attempt can be made. The RAR window size and Contention Resolution window sizes are also configured at this point. The control is then sent to the PHY layer model, for the actual transmission, where a single transmission is attempted. The PHY layer doesn’t expect a response until all the repetition bundles are complete, each triggered by the MAC layer. This marks the completion of a single attempt. Due to repetition, coherent energy accumulation improves the effective SINR, which increases the chances of successful decoding after the last repetition transmission. The error probability of the attempt is calculated by the model as explained in the Assumption section 4.5.

The detailed algorithm for the implementation is described as under:

The RSRP value is ideally measured by the UE and compared with the configured threshold RSRP values for the three levels, if the value is greater than the lowest CE level (CE Level 0) threshold RSRP, the UE is assigned with CE level 0. Similarly, if the measured RSRP values lies between the threshold RSRP of CE level 0 and CE level 1, the UE is assigned with CE level 1, similarly for others. Therefore, with three values of RSRP, all the UEs can be assigned with any one of the CE level parameters to attempt the preamble transmission. The assignment of the CE levels to the UE
allows them to be ready for the Msg 1 (preamble) transmission of the connection setup procedure. The repetition count is incremented by one and the first transmission of the preamble is initiated by giving the control to the PHY layer. The PHY layer checks for the allowed sub-frame number (i.e. starting sub-frame number for the first repetition, and the other repetitions are validated with the allowed preamble transmission spectrum resource or RAO) corresponding to the particular CE level, and initiates the attempt. Similarly, all the repetitions are carried out, till the entire bundle of repetition for the particular CE level is complete. The PHY layer (L1) modelled for PRACH, measures the effective SINR value, and checks for any preamble collision. If there is no collision of preamble between any attempts of different devices in the same spectral resource or the effective SINR does not cause transmission error due to radio channel effects, then the attempt is considered a success and the eNodeB proceeds with the next steps of connection setup. If there is an attempt failure because of any of the above two reasons, then the attempt is considered a failure and the next attempt is initiated by incrementing the attempt counter. This step continues until one of the attempt is a success.

If no attempt is successful and the maximum number of attempt for the corresponding CE level is reached, the UE is assigned with the next higher CE level, and all the parameters are assigned with the corresponding values. Subsequently, the UE starts with the new attempt, after a back-off duration, with the newly attained CE level, till any of the attempt is successful. If the UE is in worse coverage zone, it may be possible that it may reach the last possible CE level (i.e. CE level 3) and after exhausting all the allowed attempts for that level it is yet not able to connect. In such a scenario, the UE will start afresh at the highest CE level, after a certain back-off period. It is worthwhile to mention that if a UE has already been successful in the preamble attempt (i.e. received RAR), but fails in any of the subsequent steps of the random access connection setup procedure, it will restart the preamble transmission with the same CE level it had the last time it succeeded. Additionally, a UE may need to undergo handover when uplink synchronization needs to be established to a new cell, or establish uplink synchronization when the UE is in connected state and uplink or downlink data arrives, in which case it has to re-measure the RSRP value and re-attempt random access procedure. The high level flow chart of the implemented Algorithm for random access procedure is illustrated in Figure 4.7.
Figure 4.7: High-level algorithm flow chart for PRACH preamble attempt
### 4.5 Simulation Setup

There are many standard LTE configurations that need to be done to set-up the appropriate simulation environment. Some of the important environment parameters are discussed here as defined by the deployment and propagation model. It should be noted that although the system bandwidth is 10 MHz (to facilitate the ‘normal’ operation of LTE for all kinds of users), the new low complexity MTC UE which are emulated as Category-M1 UEs will operate with a user bandwidth of 1.4MHz. The frame structure used for simulation is FDD, with carrier frequency of 900 Mhz. The GERAN scenario 2 is deployed for 7 sites each covering 3 cells, making 21 cells in total. Round-robin based greedy algorithm is used for scheduling. The eNB transmitter power is kept at 40W, with two transmissions and receiving chains, and has a receiver noise figure of 3 dB as per GERAN model. The details for some of the system level configurations are listed in Table 4.2.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Parameters</td>
<td></td>
</tr>
<tr>
<td>System Bandwidth</td>
<td>10 [MHz]</td>
</tr>
<tr>
<td>Frame Structure</td>
<td>FDD</td>
</tr>
<tr>
<td>Nr of Cells (Sites)</td>
<td>21 (7 Sites)</td>
</tr>
<tr>
<td>Carrier Frequency</td>
<td>900 [MHz]</td>
</tr>
<tr>
<td>Inter-site Distance (ISD)</td>
<td>1732 m</td>
</tr>
<tr>
<td>Scheduler Algorithm</td>
<td>Round-robin with greedy scheduling</td>
</tr>
<tr>
<td>Highest Modulation Scheme</td>
<td>64QAM (DL), 16QAM(UL)</td>
</tr>
<tr>
<td>Thermal Noise PSD</td>
<td>-174 dBM/Hz</td>
</tr>
<tr>
<td>eNodeB Parameters</td>
<td></td>
</tr>
<tr>
<td>eNB Tx Power</td>
<td>40 W</td>
</tr>
<tr>
<td>eNB Antenna Configuration</td>
<td>2 Tx/2 Rx</td>
</tr>
<tr>
<td>eNB Elevation</td>
<td>30 m</td>
</tr>
<tr>
<td>eNB Noise Figure</td>
<td>3 dB</td>
</tr>
<tr>
<td>MTC UE Parameters</td>
<td></td>
</tr>
<tr>
<td>MTC arrival intensity (per site)</td>
<td>GERAN traffic model (type 2 and 3)</td>
</tr>
<tr>
<td>MTC UE Category</td>
<td>Category M1</td>
</tr>
<tr>
<td>MTC Tx Power</td>
<td>23 dBM</td>
</tr>
<tr>
<td>MTC Antenna Configuration</td>
<td>1 Tx/1 Rx</td>
</tr>
<tr>
<td>UE Height</td>
<td>1.5 m</td>
</tr>
<tr>
<td>UE Noise Figure</td>
<td>5 dBM</td>
</tr>
</tbody>
</table>

**Table 4.2: System level configuration for simulation**

Although the Release 13 specification for MTC targets MCL of 155.7 dB, the simulation is conducted for three different scenarios, to ascertain the impact of different coverage that could be supported by the system. The three scenarios are:

1. This scenario does not have any cut-off for MCL, and the network tries to accommodate all the devices which are able to initiate connection setup. All four PRACH CE Levels are present here.
2. The coverage support cut-off of MCL is 155.7 dB, which includes all four PRACH CE Levels. 0.8% of the UEs are out of coverage.
3. The coverage support cut-off of MCL is 146 dB, which includes only CE Level 0, and 1.4% of the UEs are out of coverage.
It is interesting to note that for the first scenario, in a real system devices in extremely poor coverage zone, i.e. beyond -156 dB of pathgain, would face difficulty in receiving the network configurations for connection setup from the corresponding SIB1-BR. It is still worthwhile to let them attempt connection setup, in order to provide a context for the other simulations, and also a fair assumption can be made that these devices may get the configurations at some point later in time due to energy accumulation from the PBCH (Physical Broadcast Channel).

The data and control flow in the system follows the E-UTRA protocol stack, which is shown in Figure 4.8. The higher layers of the Internet protocols (UDP, CoAP, PDCP etc.) are simplified to allow the passage of the data units without any error probability. The traffic model is emulated in the application layer as mentioned in section 4.2. The MAC and PHY layer are modelled for all the channels (uplink and downlink) as per Release 13 MTC specifications.

![Figure 4.8: Data and control flow of E-UTRA protocol stack as configured for simulation](image)

The PHY layer (L1) modelled for PRACH has a receiver model, which estimates the BLEP (Block Error probability i.e. probability that the transmitted block is going to be in error), from the calculated effective SINR, with the help of the RACH decoding model as shown in the Figure 4.9. The effective SINR is calculated after equalization, which is calculated according to the Minimum Mean Square Error equalizer. The effective SINR value ($\text{SINR}_{\text{eff}}^{\text{rep}}$) is aggregated for each repetition and decoded for error probability which is statistically obtained (with linear extrapolation) from the calculated effective SINR values as shown in Figure 4.10.

$$\text{SINR}_{\text{eff}}^{\text{rep}} = \sum_{i=1}^{\text{rep}} \text{SINR}_{\text{equalized}}^{i}$$

Where, $\text{SINR}_{\text{equalized}} = \left( \frac{1}{\sum_{k=1}^{K-1} \text{SINR}_k} \right) - 1$, $K$ is the total number of PRBs, and $\text{SINR}_k$ is the SINR value calculated for each PRB.
The configuration for RACH related parameters defined for each CE Level are listed in Table 4.3 below. It can be observed that as the CE Level increases, the repetition and attempt values are also increased to overcome coupling loss. It is approximated from previous researches that in an ideal scenario the coupling loss of 3dB can be overcome by doubling the repetition values. Therefore, the choices for the repetition values per attempt for each level to overcome the desired coupling loss are shown in Table 4.3. Since the starting sub-frame values are bound to repetition values as per the specification, a higher repetition value denotes a higher starting sub-frame value, which can decrease the random access opportunity as described below.

The resources allocated to each level is determined by the probability of collision that can be tolerated for a given level based on its arrival intensity. In LTE, the
Capacity Study for LTE Release 13 eMTC

For MTC, RAO can be defined for each CE level, as the product of No. of available Preambles and Attempt frequency (i.e. product of attempts per second and Starting sub-frame) at a single frequency band for an MTC device. Therefore, the probability of collision for an MTC device attempting a preamble is given by the equation [5]:

$$ P_{c,MTC} = 1 - e^{-\frac{\gamma}{L}} $$

Where, $P_{c,MTC}$ is the probability of collision for a device, $L$ is the RAO per sec, and $\gamma$ is the random access intensity per second per cell based on the Poisson arrival rate of the MTC devices, as defined by the traffic model. In the simulation for MTC devices based on Release 13 specifications, $L$ is calculated on the new preamble opportunity which is governed by the starting sub-frame and preamble config index.

To emulate the scenario when the PRACH resources are optimally configured for each CE level to target the desired collision probability, higher value for RAO per second is chosen for the CE levels having higher distribution of UEs. This is a fair assumption since the network, although not aware of the exact distribution of the UEs, can estimate over time that the number of UEs for top two CE levels would be maximum, as compared to a small percentage of very poor coverage UEs which are distributed in the lower two CE levels (i.e. CE level 2 and 3). This will be a typical scenario based on the assumption that the placement of eNodeB in the network is optimal. Therefore, the network decides and broadcasts the resource configurations for each CE level. Hence, in an attempt to provide higher value for RAO per second ($L$), the levels which have a higher distribution of users (e.g. CE level 0 and 1) based on the GERAN deployment and propagation model, have been configured using the standardized parameter of ‘Frequency Offset’ with resources in a separate frequency band (6 PRBs) of 1.08 MHz as shown in Table 4.3. The other two levels are configured such that they share the same frequency band, but differ in the available preamble group in each CE level.

<table>
<thead>
<tr>
<th>CE Level</th>
<th>Available Preamble</th>
<th>Starting Sub-frame</th>
<th>Preamble Config Index</th>
<th>Frequency Offset (PRB)</th>
<th>Nr. Attempt</th>
<th>User (% Distribution)</th>
<th>Target MCL (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1-54</td>
<td>1</td>
<td>3</td>
<td>0-5</td>
<td>3</td>
<td>91.8</td>
<td>140.7</td>
</tr>
<tr>
<td>1</td>
<td>1-54</td>
<td>4</td>
<td>3</td>
<td>12-17</td>
<td>5</td>
<td>4.2</td>
<td>146</td>
</tr>
<tr>
<td>2</td>
<td>1-27</td>
<td>16</td>
<td>6</td>
<td>24-29</td>
<td>7</td>
<td>2.2</td>
<td>151</td>
</tr>
<tr>
<td>3</td>
<td>28-54</td>
<td>64</td>
<td>6</td>
<td>24-29</td>
<td>10</td>
<td>1</td>
<td>155.7</td>
</tr>
</tbody>
</table>

Table 4.3: RACH configuration of parameters for simulation

The bandwidth of the system is 10 MHz, which translates to 50 PRBs in total. The number of attempts for each level is increased linearly, with maximum value for the
highest CE Level. Based on the allocated resource for PRACH in uplink channel, it is found that the PRACH translates to 4.8% of the resources of the uplink channel.

As mentioned earlier in section 4.2, the scenario 2 and 3 of the IoT GERAN traffic model is implemented in the system. The distribution for MAR type of traffic is estimated to be around 80% and for NC type of traffic it is estimated to be 20% [4]. Based on the above assumption and the frequency of the traffic model specifications, the intensity of the generated traffic for $N_c$ number of MTC devices per cell is calculated as shown below:

$$\text{Traffic Intensity /cell /day} = N_c (\text{MAR} + \text{NC})$$

$$= N_c \times (80\% \times (40\% \times 1 + 40\% \times 12 + 15\% \times 24 + 5\% \times 48)$$

$$+ 20\% \times (40\% \times 1 + 40\% \times 12 + 15\% \times 24 + 5\% \times 48))$$

$$= N_c \times (8.96 + 2.24) = N_c \times 11.2$$

From the above equation, we get different intensity of traffic per cell per second for different number of devices ($N_c$) per cell. These values are used for simulation, for a simulation duration of 100 seconds. However, the data observed for the results is obtained after the 10th second to allow the system to be substantially loaded, and the end data is observed up till 100th seconds, but only for users created until 80th seconds, such that those devices which may be abruptly removed from the system after the 100 seconds of simulation time is over, are not considered in the results. The simulations conducted for different intensity of devices is listed in Table 4.4.

![Table 4.4: Different intensities of devices for simulation. Value shown for 21 cells, per cell and also for per sq.km.](image)

*Cell area = 0.86 sq.km

### 4.6 Other Assumptions

The random access preamble format 0 is chosen which has cyclic prefix of length $T_{cp}$ 3168 $T_s$, and a sequence part of length $T_{seq}$ as $24576 T_s$, where $T_s = \frac{1}{15000 \times 2048}$ seconds, as shown in Table 4.5.

![CP and Sequence](image)
The other downlink and uplink channels such as PUSCH, PDSCH, and M-PDCCH has been modelled as per Release 13 specifications, with the exception of PUCCH. It is expected that the impact on results from PUCCH channel would be less since it is not used in the initial connection setup messages and is used to send HARQ ACK no sooner than after Msg4 has been transmitted. Channels such as BCH and Paging are not used, and the relevant configurations provided by these are instead picked from configuration files at the time of simulation.

For the random access mechanism, preamble (Msg1) is modelled and implemented as per Release 13 eMTC specification. The Msg2 (RAR) and Msg3 (RRC Connection Request) are not modelled. However, Msg4 onwards all the messages are modelled as per Release 13 specification for MTC. For LTE, successful completion of one random access procedure means the successful reception of Msg4.

To evaluate the RACH capacity, the simulation is carried out with the presence of only MTC type of devices, and with no background traffic caused by non-MTC type of UEs. The result thus obtained provides an isolated scenario where only MTC users are present in the system, and informs about the capacity that the system can accommodate.

Optimistic model is used at PHY layer, with 3dB gain in SINR for every doubling of repetition especially for UEs in bad coverage zone. After the implementation of RACH repetition, it is found from the PHY layer radio link simulation, that the system behaves as expected, shown in Figure 4.11.

![Figure 4.11: Link simulator results after PRACH implementation with Rel-13 specifications, shows 3dB gain for every doubling of repetition. Result as expected.](image)

### Table 4.5: Random access preamble format [23]

<table>
<thead>
<tr>
<th>Preamble Format</th>
<th>$T_{cp}$ (in $T_s$)</th>
<th>$T_{cp}$ (in ms)</th>
<th>$T_{seq}$ (in $T_s$)</th>
<th>$T_{seq}$ (in ms)</th>
<th>Total Length (in ms)</th>
<th>Number of Sub-frames</th>
<th>Guard Time (in ms)</th>
<th>Cell Radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3168</td>
<td>0.103</td>
<td>24576</td>
<td>0.800</td>
<td>0.903</td>
<td>1</td>
<td>0.097</td>
<td>~ 14 km</td>
</tr>
</tbody>
</table>

Capacity Study for LTE Release 13 eMTC 38
Chapter 5

5 Results and Analysis

The simulation results are presented below, which focuses on the capacity from both the system and RACH perspective. Additional results on performance also gives an indication of the stability of the system. The three simulation scenarios are shown in the results with red, green and blue curves.

The red curve displays the scenario when all the UEs (i.e. even the ones in poor coverage) are allowed to attempt connection setup therefore having all four PRACH coverage enhancement levels. The blue curve only allows those UEs to attempt connection setup which are within the 155.7 dB of MCL limit supported by the network, and comprises of 99.2% of the total UEs. The green curve looks at the scenario when only CE Mode A is supported by the network, and therefore only allows UEs with relatively strong coverage to be allowed to attempt connection setup. Hence, only PRACH coverage level 0 and 1 are present in this simulation result, which results in the MCL limit of around 146 dB for this type of simulation scenario (i.e. green curve), and comprises of 96% of the total UEs.

5.1 System Capacity

The system capacity for the simulation shows varied results for the three different simulation setup discussed earlier. About 3 million users per cell can be supported when 3-4% of the poor coverage UEs are not supported. This figure drops to around 1.5 million users per cell, if these poor coverage UEs are also allowed to attempt connection to the network. From the Figures 5.1 and 5.2, it is observed that for both MAR and NC types of user traffic, 4% of the users are not served when only CE 0 and 1 (i.e. green) are supported and 0.8% of the users are not served when all CE levels are supported (i.e. blue). If all the users are present (i.e. red), the system supports these poor coverage UEs as well for small traffic load. As the traffic intensity increases the system gradually starts dropping users for all scenarios, and it is found that even users which are in good coverage are also dropped for higher intensities of traffic, as shown in Figure 5.3.

| Capacity Study for LTE Release 13 eMTC | 39 |
As shown in Figure 5.1 and 5.2, for the scenario when all users are present, the system shows instability after 1.5 - 2 million devices per cell, as can be observed from the steep rise in user drop rate. These results suggest that the capacity is almost double (around 3 million devices per cell) for limited coverage support compared to the scenario when all users (i.e. additional 3-4% users) are attempted to be served.

![Dropped Users (Scenario: MCL limit -155.7 dB)](image1)

**Figure 5.3:** Dropped users in different scenarios for MCL (i.e. negative pathgain). It is seen that for high intensities per cell, even the good coverage users i.e. below -140 dB, are also dropped. If all users are present this drop is more for the same traffic intensity per cell.

The physical resource blocks of the downlink and uplink channels are used by the UEs, and as the traffic load increases these resources are occupied with more and more data or control information. From the simulation results in Figure 5.4, it can be observed that the downlink channel (PDSCH and MPDCCH) is substantially utilized for up to 60% for 2 million devices per cell when all users attempt connection setup (i.e. red). However, the utilization in the uplink data channel (PUSCH) is significantly lower even for higher intensities.

![Mean: Used subbands in downlink](image2)

**Figure 5.4:** Resource utilization - Downlink (PDSCH+MPDCCH) and Uplink (PUSCH). The resources used nearly doubles due to presence of very poor coverage UEs for the same traffic intensity.

For the scenario where 4% of the users are not present (i.e. green), the downlink utilization rises exponentially after 2.5 million devices per cell, and suggests a possible bottleneck after 3 million devices per cell. The comparison between the scenario when all users are present (i.e. red) and when only CE 0 and 1 are present (i.e. green), shows that resources are nearly doubled, with the inclusion of poor
coverage users (3-4 % of the users). This affects the capacity drastically, and causes around 1 million devices per cell to not be served. The comparison of the scenario when all users are present and when only the very poor coverage users are excluded (i.e. blue) suggests that nearly 20% more resources in downlink and 10% more resources in uplink are used when these very poor or out of coverage users (0.8% of the users) are present and try to attempt connection setup.

5.2 RACH Capacity

The results of the capacity study for RACH channel provides an understanding on the behaviour of the UEs having different coverage requirements while attempting the preamble transmission. To simplify the analysis, the results of different coverage levels are shown separately with the important results for RACH capacity analysis such as success rate per attempt, collision probability for each attempt, attempt number for a successful preamble attempt etc.

5.2.1 CE Level 0

The success rate per attempt of the CE Level 0, is shown in Figure 5.5. It can be observed that the preamble transmission for each attempt success rate gradually decreases as intensity of the random access attempts increases (i.e. more users attempt random access). For high intensity (i.e. around 2 million devices per cell) 20-30% failure probability is observed. Apart from collision, the increased failure rate is due to the radio channel effects and interference as shown in Figure 5.6, which is caused by the presence of many strong coverage UEs close to the eNB, that affects UEs farther away in the same coverage zone. The detail analysis and explanation to this behaviour can be found in Appendix A.

Although these ‘good’ UEs belonging to the strong coverage range of CE level 0, the three scenarios show variations in results for this coverage level. This is attributed to the fact that some of the UEs of stronger coverage level fail in later messages which prompts a fresh preamble attempts (re-connection) for these UEs that adds to the network load and subsequently creates more collisions and interferences. The Figures 5.7 and 5.8 shows the corresponding collision probability and the percentage of the UEs attempting re-connection which shows a slightly higher values, for scenarios when all users are present (i.e. red) or when only very poor coverage users are absent (i.e. blue), than the expected range because of the above stated reasons.

![Success Rate for CE Level 0](image1)

![Failure due to Collision for CE Level 0](image2)

Figure 5.5: Success Rate for CE level 0. High failure rate compounded due to interference
Figure 5.6: Failure due to collision for CE level 0. 50% of the failure is due to interference etc.
50% of the failure is due to collision. In addition, Figure 5.9 shows the distribution of the number of attempts made by the UEs in CE level 0, with high intensity of random access attempts, i.e. around 2.14 M devices per cell, and when all the users are present in the network. It is found that more than 25% of the UEs need more than one attempt to connect, and around 5-8% of the UEs need at least 3 attempts, some of which may also jump to next CE level, which also suggests that more attempts may be required in this level to prevent UEs from jumping to the next level. The average attempt number values from low to high random access intensities is shown in Figure 5.10.

5.2.2 CE Level 1

For the results of this CE Level it can be observed from Figure 5.11 that the success rate per attempt is affected more for higher intensities, since some of the UEs from CE Level 0 jump to this level which causes more collisions and attempt failures. However, since the number of UEs are less in this level the failures due to radio channel effects is minimal as evident from Figure 5.12. The increased collision probability (Figure 5.13) especially for the scenario when all users are present, is also due to the fact that more re-connection attempts are made as shown in Figure 5.14, implying that more failures occur in later messages of the random access procedure due to users in poor coverage levels.
The distribution of the number of attempts in this level for intensity of random access attempts of 2.14 M devices per cell, is shown in Figure 5.15, in the scenario when the very poor coverage users are not present (i.e. blue). It can be seen that mostly all the UEs in this level are able to successfully attempt preamble within the five allowed attempts. However, due to increased collisions more attempts are required for the scenario when all the UEs are present, as evident from Figure 5.16.
5.2.3 CE Level 2

The success rate per attempt is relatively better than other levels, as shown in Figure 5.17. This is because the number of UEs in this level are less and not many UEs have jumped from previous levels thereby not affecting the collision probability, as shown in Figure 5.18. Similar to previous level results the failure due to radio channel effects and interference is minimal. The configured number of repetitions for this level is able to overcome the coverage enhancement that is required, and therefore, mostly all the UEs in this level are able to successfully attempt preamble within the seven allowed attempts as shown in Figure 5.19. The figures do not contain the scenario where only Coverage 0 and 1 are present (i.e. green) since this is CE level 2.

![Figure 5.17: Success Rate for CE level 2. Low failure rate because lot less UEs in this level.](image)

![Figure 5.18: Collision probability for CE level 2. Mostly all failures due to collision.](image)

5.2.4 CE Level 3

The results for CE level 3 is most interesting to ascertain the impact of the poor coverage UEs on the network and the other UEs. The success rate per attempt plot is shown in Figure 5.20, where the difference in curves for the two given scenario shows that the UEs in very poor coverage (i.e. beyond 155.7 of MCL) are mostly unable to connect at all, and hence contribute to the instability of the entire system as they eventually affect ‘good’ users. For higher intensities of random access attempt, when all users are present, the success rate drops down to as low as 10% which shows a clear bottleneck in the network at the preamble stage of the connection setup.

![Figure 5.19: Attempt distribution for CE level 2 with a successful attempt, when all users are present.](image)
procedure. For the scenario where the very poor coverage UEs are absent (i.e. blue) the system is able to support higher intensities with acceptable success rate. It is worthwhile to note that the difference between these two scenarios is the additional 0.8% of the UEs which are out of coverage that are attempting preamble transmission. The Figure 5.21 shows that for low intensities most of the failures is due to radio channel effects as collisions are comparatively less for the scenario where all UEs are present. However, for high intensities, it is seen that the collision increases drastically since more UEs are unable to connect and retry fresh attempts.

![Figure 5.20: Success rate for CE level 3](image)

**Figure 5.20: Success rate for CE level 3.** Very high failure rate due to very poor coverage UEs, when all users are present.

In case, these UEs are not able to connect at all after exhausting all the allowed attempt for this CE Level, they wait for connection setup timer to be expired before they start retrying again with their last attempted CE level. Therefore, adding further to the network load which increases collision as shown in Figure 5.22. The Figure 5.23 shows the re-connection attempts due to failure at later messages of random access procedure. Although the values are expectedly slightly high, the curve for scenario when all the UEs are present is less than the scenario when very poor coverage users are absent (i.e. blue); this is because only a very small number of UE are able to successfully attempt preamble in the first place.

![Figure 5.21: Failure due to collision for CE level 3](image)

**Figure 5.21: Failure due to collision for CE level 3.** For higher intensity, mostly all are collision since many UEs are unable to connect and re-try.

![Figure 5.22: Collision probability for CE level 3](image)

**Figure 5.22: Collision probability for CE level 3.** Collision increases drastically for high intensity, when all UEs are present.

![Figure 5.23: Percentage of users re-connecting for CE level 3](image)

**Figure 5.23: Percentage of users re-connecting for CE level 3.** The UEs reconnecting is lesser since very small number of UE connected in first place.
The distribution of the number of attempts for the scenario when all the UEs are present in the network (i.e. red) shown in Figure 5.24, gives an understanding of the above stated causes of the increased collision. In contrast, the Figure 5.25 shows the distribution of the number of attempts for the scenario when the very poor coverage users are absent (i.e. blue). As evident from the figure, most of the UEs are able to successfully attempt connection setup within the allowed ten attempts for this CE Level. The average attempt number values from low to high random access intensities is shown in Figure 5.26.

![Figure 5.24: Attempt distribution for CE level 3 when all users present. Many UEs unable to connect, and exhaust all available attempts, and re-try.](image1)

![Figure 5.25: Attempt distribution for CE level 3 when very poor coverage users absent. Mostly all UEs eventually have successful attempt.](image2)

![Figure 5.26: Average attempt for all UEs in CE level 3.](image3)

### 5.3 Performance

The performance of the UEs for the simulations are shown in this section, with emphasis on the access delay and throughput. The delay shown is inclusive of the connection setup phase and the data transfer. However, it does not include the synchronization and paging duration, and also does not include the time it takes for the UE to decode the MIB or SIBs to configure itself. The Figures 5.27 and 5.28 shows that the delay is less than 1 second for both MAR and NC type of users, although the performance degrades as the network gets more loaded. The major share
of this delay is by the connection setup procedure which transmits in excess of around 200 bytes of data back and forth before establishing connection as shown in Figure 3.1. This is comparable to around 20 bytes of data traffic for NC downlink command and around average of 35 bytes of data for MAR uplink reports. The sudden stabilizing after 1.5 M devices per cell for the scenario when all users are present is due to the fact that many users are unable to connect and start getting dropped after this point. Further it is also seen from these figures that the UEs in very poor coverage, denoted by the scenario when all users are present, impact the delay performance drastically and also affect the other users, in contrast to the scenarios when these UEs are not present in the network (i.e. blue or green).

The plot for user throughput given in Figure 5.30 and 5.31, shows a gradual decrease for high intensity which is expected, but does not affect the throughput performance drastically. This is because the ‘worst’ users had very low throughput initially when the traffic intensity was less. For high intensities these ‘worst’ users are dropped, which does not contribute much to the drop in average throughput values. It is found that the cell throughput (figure not shown) is not affected by the increased number of devices per cell, but increases linearly since the traffic is very small.
5.4 Reflection

The above results clearly suggest that the system capacity is significantly high with the presence of only MTC type UEs in the network and can accommodate more than 2 million devices per cell with the current LTE Release-13 specification. This is much higher compared to the total number of devices that the system accommodates in the presence of non-MTC UEs with FTP type of traffic. However, UEs which are in poor coverage zone, although in small numbers, impact the network much more than the UEs which are in strong coverage. The resources consumed gets nearly doubled with the inclusion of the 3-4% very poor coverage UEs, and as a result the system capacity is also affected. The bottleneck is seen at the PRACH CE Level 3 UEs for a system where all users are allowed to connect, which also affects the UEs present in good coverage regions. There are nearly 3-4% of such poor coverage UEs in the network which are beyond 140.7 dB of MCL, as per GERAN, out of which 0.8% of them are out of coverage (i.e. beyond 155.7 dB of MCL). These UEs require coverage enhancements to be able to achieve the required pathgain and have high repetitions for each channel which results in high resource usages for poor coverage UEs compared to the UEs which are in good coverage.
From the simulation it is observed that due to the increased number of users the downlink SINR is affected as shown in Figure 5.32; therefore, the probability of failure for some of the later messages increases that causes the UEs to re-attempt connection setup procedure thereby increasing the network load further and causing more collision and congestion in PRACH and other channels. Due to congestion, the poor coverage UEs block the ‘good’ UEs at the network which results in timer expiry or failure for these. For higher intensities even the good coverage UEs are dropped, which brings unreliability to the system.

The throughput performance is not much affected as discussed earlier, but there is a gradual decrease in delay performance and system shows substantial delay for high intensities. Although, the average delay is still less than 0.5 second, which can be useful to provide service to most of the IoT use cases as listed in [26] and in [4] where the tolerable latency is ten seconds. It is found that some of the UEs require more than ten seconds to connect and transmit data which brings unreliability for IoT devices in critical operations. If the network does not support the poor or very poor coverage UEs e.g. CE Mode B types or PRACH CE Level 2 and 3, then the system can support higher capacity and improved performance is observed with more consistency.

A different traffic model with bigger report and message sizes can affect the capacity of the system which can therefore, affect the utilization of the resources as well. Since, it is observed that the PRACH CE level 3 creates the bottleneck for the system capacity, therefore, the factors affecting RACH capacity also impacts the system capacity. In addition to the limited coverage support, the different configurations of the PRACH CE levels affect the RACH capacity which in turn also impacts the system capacity as evident from the results. Therefore, a configuration where more random access opportunity (RAO) can be configured for a particular CE level will reduce the collision probability and hence increase the RACH capacity. However, a trade-off to this scenario is that it would use more resource from the available uplink channel and may affect the cell throughput. Hence, a balanced configuration could be chosen depending on the requirement of the system in question.
Chapter 6

6 Future Work

The work in this thesis focusses on the aspect of Release 13 eMTC specification which among other things deals with the coverage enhancement of PRACH. The implementation of PRACH with the new specification has given further simulation and research opportunities that could target different scenarios and use-cases.

The results obtained in this research also suggests the possibility of a more robust PRACH parameter configurations that could minimize the failures etc. and can accommodate more devices. Therefore, different configurations of the various CE levels can be explored to find a more appropriate setting for the levels.

The RSRP measurement could vary significantly in a fast fading channel and the selection of the initial level is based on measurement of the RSRP value, therefore, to avoid unnecessary CE Level jumps and resource wastage, an alternate mechanism/algorithm to select the initial CE Level for a UE could be studied.

As mentioned earlier, Msg2 and Msg3 could be modelled and included in the simulation and CE Mode A or B could be selected based on the success of the PRACH CE Level. In addition, the PUCCH could be modelled as per Rel-13 eMTC specification for a more realistic emulation of the scenario. However, these change may not impact the conclusions obtained in this study.

Although, the chosen setup and scenario was appropriate for the scope of this thesis, other traffic models and deployment scenario could also be investigated to study the performance and capacity for Release 13 eMTC specification.
Chapter 7

7 Conclusions

This thesis work, apart from the capacity and performance analysis, also gives light to the LTE Rel-13 eMTC specifications of the Physical random-access channel. It illustrates and explains the specification details and how it co-exists with the previous releases.

The complete implementation for LTE Release 13 eMTC PRACH and partial implementation of the GERAN IoT traffic model, helped in modelling the M2M scenario in LTE network more accurately, and hence the results obtained qualify for the properties of integrity, reliability and validity.

The simulation conducted for the capacity analysis gives promising result, and it is observed that a significant large number of devices can be accommodated in the network with a realistic IoT traffic model. Around 2 million devices per cell can be accommodated with good reliability, as per the current specification; and around 3 million devices can be accommodated with better reliability, if devices with stronger coverage is only allowed to attempt connection setup. In addition, it is also found that the poor coverage users (3 - 4% of the total users) nearly double the resource utilization and use more downlink and uplink resources that other good coverage users. Therefore, from the above findings, it is clear that not supporting UEs in poor coverage can be advantageous where UE density is very high (i.e. 2 - 3.5 million devices per cell), or where performance and reliability is needed such as critical infrastructures and usages (e.g. Smart Grids, Tactile Internet, Smart cities etc.), i.e. a trade-off scenario exists.

Sporadic failures of UEs even though some are in good coverage is observed for higher density (i.e. beyond 1.5 million) of UEs in a cell. This suggests unreliable nature for such intensities. This was due to the fact that the UEs in bad coverage tend to slow down (block) the UEs in good coverage during the connection setup phase which may eventually cause more failures.

With a relevant traffic model and if all the users are allowed to connect, the bottleneck is observed at the connection setup phase (i.e. PRACH), which is different from the previously obtained simulations when PRACH was not implemented, that suggested the bottleneck as PDSCH. However, with an optimised configuration and careful dimensioning of PRACH, this could be avoided and the bottleneck could still be the downlink data channel.

Hence, the finding from this thesis work gives new light to the Release 13 specification and equips operators and other stakeholders for an informed business decision.
References


Appendix A

To understand the results for PRACH CE Level 0, an additional experiment was conducted which focused on identifying the cause of failure due to interference. A strong UE closer to the eNodeB can cause significant interference for the UEs which are farther away, because of high relative signal strength for two UEs in the same CE level (i.e. using the same frequency and time PRACH resources). In the uplink, the propagation distance and thus the path loss of the different mobile-terminal transmission may differ significantly [13]. This implies that the possibility of interference can occur from the stronger signal to the weaker signal, and hence they could cause a preamble attempt failure.

To show the above behaviour, two simulations with same MCL limit of 140.7 dB was used (i.e. simulating only CE Level 0). For one of the simulation (marked in black), there was an additional CE level 1, defined in such a way that the two CE level divide the UE distribution in equal halves. The other simulation (marked in pink) uses only one CE level 0 which has all the UEs that could be accommodated in MCL limit of 140.7 dB. Figure A.1 illustrates the setup.

![Figure A.1: Simulation Setup illustration for two simulations (exclusive for CE level 0)](image)

The resources allocated for each simulation is shown in Table A.1, such that the collision probability is same for both the simulations, and the results only displays variations (if any) for failure due to interference only.

<table>
<thead>
<tr>
<th>Total PRB = 50</th>
<th>Available Preamble</th>
<th>Starting Sub-frame</th>
<th>Time offset (ms)</th>
<th>Rach period (ms)</th>
<th>Frequency Offset (PRB)</th>
<th>Nr. Attempt</th>
<th>User (%) Distribution</th>
<th>Target MCL (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CE Level 0</td>
<td>1-27</td>
<td>1</td>
<td>0</td>
<td>20</td>
<td>0-5</td>
<td>3</td>
<td>45.9</td>
<td>121</td>
</tr>
<tr>
<td>CE Level 1</td>
<td>28-54</td>
<td>1</td>
<td>10</td>
<td>20</td>
<td>0-5</td>
<td>3</td>
<td>45.9</td>
<td>140.7</td>
</tr>
<tr>
<td>CE Level 0</td>
<td>1-54</td>
<td>1</td>
<td>0</td>
<td>10</td>
<td>0-5</td>
<td>3</td>
<td>91.8</td>
<td>140.7</td>
</tr>
</tbody>
</table>

Table A.1: Simulation parameters for two simulations. Collision probability same for each.

It can be observed from the results in Figure A.2, that the failure at CE 1 (black), is mostly due to collision as expected since no interference occurs by strong or closer to eNodeB UEs as they are not transmitting in the same RACH opportunity as the UEs.
in CE level 1. However, as evident from Figure A.3, if all UEs are in the same CE level (pink) i.e. transmitting in the same RACH opportunity, the interference from much stronger UEs cause high failure for other UEs.

**Appendix B**

The building penetration loss model is based on the Non Line of Sight (NLOS) model which reflects the attenuation characteristics of both old and modern construction materials. These also include parameters which help to emulate the expected environment for IoT applications. [4]

Therefore, the Building Penetration Loss is given by:

\[
\text{Building Penetration Loss} = \text{External wall penetration loss} + \max((W_i \cdot p), (\alpha \cdot d)) - (n \cdot G_n)
\]

Where,

- $W_i$ is the loss in internal walls (4-10 dB uniformly distributed),
- $p$ is the number of penetrated internal walls (0, 1, 2 or 3, with $p = 3$ also accounting for devices in deep penetration loss e.g. basement),
- $\alpha$ is the penetration distance coefficient (0.6 dB/m),
- $d$ is the penetration distance (range 0-15m),
- $n$ is the floor number (0,1,2,3 or 4) and
- $G_n$ is the floor height gain per floor (1.5 dB/floor)

The External wall loss is modelled as uniformly distributed either in range 4-11 dB, 11-19 dB or 19-23 dB, as shown in the Table B.1 below:

<table>
<thead>
<tr>
<th>Table B.1: Distribution of external wall penetration loss [4]</th>
</tr>
</thead>
<tbody>
<tr>
<td>External wall penetration loss</td>
</tr>
<tr>
<td>Percentage of devices uniformly distributed in range</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>4-11 dB</td>
</tr>
<tr>
<td>25%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Assumptions related to additional penetration loss due to internal walls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of devices mapped to case $p=3$ (with remaining devices equally distributed among cases $p=0,1,2$)</td>
</tr>
<tr>
<td>Assumption for dependency of penetration loss of internal walls of a building.</td>
</tr>
</tbody>
</table>