Performance Evaluation of Mission Critical Communications Services over LTE Networks

Kehinde Olumide Olasupo

Follow this and additional works at: https://repository.fit.edu/etd

Part of the Electrical and Computer Engineering Commons
Performance Evaluation of Mission Critical
Communications Services over
LTE Networks

by

Kehinde Olumide Olasupo

A dissertation submitted to
the College of Engineering at
Florida Institute of Technology
in partial fulfillment of the requirements
for the degree of

Doctor of Philosophy
in
Electrical Engineering

Melbourne, Florida
December 2017
The undersigned committee,
having examined the attached dissertation,

“Performance Evaluation of Mission Critical Communications Services over LTE Networks,"

by

Kehinde Olumide Olasupo

hereby approve to style and content.

Ivica Kostanic, Ph.D.
Associate Professor
Electrical and Computer Engineering
Dissertation Advisor

Carlos Enrique Otero, Ph.D.
Associate Professor
Electrical and Computer Engineering

Susan Earles, Ph.D.
Associate Professor
Electrical and Computer Engineering

Munevver Subasi, Ph.D.
Associate Professor
Mathematical Sciences

Samuel Kozaitis, Ph.D.
Professor and Head
Electrical and Computer Engineering
Abstract

Performance Evaluation of Mission Critical Communications Services over LTE Networks
by
Kehinde Olumide Olasupo

Dissertation Advisor: Ivica Kostanic, Ph.D.

The existing Private/Professional Mobile Radio (PMR) technologies designed specifically for Mission Critical Communication (MCC) systems are narrowband and wideband devices, with limited network data capacity in emergency scenarios. They are majorly used to support MCC voice communications and low data rate applications during mission critical operations. However, the need for broadband systems that would support high radio data capacity keep increasing during major incidents and accident scenarios. Because of this, the MCC agencies were attracted by the broadband capabilities of Long Term Evolution (LTE) technology. But, the uplink capacity of LTE-based MCC systems is still a concern. In planning for improved response in emergency situations, there is need to evaluate the performance of LTE-based MCC systems. This will involve quantifying the uplink capacity and quality of service this system will offer. Therefore, this study describes analytical traffic modeling and simulation approach to model LTE-based MCC networks. The network performance is investigated when it is presented with
heterogeneous data applications during emergency situations. The relation between the traffic load (video, data, and voice, short messaging) and waiting time is presented. ARENA simulation tool is used to show the throughput, waiting time, and resource utilization to be expected when using LTE-based MCC networks. The simulation results are compared with the analytical and 3GPP models. The results demonstrate that the modeled LTE-based MCC cell provides enough uplink capacity to simultaneously serve up to 10 users; each with traffic less than 3.6 Mbps data on the uplink of the LTE-based MCC network. The results from this study can help the network designers in the implementation of equipment and devices that could support MCC services over LTE networks.
# Table of Contents

## Chapter 1: Introduction  
1.1 Problem Statement ................................................................. 6  
1.2 Research Objectives ................................................................... 9  
  1.2.1 Research Approach ............................................................... 10  
1.3 Summary of Research Contributions ........................................... 11  
  1.3.1 Research Impact: .................................................................. 11  
  1.3.2 Discrete Event Simulation (DES): .......................................... 12  
1.4 Dissertation Structure and Layout .............................................. 12  

## Chapter 2: Background and Literature Review  
2.1 LTE-based MCC Network Deployment Process ......................... 15  
2.2 LTE-based MCC Network Deployment Options .......................... 17  
  2.2.1 A Dedicated Network Approach .......................................... 18  
  2.2.2 A Commercial Approach .................................................... 19  
  2.2.3 A Hybrid Network Approach .............................................. 21  
  2.2.4 Deployment Option Used in this Research: ............................. 22  
2.3 Traffic Models of Trunked Dispatched PMR Systems .................. 23  
2.4 Traffic Modelling of LTE-based Networks for Public Safety ....... 25  

## Chapter 3: Private Mobile Radio Technology  
3.1 Existing Private Mobile Radio ...................................................... 26  
  3.1.1 TETRA .............................................................................. 27  
  3.1.2 Project 25 .......................................................................... 31
3.1.3 TETRAPOL .................................................................33
3.2 PMRs for Mission Critical Services .........................................................33
  3.2.1 Mission Critical Voice .................................................................34
  3.2.2 Mission Critical Data .................................................................34
  3.2.3 Mission Critical Video .................................................................35

Chapter 4:  LTE as Broadband Technology for MCC services  37
  4.1 Mobile Broadband: .................................................................37
  4.2 LTE Overview: .................................................................39
  4.3 Benefits of LTE for Public Safety .........................................................41
  4.4 LTE Network Architecture .................................................................43
    4.4.1 Evolved Node-B (eNodeB) .................................................................45
  4.5 LTE Air Interface /Physical Layer .................................................................46
    4.5.1 OFDMA .................................................................47
    4.5.2 SC- FDMA .................................................................48
    4.5.3 LTE Uplink Scheduling Model .........................................................50
    4.5.4 LTE Uplink Physical Channels .........................................................50
  4.6 Traffic Prioritization Mechanism in LTE .........................................................51
  4.7 LTE for Critical Communications .................................................................52

Chapter 5:  Analytical Modeling of LTE-based MCC Networks Capacity  56
  5.1 Overview ..........................................................................................56
  5.2 Traffic Probability distributions in MCC .........................................................57
    5.2.1 Poisson distribution ........................................................................57

vi
5.2.2 Lognormal distribution .................................................................59
5.2.3 Exponential distribution..............................................................60
5.2.4 Normal distribution .................................................................61
5.3 Analytical flow chart: .................................................................62
5.4 Traffic modeling and network deployment process .........................64
  5.4.1 Modeling Traffic Volume: .........................................................65
  5.4.2 Modeling Number of Traffic Channels: ......................................66
  5.4.3 Modeling Broadband Capacity for PSS Traffic Volume and Real Time Operation using LTE Service: ......................................................71
5.5 Results and Analysis: ..................................................................75
  5.5.1 Traffic Volume and Required Trunks: ..........................................75
  5.5.2 Calculating Time and Test of Broadband Capacity: ......................81
  5.5.3 Evaluation of cost of deployment of LTE network for PSC: ............83
5.6 Comparison of Analytical Traffic Simulation Model with Erlang C: ....85

Chapter 6:  Simulation Models and Results  88

  6.1 Theory of ARENA and Methodology ..............................................88
  6.2 LTE-based MCC System Design: ..................................................89
  6.3 Channel Scheduling Algorithm with priority levels: .......................92
    6.3.1 Traditional uplink scheduling algorithm for LTE......................92
    6.3.2 Proposed uplink scheduling algorithm for MCC over LTE ............93
  6.4 Demonstration and simulation Results .........................................97
  6.5 Channel Scheduling Algorithm without Priority levels: .................102
     6.5.1 Demonstration and Simulation Results .....................................102
Chapter 7: Conclusion and Future Work 121

7.1 Summary of Results .................................................................121

7.2 Future Work ............................................................................123

Appendix: Statistical Analysis 124

A. Forecasting Statistics ..................................................................124

B. Research Publications ..................................................................125

Chapter 8: References 126
List of Figures

Figure 2.1: Public Safety Spectrum Allocation in the 700 MHz Band .........................17
Figure 2.2: Deployment of Public safety over mobile broadband ..........................21
Figure 3.1: PMR systems used for MCC services [48] .............................................32
Figure 4.1: Evolution in TETRA and Commercial Cellular Networks (CCN) .....40
Figure 4.2: Basic EPS entities and interfaces [13] .....................................................44
Figure 4.3: E –UTRAN Architecture ........................................................................45
Figure 4.4: Comparison between OFDMA and SC - FDMA [61] ............................49
Figure 5.1: Probability Mass Function of Poisson distribution [70] .......................58
Figure 5.2: Probability Density Function of Lognormal distribution [70] ...........60
Figure 5.3: Probability Density Function of Exponential distribution [70] ........61
Figure 5.4: Probability Density Function of Normal distribution [70] ...............62
Figure 5.5: Flow chart for analytical prediction of LTE-based MCC Network. ....63
Figure 5.6: M/M/C queueing system .........................................................................67
Figure 5.7: Markov process of Birth- death rate ......................................................67
Figure 5.8: (a) Bandwidth capacity deployment plan for TETRA and LTE (b) Queue system for bandwidth capacity in LTE- based public safety network ....72
Figure 5.9: LTE- based Public safety communications (LTE- based PSC) radio air interface ............................................................................................................74
Figure 5.10: Number of trunk versus offered traffic at different grade of service--- .................................................................................................................................78
Figure 5.11: Channel utilization versus probability of delay..............................79
Figure 5.12: Channel utilization versus number of users.................................79
Figure 5.13: Waiting time versus probability of delay.................................80
Figure 5.14: Waiting time versus number of users ..................................80
Figure 5.15: Plot for cost of deployment of LTE network for public safety ....84
Figure 5.16: ANOVA result........................................................................86
Figure 5.17: Plot for Tukey simultaneous data comparison .......................86
Figure 5.18: Plot the Hsu simultaneous data comparison............................87
Figure 6.1: LTE-based MCC network. ..................................................91
Figure 6.2: Uplink scheduling algorithm..................................................95
Figure 6.3: ARENA simulation of MCC load scheduling.........................96
Figure 6.4: Throughput vs number of users.............................................101
Figure 6.5: ARENA simulation of MCC traffic model................................104
Figure 6.6: Traffic generation setting in the ARENA create module........105
Figure 6.7: (a) Traffic processing setting in the ARENA process module (b)
resource setting in the resource module of ARENA.............................106
Figure 6.8: Processed traffic exit setting in ARENA................................106
Figure 6.9: Traffic processing setting in ARENA......................................107
Figure 6.10: Outcomes of simulation from ARENA showing the resource
utilization..........................................................................................109
Figure 6.11: Outcomes of simulation from ARENA showing traffic in, out and
waiting time..................................................................................109
Figure 6.12: Throughput vs simulation time categories. .................................115

Figure 6.13: Simulation time vs Throughput..................................................115

Figure 6.14: Throughput and waiting time vs different cases of probability distributions........................................................................................................116

Figure 6.15: Resource utilization vs simulation time categories. ......................116

Figure 6.16: Waiting time vs simulation time categories. ...............................117

Figure 6.17: Service time vs simulation time. ...............................................117

Figure 6.18: Throughput vs number of users...................................................118
List of Tables

Table 4.1: Number of REs for LTE bandwidths .........................................................50
Table 4.2: 3GPP features for Public Safety .................................................................54
Table 5.1: Traffic Volumes for different Public Safety Network users .....................76
Table 5.2: Different Priority levels and the associated Grade of Service (GoS) ....77
Table 5.3: Simulated Number of Traffic Trunks for LTE-based Public Safety
Network for given SLA ....................................................................................................77
Table 5.4: Comparison between Simulation Model and Erlang C table for Number
of Trunks ..........................................................................................................................78
Table 6.1: ARENA Module Block Symbol and Functions ........................................99
Table 6.2: Simulation Parameters ..............................................................................99
Table 6.3: Simulation Results .....................................................................................100
Table 6.4: Maximum Parameter Comparison ..........................................................100
Table 6.5: Compressed Digital Video for Resolution of 320 X 240 ......................101
Table 6.6: ARENA Module Block Symbols and Functions .....................................104
Table 6.7: Results for 5 Users, 7.2 Mbps each, 20 Secs Service Time, for Different
Traffic Generation and Service Distributions .............................................................110
Table 6.8: Results for 5 Users, 7.2 Mbps each, Different Simulation Times, for
Normal Traffic Generation and Exponential Service Distribution ......................110
Table 6.9: Results for 3 Users, 12 Mbps each, Different Simulation Times, for Normal Traffic Generation and Exponential Service Distribution ......................111

Table 6.10: Results for 1 User, 36 Mbps Different Simulation Times, for Normal Traffic Generation and Exponential Service Distribution ..........................111

Table 6.11: Maximum Parameter Comparison ........................................................112

Table 6.12: Probability distribution comparison using t-statistics .........................113

Table 6.13: Probability distribution comparison using MAPE and MSE .............120
# List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3G</td>
<td>Third Generation cellular radio technology</td>
</tr>
<tr>
<td>3GPP</td>
<td>Third Generation Partnership Project</td>
</tr>
<tr>
<td>4G</td>
<td>Fourth Generation cellular radio technology</td>
</tr>
<tr>
<td>ANOVA</td>
<td>Analysis of Variance</td>
</tr>
<tr>
<td>AS</td>
<td>Application Server</td>
</tr>
<tr>
<td>bps</td>
<td>Bits per second</td>
</tr>
<tr>
<td>CAPEX</td>
<td>Capital Expenditure</td>
</tr>
<tr>
<td>DL</td>
<td>Downlink</td>
</tr>
<tr>
<td>DMO</td>
<td>Direct Mode Operation</td>
</tr>
<tr>
<td>DR</td>
<td>Data Rate</td>
</tr>
<tr>
<td>EDGE</td>
<td>Enhanced Data Rates for GSM Evolution</td>
</tr>
<tr>
<td>EMS</td>
<td>Emergency Medical Services</td>
</tr>
<tr>
<td>eNodeB</td>
<td>Evolved Node B</td>
</tr>
<tr>
<td>Acronym</td>
<td>Full Form</td>
</tr>
<tr>
<td>----------</td>
<td>----------------------------------------------------------------</td>
</tr>
<tr>
<td>EPC</td>
<td>Evolved Packet Core</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-UTRAN</td>
<td>Evolved Universal Terrestrial Radio Access Network</td>
</tr>
<tr>
<td>FCC</td>
<td>Federal Communication Commission</td>
</tr>
<tr>
<td>FDMA</td>
<td>Frequency Division Multiple Access</td>
</tr>
<tr>
<td>FIFO</td>
<td>First In First Out</td>
</tr>
<tr>
<td>FirstNet</td>
<td>First Responder Network Authority</td>
</tr>
<tr>
<td>GB</td>
<td>Gigabyte</td>
</tr>
<tr>
<td>GoS</td>
<td>Grade of Service</td>
</tr>
<tr>
<td>GSM</td>
<td>Global System for Mobile Communication</td>
</tr>
<tr>
<td>HSPA</td>
<td>High Speed Packet Access</td>
</tr>
<tr>
<td>IP</td>
<td>Internet Protocol</td>
</tr>
<tr>
<td>kbps</td>
<td>Kilobits per second</td>
</tr>
<tr>
<td>LMR</td>
<td>Land Mobile Radio</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>LTE</td>
<td>Long Term Evolution</td>
</tr>
<tr>
<td>MBMS</td>
<td>Multimedia Broadcast/ Multicast Service</td>
</tr>
<tr>
<td>Mbps</td>
<td>Megabits per second</td>
</tr>
<tr>
<td>MCC</td>
<td>Mission Critical Communications</td>
</tr>
<tr>
<td>MCPTT</td>
<td>Mission Critical Push To Talk</td>
</tr>
<tr>
<td>MCUE</td>
<td>Mission Critical User Equipment.</td>
</tr>
<tr>
<td>MIMO</td>
<td>Multiple Input Multiple Output</td>
</tr>
<tr>
<td>M-M</td>
<td>MOBILE to Mobile</td>
</tr>
<tr>
<td>MME</td>
<td>Mobility Management Entity</td>
</tr>
<tr>
<td>MNO</td>
<td>Mobile Network Operator</td>
</tr>
<tr>
<td>OFDM</td>
<td>Orthogonal Frequency Division Multiplexing</td>
</tr>
<tr>
<td>OFDMA</td>
<td>Orthogonal Frequency Division Multiple Access</td>
</tr>
<tr>
<td>OPEX</td>
<td>Operational Expenditures</td>
</tr>
<tr>
<td>P25</td>
<td>Project 25 digital radio</td>
</tr>
<tr>
<td>P- GW</td>
<td>Packet Data Network Gateway</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>PMR</td>
<td>Private Mobile Radio</td>
</tr>
<tr>
<td>PPDR</td>
<td>Public Protection and Disaster Relief</td>
</tr>
<tr>
<td>PRB</td>
<td>Physical Resource Block</td>
</tr>
<tr>
<td>PRACH</td>
<td>Physical Random Access Channel</td>
</tr>
<tr>
<td>PTT</td>
<td>Push to Talk</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>QCI</td>
<td>QoS Class Identifier</td>
</tr>
<tr>
<td>QoS</td>
<td>Quality of Service</td>
</tr>
<tr>
<td>RAN</td>
<td>Radio Access Network</td>
</tr>
<tr>
<td>RNC</td>
<td>Radio Network Controller</td>
</tr>
<tr>
<td>SC-FDMA</td>
<td>Single Carrier Frequency Division Multiple Access</td>
</tr>
<tr>
<td>S-GW</td>
<td>Serving Gateway</td>
</tr>
<tr>
<td>SISO</td>
<td>Single Input Single Output</td>
</tr>
<tr>
<td>SLA</td>
<td>Service Level Agreement</td>
</tr>
</tbody>
</table>

xvii
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEDS</td>
<td>TETRA Enhanced Data Service</td>
</tr>
<tr>
<td>TETRA</td>
<td>Terrestrial Trunked Radio</td>
</tr>
<tr>
<td>TETRAPOL</td>
<td>TETRA for Police</td>
</tr>
<tr>
<td>TDMA</td>
<td>Time Division Multiple Access</td>
</tr>
<tr>
<td>TTI</td>
<td>Transmission Time Interval</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 Telecommunication System</td>
</tr>
<tr>
<td>X2</td>
<td>Interface between eNodeBs</td>
</tr>
</tbody>
</table>
Acknowledgment

I thank God for giving me the privilege of completing my PhD degree at a reputable institution such as Florida Institute of Technology. Through the months I have been working on this project, He has been my source of strength. I owe my life and health to Him.

I am indeed grateful to my advisor, Dr. Ivica Kostanic whose encouragement, direction and support from the initial to the final stage enabled me to develop an understanding of the subject of this research. I am delighted to work with you as you set an example of an excellent researcher by your rigor and passion on research. His guidance helped me in all the time of research and writing of this dissertation. I could not have imagined having a better supervisor for my PhD study. Also, Dr. Carlos Otero deserves special thanks for his support for me and my family and for being a member of my dissertation committee. I will like to appreciate Dr. Susan Earles for her guidance in my final defense and Dr. Munevver Subasi for taking time out of their tight schedules as members of my dissertation committee. Special thanks to the head of Electrical Engineering in person of Prof. Samuel Kozaitis for his constant support in all my teaching assistantship activities.

I am very much grateful to my husband (best ever!) for making my PhD journey easier through his guidance in helping me to overcome many of the difficulties I encountered over the duration of this research. I will use this medium to appreciate my God’s given seed: my triplets- Gloria, Glory and Golden. You have been so wonderful and highly encouraging throughout my study. God keeps you all
in His grace and wisdom.

My deepest gratitude goes to my mother, Pastor (Mrs.) Deborah Adejumo for her love, support, encouragement and for believing in me all these years. Words cannot express how grateful I am for all you have done for me. To my siblings: Adesoji, Taiwo and Bisola: thanks for being the best siblings a sister can have. My fondest memories of growing up with you will always be with me. To my wonderful in-law, Dr. Feyisola Awonuse and family, thanks for your financial support and encouragement. Also, special appreciation to my parent - in - law, Mr and Mrs S. B. Olasupo, for their support and prayers during my study.

I want to express my gratitude to every member of RCCG, victory parish, Melbourne, Florida. I want to say that joining victory parish was not only a turning point in my life, but also a wonderful experience. I cherish the prayers, support and friendship with my Christian brothers and sisters. Thank you all.

I would like to acknowledge the department of Electrical Engineering and Computer Engineering, Florida Institute of Technology for granting me the graduate teaching assistantship to study for my PhD degree. Without their support, my ambition to study to PhD level can hardly be realized.

Lastly, to everybody that has been a part of my life but I failed to mention, thank you very much. There will not be enough space if I will mention you all.
Dedication

To:

My darling husband, Olawale Olasupo for his unconditional love and consistent support.

My beloved Triplets, Gloria, Glory, and Golden. You are my joy!

The memory of my father, Jewoade Adejumo (God bless his soul)

My mother, Deborah Adejumo, for her love, prayers, unending support and inspiration.
Chapter 1: Introduction

The growth of mission-critical communication networks for public safety has increased significantly in recent years around the world. Mission-critical communication as defined by TETRA and Critical Communication Association (TCCA) is “special communications systems where the reliability, availability, stability and security of mobile communication is vital to ensure continuous availability of functions critical for society or a function whose failure leads to catastrophic degradation of service that places public order or public safety and security at immediate risk [1]”. Mission-critical communication systems must be resilient and highly available, reliable, secure and should be able to support point-to-multipoint communications. In public safety and mission critical operations, the users in the field depend on effective communications for their safety and effectiveness. Both the transmitting and the receiving ends of the voice link should be able to clearly understand each other because minor errors in a voice call at critical times can be costly. Mission-critical communication users can be categorized as those whose daily operations are to ensure safety and welfare of people around the world. These include Public Safety (police, fire fighters and emergency medical services) agencies. Some other users of MCC are the intelligent and battle field operators, transportation sectors (buses, taxis, trains, airports and ports), utility companies (gas, electricity, water), alarm companies, and voluntary organizations
active in disaster. The primary user of MCC is the public protection and disaster relief (PPDR) agencies like the police, fire fighters and emergency medical services (EMS) [2, 3]. These primary users are also referred to as the First Responders.

The major users of MCC networks and their functions during emergency scenarios are highlighted below [4]:

- **Police agencies** pursue the achievement of a safe and secure environment for the community. They achieved this through investigation of criminal offences, response to life threatening situations, and provision of road safety and traffic management. Police agencies also assist the judicial process by providing custody services.

- **Fire service organizations** work to minimize the impact of fires, which include structural fires, grassfires and bushfires, and vehicle and other mobile property fires. Fire services are also involved in search, rescue and recovery operations, fire prevention activities, and building community resilience.

- **Ambulance service organizations** prepare for, provide and enhance: pre-hospital and out-of-hospital patient care and transport; inter-hospital patient transport; specialized rescue services; ambulance services to multi-casualty events; and capacity building for emergencies.

- **State Emergency Services (SES)** help communities prepare for, respond to, and recover from unexpected events, such as road accidents, floods, earthquakes, cyclones, and search and rescue.
• Marine rescue and coast guard organizations provide marine rescue, boating safety and communications services.

During response in mission-critical operations today, the PPDR services and other first responders utilize Private Mobile Radio (PMR) such as TETRA, TETRAPOL and Associated Public Safety Communication Officials (APCO) Project 25 for mission critical voice communications. These systems are narrowband and initially designed to support voice and low bit data rate services. PMR networks are designed to meet emergency responders’ unique mission-critical requirements and provide guaranteed priority access to responders. In addition to PMR, some emergency responders are using mobile data services and applications provided by commercial carriers to share information and supplement their mission critical voice capabilities [5].

TETRA, a digital PMR system was developed by the European Telecommunication Standards Institute (ETSI) to create a more efficient and flexible communication services for PMR users. Telecommunication standards for TETRA is published by ETSI in 1996 and are being used in Europe and now globally deployed especially in emergency cases [6]. Short data messages and speech call can be sent and received simultaneously by TETRA. In order to meet the needs of mission critical communication users, some of the unique features of TETRA standard were [7]:

3
• Group calls (wide area fast call set-up)
• Direct Mode Operation (DMO) allows communications between radio terminals without the intervention of network infrastructure.
• High level voice encryption to meet the security needs of public safety agencies
• Priority call (an emergency call facility that gets through even if the system is busy)

New features and services will continue to be added to TETRA in the future as cellular mobile networks are continuously evolving. There is a clear difference between TETRA-based networks and commercial cellular networks as the operational needs of the users for the two networks are different. TETRA systems make use of ‘Push-to Talk’ (PTT) radio systems, and also possess distinct security property such as end to end encryption, field control by a dispatcher type of capabilities as well as trunking (switching) capability that make it different from cellular systems [8]. Also, there are some important TETRA requirements such as DMO, group calls, priority calls etc. that cannot be provided by the commercial mobile cellular networks. TETRA networks are designed to support data rates compared to the second generation (2G) commercial cellular networks such as Global System for Mobile Communication (GSM) and General Packet Radio Service (GPRS). When disasters and emergencies occur, response organizations and government public safety agencies need broadband data services to deliver real-time updates of events, start relief operations, and provide continuing assistance in the
affected regions. Now, in supplement to voice, public safety organizations are using voice and data. These new services place higher demand on the network and tremendously increase the traffic capacity. Hence, there is a need for broadband systems that support high data demanding services. There are various suggested options to handle increase in the traffic volume. Presently, Long Term Evolution (LTE) and LTE-Advanced; a generation of the mobile broadband technology after 3G technologies with much higher data rates of 100 Mbit/s (Release 8 and 9) and 1Gbits/s (Releases 10 - 13) standards for mobile broadband is being recognized as the technology of choice for the future PPDR communications [9]. Also, technical work is currently being carried out within the 3rd Generation Partnership Project (3GPP) - the organization in charge of LTE standardization – to further improve the capabilities and features of LTE standard which will make it suitable for the requirements of PPDR and other professional users [10].

LTE, a standard for mobile phones and data terminals is based on the GSM and Universal Mobile Telecommunications Systems (UMTS) network technologies. It is an Internet Protocol (IP) - based systems designed to cope with the challenges of the growing broadband mobile market. LTE is continuously evolving to meet the needs of industry demands through 3GPP standardization activities. This permits the mission critical communication personnel to take the advantage of LTE as mobile broadband networks for real – time data updates on incidents, high quality video streaming, and quick response during emergencies and day-to-day activities. By doing so, the situation awareness will be improved and safety of first responders will
be better. Also, mission-critical communications over LTE networks will allow the use of many multimedia services such as text, voice, video, file/picture sharing etc. with quality, resilience and reliability [11].

In order to guarantee the performance of MCC over LTE networks, detailed analysis of the traffic characteristics is crucial. Presently, there is limited research on good traffic modeling for accurate capacity planning for MCC over LTE networks either by simulation or measurement. This research thereby aims to develop a traffic model for an optimal mission-critical voice communications network over LTE in terms of number of channels, delay probability and number of users in the network to guarantee the service level requirement (SLR) for the network. In addition to this, packet data characterization of the network and link performance modeling of the network for mission critical services is investigated.

1.1 Problem Statement

There has been much concern on the need for performance evaluation of MCC over LTE networks in terms of capacity. Why is this an issue?

In the existing MCC technology, we have already the statistics for the first responders when they show up during major incident or accidents scene. There is enough capacity to support the traffic needed which is voice centric with low data applications. There is no issue at all with voice capacity.

Now, for mobile broadband with heterogeneous traffic (voice, video and data), the network capacity is not yet guaranteed. It is quite possible that when the first responders come to an incident scene, everybody turns on their video cameras for
live video streaming and transmission to dispatch center. This will definitely bring down the communication network.

In order to prevent this from happening, there is need to establish some rules or procedures that have to be followed. So we know, for example, for police, there is a decision maker (might be dispatcher from the control room) that will approve every video communication or there is a software that can prevent the first responders from turning on video if it is not approved. This will disallow simultaneous running of more than the required videos as to avoid traffic congestion. Though, they may still record video and await further instruction on when to upload.

Presently, there is no established process for management of capacity on the radio interface. All what we have is LTE network and nothing is preventing anyone from turning on the video or control channel access for live video streaming and transmission. Also, LTE is capable of 100Mbps in the downlink and 50 Mbps in the uplink, and most of our videos are downloads. We do not upload videos often. In the MCC, reverse is the case, more of videos are uploads than downloads. So there need to be some rules of engagement or some procedures that need to exist to prevent traffic congestion.

Similarly, a number of characteristics of mobile broadband service quality are important to MCC users. These include the ability of MCC users to get connected to a mobile network, probability of waiting if they are not connected to the network resources, and ability of authorized users to have preferential access by making use of user prioritization mechanisms. For instance, if first responders show up at an
incidence scene and each with different level of priorities; the highest priority will be given to the emergency medical services. This is because there might be an assistance needed to save lives.

In planning for all these responses, we need to be able to quantify the capacity, quality of service (QoS) and performance of MCC over LTE.

In this research, the focus is on a single eNodeB cell because unlike the commercial networks where the capacity is distributed across wider area. Here, we have an emergency situation that will typically happen around one location and will be served by one or two cells. The study simulates different type of events and investigates the system’s behavior when presented with heterogeneous traffic. The research comes out with suggestions on how to make the procedures work and how we can communicate in this network during emergency situations.

Couples of literature are reviewed and did not find any substantial publications that talk about MCC services over the upcoming LTE networks. This is not a surprise at all because the final specifications for MCC video and data services would be completed in June 2018 [12]. The vendors are still finalizing the manufacturing and implementation of the equipment and devices that could support the MCC services over LTE. This study in this respect is timely, because there is no sufficient publications yet in this particular area. There are some publications on traffic analysis of trunked dispatch PMR systems. They do not support high data services.

What we have now is a technology that is still being built and still being standardized, but there is no much research on its performance. We are still in the investigating
stage. What is done in this research is building an event based simulator that allows running of different scenarios of MCC and analyses its performance.

1.2 Research Objectives

In order to solve the above problem, there are some questions that are answered in this research. Hence, the objective of the research in this dissertation is:

- To investigate the broadband air- interface capabilities of LTE – based MCC Networks.
- To properly dimension mission critical traffic over LTE, the following questions are answered:
  a. How many voice call can the deployed network support?
  b. How many simultaneous video can the deployed network support?
  c. What type of combinations of traffic is expected on the network?
  d. How would the mission critical packet data be characterized on the network?
  e. How long can the priority calls be in the queue?
- To evaluate performance of the network in terms of number of required traffic channels, channel utilization, delay probability and message delivery ratio.
- To develop the link performance model for MCC over LTE networks
• To provide a realistic traffic model that would predict future performance of MCC over LTE networks

1.2.1 Research Approach
In order to accomplish the goals of these objectives, the following method or approach is used:

Task 1 Literature
• Research into different PMRs for MCC services.
• Research into various options for LTE as an alternative for MCC services.

Task 2 Traffic models
• Research in the area of types of traffic model to be used to understand the flow of traffic in the network and determine how closely the model would describes the real-time characteristics of the network.
• Develop analytical traffic models for heterogeneous traffic in MCC over LTE networks

Task 3 Discrete event simulation of traffic
• Develop event simulator for MCC traffic over LTE network.
• Use several MCC scenarios for simulations.

Task 4 Traffic Model Verification, Validation and Reliability
• Validate the analytical voice traffic model by comparing with Erlang C, Tukey, Hsu, MSE and MAPE.
• Validate the simulation model by comparing with analytical model.

The computer-based simulation tools used in this research are ARENA, Matlab and Minitab. The scenarios for traffic modeling are obtained from European Telecommunications Standard Institute (ETSI) Technical Report [13] and typical PPDR incidence peak data rate from [14].

1.3 Summary of Research Contributions

1.3.1 Research Impact:

Carrying out a sufficient and viable research work to answer the above questions would help in accurate design and planning of LTE networks for MCC services.

Investigating the capability of LTE for MCC would provide better performance prediction of the network. Emergency and public safety agencies would benefit by improving their situation awareness during major incidence and accident scenarios. Also, the outcome of this research would improve their working methods, since we can predict in advance what the capacity of LTE-based MCC network will be.
1.3.2 Discrete Event Simulation (DES):

This study presents the theory and one of the practical applications of DES modeling and simulation. This is achieved with Arena simulation tool. The methodology of the research can be useful to the academic communities and other users of DES.

1.4 Dissertation Structure and Layout

This dissertation gathers and summarizes research outcomes of the PhD project on the future MCC technologies. MCC services require various types of broadband applications. This PhD research is concerned on the acceptable capacity for heterogeneous traffic on the future LTE-based MCC networks. The content is based on research work that has been published in Journal and conference papers (see the Appendix).

The rest of the dissertation is organized as follows:

- Chapter 2 describes the background of MCC networks and reviews some literature about the study.
- Chapter 3 introduces common types of the existing PMR technologies for mission critical applications and services. The main shortcomings of the existing PMRs are identified and analyzed.
- Chapter 4 discusses LTE as an alternative technology for mission critical applications and services. This is the main focus of this dissertation. The
main motivation and targets of LTE are explained. Then, the LTE network architecture with each of the LTE entities are described in details. In addition, the LTE quality of service bearer concepts are discussed. The shortcomings of PMRs are used as the starting point for a discussion on the LTE-based MCC network. One of the main reasons of LTE for mission critical services is high data applications capability. Therefore, high data transmission (e.g. video) performance over LTE is investigated in a series of simulation scenarios. The performance obtained by LTE is compared with the 3GPP requirements for public safety.

- Chapter 5 presents the detailed analytical models of LTE-based MCC networks. The models are based on queuing theory, Markov chain. Furthermore, this chapter explains the different traffic distribution models used in this work with their corresponding parameters. Finally, the results obtained is compared with Erlang C and the 3GPP standard respectively.

- Chapter 6 presents the design and development of the detailed LTE-based MCC network simulator developed in this dissertation work. The LTE–based MCC network simulator is implemented using ARENA simulation tool for heterogeneous MCC traffic in emergency scenarios. Its performance is investigated, and validated and compared with the requirements set by the 3GPP. The results of the analytical models in chapter 5 are compared with these simulation results.
Chapter 7 gives the overall conclusion of the dissertation, highlighting all the main points and research impact. Finally, an outlook on the future work on LTE-based MCC services is given.

In addition, there are two appendices attached to this dissertation. The first presents the details of the statistical analysis used for validation of the analytical and simulation results. The last appendix gives the list of all publications on this research.

- Appendix A includes forecasting statistics used for validation of results.
- Appendix B gives the lists of all publications.
2.1 LTE-based MCC Network Deployment Process

There is no sufficient work in term of simulation or practical demonstration of deployment of LTE-based public safety network in literature. There are couple of white papers and technical reports that present various deployment options [15]. The process of deploying mobile broadband for public safety started in USA. The National Public Safety Telecommunications Council (NPSTC) and other organizations acknowledge the need for next generation public safety networks with broadband capabilities. Initially, in July 2007, 2 X 5 MHz spectrum was allocated by the FCC, designating the lower half of the 700 MHz (763 – 768 / 793 – 798 MHz) for broadband communications. This spectrum has been cleared by the Digital Television and Public Safety Act of 2005.

In early 2009, congress directed the FCC to develop a National Broadband Plan, including recommendations for a dedicated public safety broadband network. Later in 2009, LTE was chosen by the public safety agencies as the primary technology for the broadband network. In March 2010, the FCC released the National Broadband Plan (NBP), which made significant recommendations for improving access to broadband communications across US. The plan gave a recommendation for the utilization of 10MHz of dedicated 700 MHz spectrum in the upper D block. The allocation is illustrated in Fig. 2.1. In 2012, congress passed the middle class tax
relief and jobs creation Act of 2012, which re-allocates the D Block (700 MHz spectrum adjacent to the existing public safety block) to public safety and allocates $7 billion of incentive auction proceeds to the build out of a nationwide, interoperable public safety broadband network. An additional 2 X 5 MHz was allocated to the dedicated broadband spectrum, extended from 758–768 MHz and 788–798 MHz for LTE-based public safety networks. The Act also created the First Responders Network Authority (FirstNet) and all the responsibilities assigned to the FirstNet for effective coordination [16], [17]. Currently, many other government organizations are proceeding to make use of LTE networks for public safety communications and services [4, 18].
FCC allocated spectrum to public safety for broadband data services

Commercial Mobile Carriers

**Figure 2.1:** Public Safety Spectrum Allocation in the 700 MHz Band

### 2.2 LTE-based MCC Network Deployment Options

There have been many reports on the possibility of deployment of LTE networks for public safety. In [15], the white paper presents four options for the implementation of public safety mobile broadband capability. Also, it considers how the combinations of these options may provide a comprehensive capability. The options include: taking service from an existing commercial mobile network operator (MNO), operating as a mobile virtual network operator, taking service from a
commercially owned dedicated network, and building, own and operate a dedicated network. The white paper also suggests the combination of these options. In the same vein, various options for delivering new generation of public safety devices [19], [20], [21], [22] are discussed.

The comprehensive report given in [4, 15] discusses various deployment options, including deploying a dedicated network approach, an approach relying on commercial networks, or a combination of two (hybrid approach). The implementation plans are on-going in many organizations of the world. The United States, South Korea and Canada are implementing dedicated approach. The commercial approach would be implemented by Belgium, United Kingdom, and New Zealand governments respectively. Also, Finland is planning to implement the hybrid approach.

2.2.1 A Dedicated Network Approach

This form of approach would mean that MCC agencies have access to and control over their own broadband network which is constructed and operated to a given set of MCC standards and requirements. In order to reduce capital deployment costs, a dedicated approach would likely involve leveraging existing network infrastructure owned by MCC users, governments and commercial mobile carriers. The infrastructure such as mobile sites and backhaul transmission could be leveraged. Though, a dedicated network would require its own dedicated radio frequency spectrum. These dedicated networks have been built for the exclusive use of MCC services (or to a few number of government agencies) and have been designed
specifically to meet their needs. The networks will be owned and operated by the
corresponding government agency. However, MCC agencies do not always own
these networks themselves. A wireless mobile company can own, operate and
manage the networks, but will be designed specifically to meet the requirements of
MCC

The primary advantage for this option is that the critical communications users
and national Government have full control over the procurement process, the
network procured and the operating assets. The users will have complete control over
the network management, thus ensuring that, through the use of priorities, the
capacity on the network can be managed and tailored to changing circumstances. In
emergency situations, the operator can ensure that those who need the service will
not be blocked by overload from the general public.

2.2.2 A Commercial Approach
A commercial approach is when the MCC users obtain services from one or more
mobile carriers through a contract for service. The mobile carriers would determine
how best to meet public safety requirements using their own mobile networks and
spectrum holdings. When using commercial approach, the MCC users are
essentially like any other customers. This approach would not involve any dedicated
spectrum for MCC agencies, but would require mobile carriers to adapt their
networks to meet the higher quality requirements implicit in a public safety mobile
broadband capability. The MCC users may negotiate priority access to the network in certain situations.

This deployment scenario is integrating public safety network over mobile broadband. The easiest and probably the cheapest option is the public safety network taking service from an existing commercial MNO. The deployment option of integrating public safety over mobile broadband is shown in Fig. 2.1. The Application Server (AS) of the existing public safety network is connected to the Packet data network gateway (PGW) of LTE. Currently, LTE networks already exist in many countries and public safety users can make use of this opportunity. The option can also be a cost effective solution in the sense that there will be low CAPEX on infrastructure. Also, operational expenditures (OPEX) will be low since the network would be supporting commercial users as well as public safety users. The main disadvantages are that the MCC users have no control over the coverage, availability or resilience of the network. The network is a standard commercial network, which will be designed to meet commercial imperatives. Many core elements of a commercial network, such as Home Location Register, are not resilient, and many failures have occurred resulting in loss of service for several hours at a time. Sites may not be protected against power failure, which makes the network totally unsuitable for a power utility and generally unsuitable for many other critical users.
2.2.3 A Hybrid Network Approach

A hybrid (combination) approach would involve elements of both the dedicated and commercial approaches. This could take various forms. For instance:

- Constructing and operating a dedicated network for a targeted coverage area (with dedicated spectrum), and using mobile carrier networks and other options elsewhere.

- Integrating dedicated spectrum into an existing mobile carrier’s network, such that MCC agencies have a ‘dedicated portion’ on the network, and the ability to overflow to a mobile carrier network as required.

Some advantages have been identified for the hybrid approach. Firstly, it addresses the problem that preferred solutions may not be available for some time to come, whether it is through spectrum, functionality or funding issues. Secondly, the various
combinations described above provide the users with considerable flexibility. In particular they will be able to experiment with the use of broadband mobile data and determine which applications or pieces of functionality are the most important and that need to be addressed in a later solution. Additionally, a combination approach would enable agencies to benefit from some broadband services whilst waiting for the full Critical Communications functionality to become available.

The major disadvantage of this approach is that this approach would require more resources to manage and greater expertise to bring these solutions together since the approach is based on multiple solutions. With a solution involving multiple elements, it will be more difficult to negotiate value for money contracts with potential suppliers, thus resulting in increased costs in the long term. Finally, multiple solutions provided by different suppliers may make it more difficult to organize cross-border and multi-agency solutions [15].

### 2.2.4 Deployment Option Used in this Research:

Public Safety networks designed as standalone networks that are usually deployed by the government to assure privacy and security of the networks is the assumed network for the simulation in this research. Deployment of networks in this way is often costly as high quality, high reliability and security are required. The dedicated deployment option for LTE for public safety is for the government to build, own and operate the network. Consequently, the government would have the full control of the network. Therefore, the dedicated LTE-based MCC network forms the basis for all simulation scenarios analyzed in this dissertation.
2.3 Traffic Models of Trunked Dispatched PMR Systems

A prerequisite to conducting research on the performance analysis of any wireless MCC mobile network is a traffic model that characterizes the voice, data, and video transmissions on the network. A number of traffic models have been proposed in the literature for analysis of public safety scenarios using the existing narrowband PMR devices. One example is the traffic analysis carried out on an incident- response scenario based on the 2007 collapse of the Interstate 35 bridge in Minneapolis, Minnesota [23].

The authors in [24, 25] carry out analysis of telephone voice conversations in 1960s and discover that on and off periods of voice are exponentially distributed. The group communications in land mobile radio systems is analyzed in the 1980s by the authors in [26, 27]. They derive models to be used in the design of the new trunked radio systems. They characterize the session length and inter-arrival times to be exponentially distributed. The authors recommend the use of Erlang C model. The results obtained from the model were confirmed by the Public Safety Advisory Committee in [28]. In the same vein, the authors in [29] perform an extended evaluation of two models for disaster area voice traffic in contrast to the commonly used three- state models. They examine network characteristic such as traffic intensity, bustiness and dependencies.

Similarly, there are several studies on the traffic models to determine the performance metrics of trunked dispatch PMR systems. Hoang et al. [30, 31] present
a system that models a central queue preceded by a group of queues. A decomposition method is used to solve the problems of both system and group delay. Likewise, Cackov et al. [32, 33] carry out extensive studies on the pattern and nature of a traffic. They perform simulations and conclude that inter-arrival call is best modeled by an exponential distribution and call duration by a lognormal distribution. The technical case study in [23] discusses a simulation model on a multi-server queue with “First –In – First – Out” (FIFO) arrangement. The simulation is done with two scenarios: one is to model call inter-arrival with a gamma distribution and call duration by a lognormal distribution; and the second scenario models empirical data with an exponential distributions. They discover that both scenarios are almost the same in performance and close to the practical performance observed on the system. Finally, they use exponential distribution for both call inter arrivals and call duration, and use Erlang C for performance analysis of the central queue.

The study on the behavior of different talk groups with exponential distribution using a complex model is done by the authors in [34]. Some studies [35, 36] demonstrate that it is inaccurate to model the channel holding times and idle times as exponential distributions. They conclude that Lognormal is the best fit for channel holding times. Also, for inter arrival time, Weibull or Gamma distribution is preferable since it is closer to reality. Finally, the authors in [37] analyze traffic that was measured during a catastrophe maneuver. They conclude that exponential distributions do not show a good fit. Lognormal distributions provide a better fit.
2.4 Traffic Modelling of LTE-based Networks for Public Safety

There are insufficient studies in the area of traffic modeling of PMR systems over LTE networks. Lin et al. [38] propose a model of Push-to-Talk over LTE system architecture. They use extended Erlang B formula to analyze the blocking probability of calls. They do not consider what traffic analysis would be when the calls are put in a queue instead of being blocked, only for the users to try again after each call failure.

Ali et al. [39] investigate the Session Initiation Protocol (SIP) signaling performance over LTE-based mission-critical communications and services. They define the performance metrics for overall system using discrete event simulator. However, there is no traffic modeling done for the estimation of calls delay. Though, the estimation of network performances of TETRA-based public safety network is done in [40] by simulating the traffic using a computer tool; there is still need for further research in estimating the traffic of LTE-based public safety networks. With insufficient research in this area, there is need for further research in estimating the traffic of LTE-based network for public safety.
Chapter 3: Private Mobile Radio Technology

3.1 Existing Private Mobile Radio

The PMR systems used for MCC, are conventional private radios that enable communications between a base station and multiple mobile radios. It is referred to as the Land Mobile Radio (LMR) in North America. These abbreviations all stand for the same type of wireless radio systems hereby referred to in this dissertation as PMR. The PMR technologies include Terrestrial Trunked Radio (TETRA), TETRA for Police (TETRAPOL), and Associated Public Safety Communication Officials (APCO) Project 25 among many others. These technologies are narrowband designed initially only for voice communications and low data rate applications [41, 42, 43].

Though, most of these radio technologies are presently evolving to a technology with increased data rate applications (wideband) [44]. But, they are not sufficient to meet the public safety agencies’ high data rate needs. The agencies need a technology that can support internet access—there may be need to access architectural plans of buildings in order to locate harmful objects in an incidence scene. Also, there should be support for possibility of video streaming and live video feed in emergency cases. There may be an urgent need to upload image or video to assist remote medical team.
3.1.1 TETRA

TETRA is a digital cellular trunked radio system that supports voice and low data communications. TETRA uses the TDMA method. In TETRA frame structure, four time slots are available on a single 25 kHz radio channel and provides 7.2 Kbit/s data transfer rate per time slot. For bigger transmission capacity, an individual user can use up to four time slots which results in a gross data rate of 28.8 Kbit/s. It provides a very fast call set–up time of 300ms that is important for mission critical services. Differential Quaternary Phase Shift Keying (π/4- DQPSK) is the modulation technique used. The TETRA specifications cover three complete different areas of application which include: Voice plus Data (V + D), Packet Data Optimized (PDO), and Direct Mode Operation (DMO) [41]. There is a specific standard developed for each of these three applications. Voice plus Data air interface is optimized for simultaneous transfer of voice and data while PDO air interface is used for packet data transmission via radio channels. PDO does not support line type and short message services. With DMO air interface, mobile stations are able to communicate with each other independent of the network. This is very useful in the emergency conditions that occur outside the V+D coverage area. The V+D air interface make use of trunking system which allocates and releases the available radio resources dynamically on demand basis. By doing this, several groups of users can efficiently share the available radio spectrum.

Except for DMO, TETRA also uses frequency–division duplex technique. This allows both the uplink and the downlink to be controlled on two different
frequencies. TETRA terminals work in half – duplex mode which means the transmission and reception cannot happen at the same time. A button (Pressel) must be pressed before transmission can take occur (Push –to – Talk). Also, repeaters and gateway functions are used to extend the radio coverage in both network operations and direct mode operations.

One of the unique features of TETRA system is that it can serve different users with different levels of priority. This is done by defining different minimum levels of acceptable GoS for users with different priority levels [8]. It also make use of “pre-emption method”, which allows the users with pre-emptive priority to drop non-preemptive calls when all the channels are busy. Also, supplementary services such as dispatch services, group and private voice services, security services, telephone interconnect services, short data and status messaging, and packet data services are all supported by TETRA. These services possess the requirements for mission critical communications such as fast call setup, fast message transmission, priority-based call handling, advanced encryption and authentication etc.

In addition to transactional data solutions for mission critical communications, TETRA also supports wireless browsing, vehicle location, email and fingerprint resolution. But, visual information such as maps, digital pictures and slow motion video are too slow when transmitted over present TETRA 1 data. Increasing the speed could allow TETRA to be used to offer fast data applications for mission critical communications. Remote surveillance and recognition in real time, fast
checking of identities, sending digital maps of buildings etc. would be possible if TETRA speeds are increased.

As a result of the rapid evolution and higher data rates enablement in the public cellular mobile radio systems (UMTS and LTE), TETRA also had to keep evolving so that the rising expectations of PMR users can be met. In the light of this, ETSI published Release 2 of TETRA which is called TETRA Enhanced Data Service (TEDS) in October 2011 [45]. With TEDS, new important functionalities were added into the standard to support higher data rates and is backward compatible with TETRA Release 1. It has wideband data capabilities of around 50 – 300 Kbit/s [46] depending on the coverage conditions. A multi-carrier modulation -D8PSK phase modulation -and QAM – modulated sub-carriers were introduced with 8 sub-carriers per each radio channel with frequency spacing of 2.7 kHz. Presently, TETRA standard is continuously evolving beyond release 1 and release 2 to give additional enhancements to meet ever increasing user needs as well as technology innovations.

In order to provide a communications system that meets the needs of professional or private communications users. TETRA offers the following services for the MCC users:

- Group calls: This is semi duplex point-to-multipoint communication. It means only one member of the group is allowed to speak at a time while others listen. In MCC networks most of the voice traffic in the network is generated by group calls.
- Closed user groups: Every MCC user in the network belongs to an organization (e.g. fire fighters). For instance, a fire fighter is able to communicate only within his or her own organization. This can be in addition to certain other organization’s groups to which the user belongs. Closed user groups permit the implementation of proper multi-agency networks which can be very useful a tool during emergency situations. The service of sharing the network between various organizations does not only allow easy cross-organizational communication, but also allows usage of resources efficiently.

- High priority calls: The network design gives the possibility to assign different priorities to different users, organizations or call types. Traffic prioritization results in a better GoS of the networks. Priorities may be given in resource queuing or speech item allocations.

- Pre-emptive Priority of traffic services: In certain cases, like emergency calls, it must be ensured that resources can be allocated immediately to a traffic. If all resources are busy, another traffic would be dropped or queued. Pre-emptive priority means, that a group member with higher priority may interrupt another user’s voice or data as the case may be.

- Direct Mode Operation: If a user equipment is out of coverage, it may communicate directly with another user equipment without using the radio network infrastructure. This operation mode may be needed in the tunnels, basements or in the situation of complete failure of a base station.
• Push-to-Talk functionality: This is the mechanism incorporated in the user equipment, at the press of a button, to switch a communications device instantaneously from receive mode to transmit mode. In contrast to public telephony, the group communication in MCC networks does not use number dialing to make a call. As an alternative, the users typically have an active group selected all the time. They are automatically listening to the group communication and if they wish to speak, they just need to press the PTT button. This mechanism gives a fast call set–up times which is an important requirement of MCC networks. Typical value less than 0.5 seconds could be achieved [8].

3.1.2 Project 25

Project 25 (P25), also known as APCO25, is a standardized digital radio communication system for public safety developed by the Association of Public Safety Organization Officials (APCO) jointly with the federal, state, and local governments of North America. It is primarily used by public safety agencies in the United States and in Canada. It fulfills the same role as the European TETRA system. Though, the two systems are not interoperable [47, 48]. It was launched in 1988 as a LMR technology used between first responders and their dispatchers.
When operating in digital mode, P25 radio systems can either be conventional or trunked. For conventional systems, a fixed infrastructure such as repeater functions by repeating radio calls from one frequency or channel to another. Conventional systems operation is user controlled. Whereas, in the management of a trunked system’s operation (including call routing and channel allocation) is automatic as shown in Fig. 3.1. A group of traffic channels are automatically shared among a large group of public safety users in a talk group. As users request access to the network, a controller in the infrastructure assigns the calls to specific traffic channels. Each public safety organization manages its own channel. APCO 25- phase 1 based on FDMA technology, 12.5 kHz. In APCO 25- phase 2, it used TDMA technology in addition to the narrow band FDMA 6.25 kHz version [50].
3.1.3 TETRAPOL

TETRAPOL is the main digital PMR system developed for public safety in France. Like TETRA, it is designed for public safety usage and also in the utilities and industry sector. Besides the fact that TETRAPOL is a proprietary technology, the differences from TETRA can be seen while comparing technological feasibility between various system implementations in terms of size and service requirements. The significant drawback for TETRAPOL is that its market is dominated by one manufacturer. This has made the TETRA market to be seen more attractive for implementation for multi-vendor technology [51]. This is established by the fact that TETRA has achieved contract base approximately 20 times larger than TETRAPOL as of 2008 [52]. The TETRAPOL technology uses FDMA with RF carrier spacing 12.5 kHz and 10 kHz [53].

3.2 PMRs for Mission Critical Services

Mission critical communication services have from the past been delivered using PMR systems. These systems are designed to meet all public safety requirements. They are being operated by individual agencies or authorities in many nations across the world.
3.2.1 Mission Critical Voice

Voice services allow real-time communication between MCC units, command centers and other resources. Traditionally, voice has comprised the greater part of MCC communications. For instance, if a MCC unit wishes to determine the status of another unit, or to receive a dispatch from central command, voice communication has been the major means to send this information. Voice is regarded as the paramount communications requirement for MCC users [54].

Reliable voice communications are essential for day-to-day operations, large-scale responses, and other tactical situations. Voice communications must be clear and free from interference to ensure that information is relayed accurately and efficiently.

Voice communications provide emergency responders with instant, reliable, and continuous connectivity between dispatch agencies and responders and also among multiple responders. Presently, mission critical voice is achieved by dedicated PMR networks. The ability to talk responder to responder, or one responder talking to many responders is a critical feature.

3.2.2 Mission Critical Data

Mission Critical Data is intelligence delivered to users on a reliable, secure IP-based critical network with high speed performance and integrated applications. It’s information that is instantly shared by all responders who can benefit from its collective value, whether they’re on the front line or in the control room. It also helps keep officers up to date and prepared when they arrive on the scene.
Mission Critical Data liberates response teams by giving rapid access to vital information for secure distribution over the critical network.

*Short data messaging and paging* — send short messages to personnel without the need to use voice channels.

*Computer Aided Dispatch (CAD)* — used to dispatch resources to an incident, often in conjunction with a mobile data terminal. CAD applications have varying degrees of functionality ranging from simple job tasking and location tracking through to detailed incident information.

*Automatic Vehicle Location* — remote GPS tracking of vehicle location to aid in asset management and CAD.

*Database access* — mobile access to records, registries and other databases.

*Man-down alarm* — an alerting device that can be quickly and easily activated when the wearer is in distress and in need of urgent assistance [55].

### 3.2.3 Mission Critical Video

The emergency response community uses limited data communications to complement mission critical voice communications. Emergency responders currently use data services for basic functions such as digital dispatch; license, vehicle, and wanted person queries; text messaging; and transmission of low resolution images. Emergency response agencies have achieved wireless data capabilities by either building their own systems or using a commercial wireless service. Although functional, current public safety data services are generally limited in speed and do not support advanced, real-time applications needed by emergency
responders. The existing PMR devices do not support broadband services involving high data applications such as video streaming, and video calls.
Chapter 4: LTE as Broadband Technology for MCC services

4.1 Mobile Broadband:

Mobile broadband and its applications is dramatically changing the way MCC users communicate and share information. Mobile broadband refers to the wireless delivery of an internet service over a mobile network, including though phones, tablets and portable modems. The underlying technologies used to deliver mobile broadband have undergone significant advances – from the 2G networks that have carried voice calls and text messages since 1990s, to the 4G networks that allow real – time video streaming today. Mobile broadband offers significant potential to improve how the fire fighters, police, ambulance (EMS) and other public safety agencies deliver their services, saving live and properties. Live video streaming between a fire crew and central command, for instance, would enhance situational awareness and facilitates the efficient deployment of resources. Mobile broadband technologies are still evolving. New features are being added to 4G networks in all the 3GPP releases.

A mobile broadband capability can be described in terms of the network capacity available to MCC users and the quality of services delivered.

1) Network capacity refers to the amount of traffic that can be transmitted on the network at any given time and is often measures in bits per second.
Also, capacity of a network can be related to the speed and volume of data that can be transmitted through a mobile network. Capacity is of prime importance to mobile users because it determines the type and amount of mobile applications that can be used. It is dependent on a range of factors, including the technology used, and the type and amount of spectrum available [56].

Mobile network capacity has two elements: uplink capacity and downlink capacity. The uplink capacity determines how much data MCC users can send. This could be field officers sending information about a scene or victims to other field officers or to central command. The downlink capacity determines how much data MCC users can receive (such as patient medical records or maps). MCC agencies are have high demand for uplink capacity, and exhibit a higher uplink – downlink ratio, relative to other mobile customers.

2) Quality of service: The mission critical nature of some public safety operations means that the quality of mobile broadband services is vital. A number of characteristics of mobile broadband service quality are important to MCC users. These include:

- Accessibility: refers to the ability of MCC users to get connected to a mobile network. It can be measured in many ways such as the portion of MCC users’ access attempts that are successful in a given period. This is also the probability that a voice or data connection can be set up within a specified timeframe. Some participants suggested that MCC users would experience
higher levels of network accessibility under a dedicated (or standalone) network approach.

- **User prioritization:** This refers to systems that prioritize some or all MCC officers, devices or applications over other traffic on a mobile broadband network. The prioritization is based on application types, user roles, agencies, incident types, quick action and jurisdiction.

- **Pre-emptive call priority:** allows an on-going to be pre-empted by another call with pre-emptive priority. Pre-emption is applicable to both group calls and individual calls; users within a group call can be pre-empted by other group calls and individual calls, and likewise individual calls and be pre-empted by other individual calls and group calls. Pre-emption can be used to override existing group calls in case of emergency.

- **Various characteristics of voice service quality are important to MCC users, especially during mission critical situations, including:** latency, quality and integrity of the audio transmitted, and the ability to operate PTT one-handed.

### 4.2 LTE Overview:

LTE, a technology based on GSM/EDGE and UMTS/HSPA network technologies was developed by 3GPP. It is also referred to as 3.9G or Release 8. The 3GPP started the work process on LTE in November 2004 with the Radio Access Network (RAN) Evolution workshop in Toronto – Canada. The 3GPP main task was to standardize a system with new design goals that can exceed older mobile standards like UMTS and
HSPA. Also the system that would be able to stay competitive for years in to the future. LTE is an all Internet Protocol (IP) based technology that is capable of providing high data rates up to 100 Mbps in the downlink (DL) and 50 Mbps in the uplink (UL).

The evolution stages in the existing PMR-TETRA and the commercial cellular networks (CCN) are illustrated in Fig 4.1. The figure also indicates an increasing data rate for each stage of evolution. Both 3.9 G and 4G stand for ‘Broadband’ as the overall name in the wireless communications systems

![Evolution in TETRA and Commercial Cellular Networks (CCN)](image)

**Figure 4.1:** Evolution in TETRA and Commercial Cellular Networks (CCN)

In order to meet all the high data services of the MCC users, LTE has been accepted by many organizations across the world as technology for mobile broadband mission critical communications and services [57, 58, 59].
4.3 Benefits of LTE for Public Safety

The adoption of LTE by FirstNet for public safety organizations in the US, the preference for LTE by the UK Home Office, and intentions of South Korea to build nationwide LTE network for Public Safety has become the catalyst for development of LTE for Critical Communications. Among many important features that make LTE to be so desired for MCC are: high date rate both in the downlink and uplink, possibility of deployment with a variety of channel bandwidth, higher spectrum efficiency and low latency.

One of the important factors that make LTE to be desired for mission critical communications is the economies of scale when compared with existing PMRs like TETRA. There will be reduction in both the Capital Expenditure (CAPEX) – infrastructure costs and the Operational Expenditure (OPEX) – operational costs. In addition to this, LTE has the ability to provide efficient high speed, low latency, low set-up time, and high-security data connectivity. All these factors are needed to establish public safety multimedia communications. Another factor in adopting LTE is the availability of radio equipment for different deployment scenarios. LTE base stations are available to cover different cell sizes such as macro, micro, pico and femto. With diverse cell size, public safety networks can be easily set up in the rural areas where there is no coverage of a macro cellular network. There are some important requirements that make LTE to be accepted for MCC applications [60].
These include the following:

1. LTE is designed to work with multiple channel bandwidths of 1.4, 3, 5, 10, 15 or 20 MHz in both DL and UL.
2. Higher spectrum efficiency
3. High level of security. Since the traffic generated, stored and exchanged by the MCC users are highly sensitive and confidential.
4. Priority and Pre-emption mechanisms are already in-built features designed for LTE and can be readily used for MCC.
5. Quality of Service applications in LTE allows traffic with high requirements on throughput an latency (e.g. video streaming) to have preference over low data applications (short message).

In addition to the above benefits, greater use of LTE mobile broadband by MCC users could change how they deliver their services during emergencies. These services offer by LTE include the following [43, 4]:

- The ability for ambulance officers to remotely access medical records or send images to the hospital could speed up treatment and save lives.
- Giving police officers the ability to access databases when in the field, and to collect and transmit key evidence, can greatly reduce time spent on administrative tasks.
- Providing firefighters with access to maps, building plans and locations of hazardous materials can help them locate more quickly and identify how best to respond.
• More effective information sharing between agencies and the community can improve the situational awareness of public safety officers and the preparedness of community members.

• Fixed image and video capabilities. This includes pictures of suspects sent to responders and the pictures received by Public Safety Answering Points (PSAPs) from the Public.

• Video: from the first responders, from the scene to other units and command, from fixed cameras to responders and to others for the identification of bomb type, etc.

• Data to and from first responders during patrol and incidents

• Advanced data applications such as:
  ▪ Fingerprints, floor plans and access to databases
  ▪ More information for those responding
  ▪ More information for incident command

• Other new applications that are not available today for the local, regional and nationwide applications.

4.4 LTE Network Architecture

The LTE system consists of core and access networks, bit with different elements and operations. LTE is an Evolved Packet System (EPS) which includes the E-UTRAN and the EPC. The EPC includes an MME, an S-GW, and a P-GW entities.
They are responsible for different functionalities during the call or registration process. The basic EPS entities and interfaces is shown in Fig. 4.2.

![Diagram of EPS entities and interfaces](image)

**Figure 4.2:** Basic EPS entities and interfaces [14].

The E-UTRAN consists of eNodeBs, providing the E-UTRAN user plane and control plane protocol terminations towards the UE. The eNodeBs are interconnected with each other by means of the X2 interface. The eNodeBs are also connected by means of the S1 interface to the EPC more specifically to the MME by means of the S1-MME and to the Serving Gateway (S-GW) by means of the S1-U. The S1 interface supports a many-to-many relation between MMEs / Serving Gateways and eNodeBs. The E-UTRAN architecture is illustrated in Fig. 4.3
4.4.1 **Evolved Node-B (eNodeB)**

The functions of eNodeB in LTE network architecture is highlighted below:

- No Radio Network Controller (RNC) is not needed anymore in the LTE network:
  
eNodeB is the only network element defined as part of the radio access network UTRAN. It is a Node B / RNC combination from 3G.

- It takes over all radio management functionality; this will make radio management faster and network architecture simpler.
- It includes old NodeB functions such as: measurements, collection and evaluation, dynamic resource allocation (Scheduler), and IP header compression/de-compression.
- An eNodeB can handle several cells.
- It enables efficient inter-cell radio: user data routing to the S-GW, transmission of paging message coming from MME, Transmission of broadcast Info (System Info, MBMS).

### 4.5 LTE Air Interface /Physical Layer

The design of the LTE air interface or physical layer is heavily influenced by the requirements for high peak transmission rate, spectral efficiency, and multiple channel bandwidths. In order to fulfil all these requirements, OFDM was selected as the basis for the air interface layer. The basic principle in of multi-carrier systems is the splitting of the total bandwidth into a large number of smaller and narrower bandwidth units. These are known as sub-channels. In OFDM, the sub-channels are orthogonal to each other. The orthogonality property does not require the addition of guard intervals between the sub-channels and hence it increases the system spectral efficiency.

The air interface of LTE provides the basic bit transmission functionality over air. It is driven by OFDMA in the downlink and SC-FDMA in the uplink. Physical channels are dynamically mapped to the available resources. All resource mapping is dynamically driven by the scheduler.
4.5.1 OFDMA

Orthogonal Frequency Division Multiple Access (OFDMA) is an access scheme that uses the OFDM principle for the distribution of the scarce radio resources among several users enabling multi user communications. This is done by using Time Domain Multiple Access (TDMA). This allows the users to dynamically get some resources at the different time instances of the scheduling. OFDMA subdivides the available bandwidth into a number of narrowband sub-carriers which are ‘mutually orthogonal’ (i.e. don’t interfere with each other) each of which can carry independent information stream. This allows flexibility in a number of ways including:

1- Ability to schedule transmission in time and frequency domains: users can be assigned a number of subcarriers at different instances in time

2- Ability to operate in different channel bandwidth depending on spectrum allocations without impacting fundamental system parameters or equipment design.

3- Allows for flexible frequency planning techniques such as fractional frequency reuse where a subset of sub-carriers is used at cell edge or in areas of high interference in order to reduce interference levels and increase the frequency reuse factor.

4- Allows the design of low complexity receivers by limiting the need for equalization that is necessary on wideband single carrier systems like WCDMA.
5- Increases the robustness of the time-dispersive radio channel because of narrowband frequency subcarriers constrain inter symbol interference. 
6- Enables easier integration of advanced antenna technologies such as MIMO and beamforming to increase capacity or robustness of the radio signals. 

There are certain complexities that arise from using OFDMA, typically arising from high peak-to-average power ratio (PAPR) which requires linearization techniques on the transmitter and/or allowing for a larger power back off from the 1dB compression point of the PA (12 dB versus about 8 dB for UMTS and only 2-3 dB for GSM) [61]. In order to allow for lower cost devices, LTE implements SC-FDMA for the uplink path, putting less demanding requirements of the power amplifier design for mobile terminals and therefore reducing cost and design complexity.

**4.5.2 SC- FDMA**

The Single Carrier Frequency Division Multiple Access is the chosen transmission scheme for the LTE uplink. The reasons behind this choice is the low peak to average power ratio it possesses. This is a good property for having efficient power amplifier that can save battery power of the mobile device for the uplink transmission.

SC- FDMA is a special form of OFDM that combines the low peak to average power ratio with multi path resistance and flexible and efficient frequency allocation. It still uses orthogonal sub-carriers similar to OFDMA, but their difference is that the
sub-carriers used for transmission are chosen to be sequential and not in parallel. The comparison between OFDMA and SC-FDMA is illustrated in Fig. 4.4.

Figure 4.4: Comparison between OFDMA and SC-FDMA [62]
4.5.3 LTE Uplink Scheduling Model

The LTE uplink scheduler is located at the base station (eNodeB) of LTE. A resource block is described as the minimum transmission unit of this LTE scheduler. RE is designed in both frequency and time domains. The number of Res for LTE is shown in Table 4.1.

<table>
<thead>
<tr>
<th>Channel Bandwidth [MHz]</th>
<th>1.4</th>
<th>3</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of RE</td>
<td>6</td>
<td>15</td>
<td>25</td>
<td>50</td>
<td>75</td>
<td>100</td>
</tr>
</tbody>
</table>

4.5.4 LTE Uplink Physical Channels

There are three physical layer channels defined for the uplink in LTE [63]. These are described below:

1. Physical Uplink Shared Channel (PUSCH): This channel carries user data. It supports QPSK and 16 QAM modulation with 64 QAM being optional. The PUSCH carries in addition to user data any control information necessary to decode the information such as transport format indicators and MIMO parameters.

2. Physical Uplink Control Channel (PUCCH)
3. Physical Random Access Channel (PRACH): This channel carries the random access preamble a UE sends to access the network in non-synchronized mode and used to allow the UE to synchronize timing with the eNodeB. It consists of 72 sub-carriers in the frequency domain (six Resource Block, 1.08 MHz).

4.6 Traffic Prioritization Mechanism in LTE

A ‘bearer’ is the term used to describe a ‘virtual’ channel established between the endpoints of an LTE network (from the end-user device to the core network). Once MCC users are allocated an access class, their bearer is the means by which the network operator can differentiate one user’s traffic from another’s and one application’s traffic from another’s (such as a video stream compared to a web browsing session). There are two types of bearer in LTE [64]:

- Default bearer: Every end user has at least one default bearer that is established when the end-user device first attaches to the network and remains available for the duration of the connection. An end-user device can have anywhere from zero to several dedicated bearers established at any given time and each is set up and taken down on an as-needed basis. The default bearer is always set up as a non-guaranteed bit rate (non-GBR).

- Dedicated bearer: This is used when the quality of service requirements for some traffic are different than the provisions provided by the default bearer. A dedicated bearer can be either guaranteed bit rate (GBR) or non-GBR.
Each bearer, whether dedicated or default is associated with two parameters. These are allocation and retention priority and QoS class identifier.

- **QoS Class Identifier (QCI):** This parameter dictates the packet-level preferential treatment a bearer receives. It provides a mapping from an integer value to specific QoS parameters that controls how bearer level packets are forwarded. QCI controls the packet forwarding, such as scheduling weights, admission thresholds, queue management thresholds, and link layer protocol configuration. QCI values are typically pre-configured by the operator. Every QCI (GBR and non-GBR) is associated with a priority level. Priority level 1 is the highest priority level.

### 4.7 LTE for Critical Communications

The main objective of 3GPP regarding critical communications is to preserve the strengths of LTE while adding features needed for public safety. The aim is to make possible mission – critical voice + video + data on a single device. LTE will continue to evolve further in both capabilities and performance. The further improvements are described in Releases by 3GPP, with new features for reliability resilience, scalability and management. LTE-Advanced is included in Releases 10 and 11 with speeds of 1Gbit/s. Additional enhancements are described in releases 12-14, all paving the way for 5G that would give a higher data throughput. Some basic 3GPP features for public safety have been incorporated in Releases 8-11 of LTE standards; such as prioritization and emergency calls. New solutions for public safety are
included in Releases 12 which include proximity services (Device-to-Device, or D2D) which facilitate the discovery and communications between nearby radio users without the network infrastructure. Also, group communication that allows one-to-many voice calls as well as dispatcher communications is made available in Release 12 [65, 66]. Presently, Enhanced proximity services and Mission critical push-to-talk is available in Release 13 [67]. The summary of all the 3GPP releases for LTE for critical communications is described in Table 4.2. The improvements in 3GPP standards for critical communications are applicable also for LTE Advanced as well as future 5G standards.
### Table 4.2: 3GPP features for Public Safety

<table>
<thead>
<tr>
<th></th>
<th>Releases 8-10</th>
<th>Release 11</th>
<th>Release 12</th>
<th>Release 13</th>
<th>Release 14</th>
<th>Release 15</th>
</tr>
</thead>
<tbody>
<tr>
<td>VoLTE</td>
<td>High power UE for Bans 14</td>
<td>Proximity services or D2D Enhancements</td>
<td>Mission Critical Video</td>
<td>Mission Critical Data</td>
<td>MC services common functionality enhancements</td>
<td></td>
</tr>
<tr>
<td>QoS</td>
<td>-</td>
<td>Group Communication system enablers</td>
<td>MCPTT</td>
<td>Mission critical Data</td>
<td>MCPTT enhancements</td>
<td></td>
</tr>
<tr>
<td>Ciphering</td>
<td>-</td>
<td>-</td>
<td>Isolated E-UTRAN operation</td>
<td>-</td>
<td>MC Data Additions</td>
<td></td>
</tr>
<tr>
<td>eMBMS</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>E911</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

54
The timeline for MCC services and 3GPP Releases is presented below:

Release 13

- MCPTT is completed in March 2016

Release 14

- MCPTT improvements completion date is September 2017
- MC Data completion date is September 2017
- MC Video completion is September 2017

Release 15 and beyond

- MCPTT improvements completion date is June 2018
- MC Data completion date is June 2018
- MC Video completion date is June 2018.
Chapter 5: Analytical Modeling of LTE-based MCC Networks Capacity

5.1 Overview

Analytical models are functional relations between the parameters of a system and the system performance expressed in equations that are solved using analytic or numeric techniques. Queueing theory is an important analytic tool used. An analytical approach for estimating the network capacity for LTE-based MCC networks for public safety is presented. The network is modeled using Markov birth and death process. In order to provide the required GoS for LTE-based public safety users, the minimum number of channels required for different levels of users’ priority is calculated. The results for some performance metrics such as throughput, delay probability, and channel utilization are obtained.

The results obtained from the simulation is compared with the existing network model such as Erlang C. Results show that the existing network model show similarities and differences in predicting the channel estimation of the deployed LTE networks for public safety communications. The results can help the network designer in the proper dimensioning of LTE-based public safety network.
5.2 Traffic Probability distributions in MCC

Traffic is characterized statistically by distributions that represent the arrival rate and duration of an event. Circuit switched voice traffic is represented by a Poisson distribution for call arrival and a Rayleigh distribution for call duration. Packet Switched data sessions, however, have to be specified at session, burst, and packet level. Sessions are defined by the length of time the user is connected to a destination. Bursts represents periods of user activity and packets represent the actual data sent by users. Sessions and bursts usually have a Poisson arrival rate, but follow long-tailed Pareto distribution for its duration. Packets generally follow a Poisson arrival with a Constant or Rayleigh distribution duration [68]. Sessions, burst and packets are defined by a distribution, inter-arrival time, and event length. The possible statistical distributions are Poisson, Weibull, Rayleigh, Exponential, Lognormal, Normal, and Pareto. For heavy – tailed traffic, Poisson model under –estimates the traffic [69]. The distributions used for high data heavy tailed in this research is Lognormal and Normal distributions. Simulations are performed to obtain best probability distributions for traffic generations and service time.

5.2.1 Poisson distribution

One of the most widely used and oldest traffic distribution is Poisson distribution. The memoryless Poisson distribution is the predominant model used for analyzing traffic in traditional telephony networks [70]. In a Poisson process, the inter-arrival times are exponentially distributed with a rate parameter $\lambda$: 
\[ P\{A_n \leq t\} = 1 - \exp(-\lambda t) \] (1)

The Poisson distribution is appropriate if the arrivals are form a large number of independent sources. The distribution has a mean and variance equal to the parameter \( \lambda \). This kind of distribution has two primary assumptions: the number of sources is infinite and the traffic arrival pattern is random. The probability mass function is shown in Fig. 5.1.

![Probability Mass Function of Poisson distribution](image)

**Figure 5.1:** Probability Mass Function of Poisson distribution [71].

\[
p(x) = \begin{cases} 
\frac{e^{-\lambda} \lambda^x}{x!} & \text{for } x \in \{0, 1, \ldots\} \\
0, & \text{otherwise}
\end{cases}
\] (2)

The Poisson distribution is a discrete distribution that is often used to model the number of random events occurring in a fixed interval of time. If the time between
successive events is exponentially distributed, then the number of events that occur in a fixed time interval has a Poisson distribution.

### 5.2.2 Lognormal distribution

This distribution is an example of heavy tail distribution. Denoting the user-specified input parameters as LogMean = $\mu_i$ and LogStd = $\sigma_i$. Then let

$$\mu_i = \ln\left(\frac{\mu_i^2}{\sqrt{\sigma_i^2 + \mu_i^2}}\right)$$

and

$$\sigma = \sqrt{\ln\left[\left(\frac{\sigma_i^2 + \mu_i^2}{\mu_i^2}\right)^2\right]}$$

The probability density function is shown in Fig. 5.2 and the equation can be written as

$$f(x) = \begin{cases} \frac{1}{\sigma x \sqrt{2\pi}} e^{-\left(ln(x) - \mu\right)^2/(2\sigma^2)} & \text{for } x > 0 \\ 0, & \text{otherwise} \end{cases}$$

The parameters are Mean LogMean ($\mu_i > 0$) and standard deviation LogStd ($\sigma_i > 0$) of lognormal random variable. And both must be strictly positive real numbers. It is represented in ARENA as: $\text{LogN(LogMean, LogStdDev)}$
5.2.3 Exponential distribution

This distribution is often used to model inter-event times in random arrival and breakdown processes. The probability density function is shown in Fig. 5.3 and the equation can be written as

\[
f(x) = \begin{cases} 
\frac{1}{\beta} e^{-x/\beta}, & \text{for } x > 0 \\
0, & \text{otherwise} 
\end{cases}
\]  

(6)

The mean (\(\beta\)) specified as a positive real number, represented in ARENA as: \textit{EXPO (Mean)}. 

\textbf{Figure 5.2:} Probability Density Function of Lognormal distribution [71].
5.2.4 Normal distribution

This distribution is used in situations in which the central limit applies. The probability density function is shown in Fig. 5.4 and the equation can be written as

\[ f(x) = \frac{1}{\sigma \sqrt{2\pi}} e^{-(x-\mu)^2/(2\sigma^2)} \text{ for all real } x \]  

(7)

The mean ($\mu$) specified as a real number, and standard deviation ($\sigma$) specified as positive real number. This is represented in ARENA as: \textit{NORM (Mean, StdDev)
5.3 Analytical flow chart:

There are three general approaches to evaluating the performance of a wireless network [71]:

1. Analysis- calculation of the probability for Poisson arrival of traffic.
2. After analysis is a computer simulation which gives a more detailed model of the system under study. This is emulated in the computer software.
3. Statistical analysis is performed on the output set in order to estimate a performance measure or metrics.

Basic things to simulate include, first, is the traffic generation. This consists traffic arrival rate which describes how the traffic is being generated. Secondly, modeling of the statistical properties of the traffic. This includes the arrival rate, call holding time, and distribution of the call holding time. For voice traffic, we assume Poisson
distribution. When it comes to video and high data applications, we assume heavy tail distribution. This is describing the volume of the traffic generated. Next step is running the traffic against the LTE resources. Parameters like delay probability, average waiting time, traffic volume served, etc. that will have in the queueing systems are obtained. Also, the performance parameters are analyzed. This is done to investigate the traffic volume that meet the MCC requirements. The steps involved in the analytical prediction of the performance of LTE-based MCC network is illustrated in Fig. 5.5.

![Flow chart for analytical prediction of LTE-based MCC Network.](image)

**Figure 5.5:** Flow chart for analytical prediction of LTE-based MCC Network.
### 5.4 Traffic modeling and network deployment process

Traffic can be seen as the driving force behind all telecommunications activities. The probability models for the traffic flow are necessary for predicting the system performance metrics to an acceptable degree of accuracy. Also, traffic modeling are needed to determine the operational status of the networks, evaluate their performance, and to easily detect possible network congestion. Therefore, the basic aim of traffic modeling of public safety communications over LTE networks is the prediction of network performance. Using the queuing theory model, voice traffic randomly arrive at the channel with service requirements which may be random in duration. The theory tries to find probabilistic descriptions of such quantities as the sizes of queue, the delay experienced by an arrival, and the availability of a channel. The queue follows Markov birth-death model and a FIFO discipline. The queue system considered is a multi-server with $N_k$, the number of channels, mean rate of call arrival, $\lambda$, and the mean call duration $\frac{1}{\mu}$. Performance metrics are based on the statistics obtained for the central queue. These include delay probability (i.e. probability of waiting in the queue for channel access), $P_d$, and average waiting time (or queuing delay) for those calls that have to wait in the central queue, $T_d$. These performance metrics are used to define the Grade of Service (GoS) for LTE-based public safety networks.
5.4.1 Modeling Traffic Volume:

The process of modeling involves voice traffic arriving a server or channel. Probability theory is used to determine the channel needed and the associated delay time. Call or traffic categories can be mobile to mobile (M-M), mobile to external fixed terminals (M-F), and others.

For a single cell site consideration, the probability that a call traffic will be delayed more than a particular time $t$ is

$$Pd_{N_k(t)} = Pd_{N_k(>0)} \times e^{-\frac{(N_k-N_c) \times t}{T_h}}. \quad (8)$$

where $Pd_{N_k(>0)}$ is the probability that a call will be delayed, $N_k$ is the number of trunks available for offered traffic, $N_c$ is the volume of traffic in Erlang, $T_h$ is the call duration or holding time in (s).

Assume $Pd_{N_k(t)}$ is similar for $k$ sites, then, $Pd_{N_k(t)\text{total}}$, the probability that all $k$ sites are involved in call after a certain waiting time is [8]

$$Pd_{N_k(t)\text{total}} = 1 - \left(1 - Pd_{N_k(t)}\right)^k \quad (9)$$

where $k$ is the total numbers of cell sites involved in the call. During major incidence and accidents, the public safety agencies are always in a location which can be served by one or two cell sites. Therefore, (8) will be used in the traffic modeling simulations.
Similarly, the total traffic offered will be:

\[ N_c = u \times \lambda \times T_h \times m. \]  \hspace{1cm} (10)

where \( u \) is the total numbers of users per cell site involved in the call. \( \lambda \) is the busy hour call attempts per subscriber in (call/s), \( m \) is of cells involved in the group call.

5.4.2 Modeling Number of Traffic Channels:

The traffic modeling process assumes infinites population source where the ratio of user to available channel is 20:1. The incoming call arrival rate follows Poisson distribution. It also assumes that the system is in equilibrium with equal traffic density per source. The incoming traffic has exponentially call holding time. Blocked requests are delayed or queued, and calls are served in order of arrival with exception of pre-emptive priority calls and other priority call levels. Call arrival follows M/M/C queueing system as shown in Figs. 5.6. M/M/C denotes a system with Poisson call arrivals, exponentially distributed service times and C identical servers/channels in parallel. The system does not reject any call request. Markov process of Birth-death rate is used to model delay probability for when the system is in equilibrium as seen in Fig. 5.7. The simulated data from scenario 8 of ETSI technical paper [13] is used in the analysis of traffic modeling for LTE-based public safety network.
Using the Markov process of birth-death rate model, from Figs. 5.6 and 5.7, traffic flow rate in to state $N_k$ is equal to traffic flow rate out of state $N_k$ for equilibrium state. The probability $P_{N_k}$ is the probability of being in the state $N_k$. 
For idle trunk state or state 0

\[ \mu_1 P_1 = \lambda_0 P_0 \]  \hspace{1cm} (11)

For one trunk available or state 1,

\[ \lambda_0 P_0 + \mu_2 P_2 = (\lambda_1 + \mu_1)P_1 \]  \hspace{1cm} (12)

For \( N_k \) numbers of trunk available or state \( N_k \),

\[ \lambda_{N_k-1} P_{N_k-1} + \mu_{N_k+1} P_{N_k+1} = (\lambda_{N_k} + \mu_{N_k})P_1 \]  \hspace{1cm} (13)

Accordingly, the sum of all probability of possible system population add to 100 % that is

\[ \sum_{N_k=0}^{\infty} P_{N_k} = 1 \]  \hspace{1cm} (14)

Similarly, the probability that an incoming request find at least one trunk is

\[ P_{N_k(>0)} = \sum_{N_k=0}^{N_k-1} P_{N_k} \]  \hspace{1cm} (15)

Also for the probability of delay \( Pd_{N_k(>0)} \) will be:

\[ Pd_{N_k(>0)} = 1 - \sum_{N_k=0}^{N_k-1} P_{N_k} \]  \hspace{1cm} (16)
If $P_{d_{N_{k(>0)}}}$ is known or given as part of SLA, therefore the probability that call will be answered or served less than a particular time $t$, and a call holding time in (s), will be

$$P_{d_{N_{k(<t)}}} = 1 - P_{d_{N_{k(>0)}}}e^{\frac{(N_{k}-N_{c})\times t}{T_{h}}} \quad (17)$$

Or for an exceeding time,

$$P_{d_{N_{k(>t)}}} = P_{d_{N_{k(>0)}}}e^{\frac{(N_{k}-N_{c})\times t}{T_{h}}} \quad (18)$$

Furthermore, the SLA for PMR-TETRA to meet its design is that probability of call delay exceeding, a time of 5s is 5% [72, 8] that is, $P_{d_{N_{k(>5)}}} = 5\%$. Substituting $P_{d_{N_{k(>5)}}} = 5\%$ into (9), it becomes,

$$\frac{5}{100} = P_{d_{N_{k(>0)}}}e^{\frac{(N_{k}-N_{c})\times 5}{T_{h}}} \quad (19)$$

Apply law of natural logarithm to (19) and simplify, that is,

$$given \ x = e^{-y}, \ then \ y = -\ln(x) \quad (20)$$
Equation (19) becomes:

\[ N_k = N_c - \left[ \frac{T_h}{5} \times \ln \left( \frac{0.05}{Pd_{N_k(>0)}} \right) \right] \tag{21} \]

where \( N_k \) is the trunk available for the offered traffic, \( N_c \)

For a given \( Pd_{N_k(>0)} \) such as 1 % or 10 %, and total offered call traffic at a particular call holding time, the required traffic channel for the service can be obtained using (21).

Similarly, the delay, \( T_d \) for traffic will be:

\[ T_d = \frac{Pd_{N_k(>0)} \times T_h}{N_k \left( 1 - \rho_{N_k} \right)} \tag{22} \]

where \( \rho_{N_k} = \frac{N_c}{N_k} \) is the trunk or channel utilization
5.4.3 Modeling Broadband Capacity for PSS Traffic Volume and Real Time Operation using LTE Service:

Considering the dedicated option for deployment strategy, the bandwidth capacity per cell site will be given as shown in Fig. 5.4:

\[ B = C \times B_w \times R \] (23)

where \( C \) is the carrier capacity per cell site, \( B_w \) is trunk bandwidth, and \( R \) is the reuse factor.

Therefore, from Fig.5.8, the bandwidth capacity for TETRA and LTE respectively will be:

\[ B_1 = C_1 \times B_{w1} \times R_1 \] (24)

\[ B_2 = C_2 \times B_{w2} \times R_2 \] (25)
Figure 5.8: (a) Bandwidth capacity deployment plan for TETRA and LTE (b) Queue system for bandwidth capacity in LTE-based public safety network

The proposed LTE trunk bandwidth is 10 MHz and the existing value for PMR-TETRA is 25 KHz, the reuse factor for LTE is higher than that of TETRA, [8, 9, 72], assuming it is double, and $C_1 = C_2$, and divide (25) by (24), therefore,
\[
\gamma = \frac{B_2}{B_1} = \frac{C_1 \times 10 \times 10^6 \times 2R_1}{C_1 \times 25 \times 10^3 \times R_1} = 800
\] (26)

where \( \gamma \) is a bandwidth constant.

Similarly the service throughput \( T_p \) (in \( s^{-1} \)) can be given as

\[
T_p = \mu - \lambda
\] (27)

Provided other factors remain constant, (23) becomes

\[
C_p = \gamma T_p
\] (28)

where \( C_p \) is the traffic capacity or broadband service

Presently, Commercial LTE is capable of 100 Mbps in the downlink and 50 Mbps in the uplink and most of our videos are downloads. But, the case is different for LTE-based Public Safety Communication (PSC) network, the uplink (as shown in Figure 5.9) is of paramount importance because the first responders transmit high information on upload link than the downlink. The uplink uses single carrier frequency division multiple access (SC-FDMA).
There are three physical layer channels defined for the uplink in LTE. These are Physical Uplink Shared Channel (PUSCH), Physical Uplink Control Channel (PUCCH), and Physical Random Access Channel (PRACH). PUSCH carries user data and PUCCH is used for Control signaling. PUCCH comprises the uplink data transmitted independently of traffic data. The PRACH carries the random access preamble that UE sends to access the network in non-synchronized mode. It is used to allow the UE to synchronize timing with the eNodeB. It consists of six Resource Block [73].

Consequently, to calculate the estimate throughput of the proposed LTE based Public safety communications. Firstly, the study determines the number of Resource Elements (RE) per 1msec subframe given as:

\[
RE = \text{Subcarriers} \times SC \times \text{FDMA symbol} \times \text{Resource block} \times \text{Slot} \quad (29)
\]
Then, the data rate (DR) when assuming 64QAM with Single Input Single Output (SISO) antenna configuration and no coding is:

\[
DR = \text{Number of bits per 64QAM symbol} \times RE
\]  

(30)

The overhead related to PUCCH, PRACH, pilot, random access, control plane, guard band overhead and other channels is approximately 71.55%, [10]. Therefore, the peak data rate or throughput is 71.55% of \( DR \).

5.5 Results and Analysis:

5.5.1 Traffic Volume and Required Trunks:

The simulated data from scenario 8 of ETSI technical paper [13] is used in the analysis of traffic modeling for LTE-based public safety network. The mobile to mobile (M-M) call rate for the simulation in Fig. 5.8a is given as 0.324 call/hour and the call holding time is 20s. Using (10), the traffic volumes for different user is given in Table 5.1. This study uses different priority levels with the associated probability of delay or Grade of Service (GoS) as shown in Table 5.2 to test the performance of the simulation model.

Similarly, using (21), number of trunks that will be required for LTE-based public safety network to be able to carry traffic volumes in Table 5.1 and delay requirements
in Table 5.2 are obtained as shown in Table 5.3. The plot of number of trunks obtained versus offered traffic at different grade of service is shown in Fig. 5.10. The plots shows that higher number of trunks need to be available as traffic volume increases and at least for 99% of the time at least a trunk must be available for preemptive calls.

Table 5.1: Traffic Volumes for different Public Safety Network users

<table>
<thead>
<tr>
<th>No of users</th>
<th>Traffic volume (Erlang)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.180</td>
</tr>
<tr>
<td>250</td>
<td>0.450</td>
</tr>
<tr>
<td>300</td>
<td>0.540</td>
</tr>
<tr>
<td>500</td>
<td>0.900</td>
</tr>
<tr>
<td>750</td>
<td>1.350</td>
</tr>
<tr>
<td>1000</td>
<td>1.800</td>
</tr>
</tbody>
</table>
Table 5.2: Different Priority levels and the associated Grade of Service (GoS)

<table>
<thead>
<tr>
<th>Priority delay requirements</th>
<th>GoS Value (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-emptive priority</td>
<td>1</td>
</tr>
<tr>
<td>Priority #1</td>
<td>10</td>
</tr>
<tr>
<td>Priority #2</td>
<td>25</td>
</tr>
<tr>
<td>Priority #3</td>
<td>50</td>
</tr>
<tr>
<td>Priority #4</td>
<td>71</td>
</tr>
<tr>
<td>Priority #5</td>
<td>89</td>
</tr>
</tbody>
</table>

Table 5.3: Simulated Number of Traffic Trunks for LTE-based Public Safety Network for given SLA

<table>
<thead>
<tr>
<th>Probability of delay</th>
<th>1 %</th>
<th>10 %</th>
<th>25 %</th>
<th>50 %</th>
<th>71 %</th>
<th>89 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic Erlang</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.18</td>
<td>12</td>
<td>12</td>
<td>11</td>
<td>9</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>0.45</td>
<td>12</td>
<td>12</td>
<td>11</td>
<td>10</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>0.54</td>
<td>12</td>
<td>12</td>
<td>11</td>
<td>10</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>0.90</td>
<td>13</td>
<td>12</td>
<td>12</td>
<td>10</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>1.35</td>
<td>13</td>
<td>13</td>
<td>12</td>
<td>11</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>1.80</td>
<td>14</td>
<td>13</td>
<td>13</td>
<td>11</td>
<td>9</td>
<td>5</td>
</tr>
</tbody>
</table>
Table 5.4: Comparison between Simulation Model and Erlang C table for Number of Trunks

<table>
<thead>
<tr>
<th>Probability of delay</th>
<th>89 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic (Erlang)</td>
<td>0.18</td>
</tr>
<tr>
<td>Simulation model</td>
<td>3</td>
</tr>
<tr>
<td>Erlang C table</td>
<td>2</td>
</tr>
</tbody>
</table>

Figure 5.10: Number of trunk versus offered traffic at different grade of service
Figure 5.11: Channel utilization versus probability of delay

Figure 5.12: Channel utilization versus number of users
Figure 5.13: Waiting time versus probability of delay

Figure 5.14: Waiting time versus number of users
The plots for channel utilization based on the traffics versus the probability of delay and number of users is shown in Figs. 5.11 and 5.12 respectively. The plots shows that channel utilization is low for pre-emptive calls. Similarly, the plots for delay versus the probability of delay and number of users is shown in Figs. 5.13 and 5.14 respectively. The plots shows that the waiting time increases tremendously as the number of users increase for given number of trunks.

5.5.2 Calculating Time and Test of Broadband Capacity:

From the data sample obtained from the ETSI report, it can be shown that:

\[ \mu = \frac{1}{T_h} = \frac{1}{20} = 0.05 s^{-1} \]  

\[ \lambda = \frac{0.324 \text{call}}{hr} = \frac{0.324}{3600} = 9.05 \times 10^{-5} s^{-1} \]  

Using (26),

\[ T_p = \mu - \lambda \]

\[ T_p = 0.05 s^{-1} - 9.05 \times 10^{-5} s^{-1} \]

\[ T_p = 0.04991 s^{-1} \]  

(33)
Using (27)

For link in Fig 5.4 (b),

Existing PMR-TETRA capacity, \( C_p = \gamma T_p \)

\[ C_p = 0.04991 \]

LTE-based public safety network capacity,

\[ C_p = \gamma T_p \]

\[ 800 \times 0.04991 \approx 40 \text{ s}^{-1} \]

Therefore, the capacity ratio of LTE-based public safety network to conventional PMR-TETRA is 40:1

Also, the time required for traffic transmission for the existing PMR-TETRA is \[ \frac{1}{0.04991} \approx 20 \text{s} \] while the time required for traffic transmission in LTE-based public safety network is \[ \frac{1}{40} \approx 25 \text{ms}. \]

From this analysis, it is shown that for a LTE-based public safety network, call or message transfer will take approximately 25 ms.

Furthermore, in an accident scene where an MCC user has traffic of 768 kbps peak rate and other data transfer of 512 kbps, the total date rate (peak traffic) for the uplink is 1300 kbps [14]. This means the total generated PSC traffic is 1300 kbps. Using this data, the LTE uplink capacity can be obtained using equations 29 and 30. For LTE uplink 10 MHz bandwidth assigned for the public safety communications, there are 12 subcarriers, 7 SC-FDMA per symbol and 16 resource block for 2 slots [73, 82]
Therefore, the LTE uplink capacity is obtained by calculating the peak data rate as illustrated below.

\[ RE = \frac{12 \times 7 \times 50 \times 2}{1 \times 10^{-3}} \]

\[ = 8400000 \]

\[ Peak \ data \ rate = 0.7155 \times 6 \times 8400000 \]

\[ = 37 \ Mbps \]

Analytically, the throughput that can be obtained for LTE uplink of 10 MHz bandwidth is 37 Mbps for SISO antenna configuration. Therefore, with PSC traffic of 1300 kbps, the LTE network is capable of carrying 28 times the PSC traffic.

5.5.3 Evaluation of cost of deployment of LTE network for PSC:

If the existing PMR-TETRA is integrated over commercial LTE network for public safety. This in turn will provide speed and broadband services for real time services with higher throughput. These benefits come with a cost. Such as, cost of migration and hardware/software upgrade and optimization, running and maintenance cost. Capital Expenditures (CAPEX) and Operational Expenditures
(OPEX) are the total expenditures for the deployment of a wireless mobile network.

For a given SLA, let us assume there are two traffic plans or usage rates, that is:

*Plan A*: Priority or preemptive calls with $30 per hour per traffic

*Plan B*: Other emergency calls with $20 per hour per traffic

*Lease/dedicated trunk* with $400 flat rate.

Using traffic volume of 1.35 Erlang from Table 5.1, the plot of cost per time for the plans is shown in Fig. 5.11, in order to optimize the cost of implementation of LTE-based public safety network, the cost (OPEX) should stay below the curves.

![Figure 5.15: Plot for cost of deployment of LTE network for public safety](image)

---

84
5.6 Comparison of Analytical Traffic Simulation Model with Erlang C:

Table 5.3 shows the number of simulated trunks that will be required for LTE network for public safety. The simulation model to determine the number of required trunks for LTE-based public safety network is compared with the Erlang C table values. Analysis of Variance (ANOVA) is used to test the significance of the comparison. In the ANOVA analysis, the null hypothesis is that the mean values of number of trunks obtained by computer simulation model is the same as the mean values of number of trunks obtained by Erlang C table given a certain traffic and grade of service. The alternative hypothesis is that the mean value of number of trunks for computer simulation model and Erlang C table is different. Table 5.4 shows the number of simulated trunks and the ones obtained using Erlang C table. The result of ANOVA as shown in Fig. 5.12 shows that the p-values, 0.025 is less than the chosen significance level 0.05. Therefore this study rejects the null hypothesis. The Erlang C tables underestimate the amount of trunks required for TETRA network over LTE network. Similarly, Figs. 5.13 and 5.14 show the Tukey and the Hsu simultaneous data comparison respectively. They show that there is a difference in the number of required trunks for computer simulation model and Erlang C table. The Erlang C tables are not precise in the prediction and that they do not take into account the time requirement for a specific traffic at given grade of service.
Analysis of Variance

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Adj SS</th>
<th>Adj MS</th>
<th>F-Value</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor</td>
<td>1</td>
<td>5.333</td>
<td>5.3333</td>
<td>6.96</td>
<td>0.025</td>
</tr>
<tr>
<td>Error</td>
<td>10</td>
<td>7.667</td>
<td>0.7667</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>11</td>
<td>13.000</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 5.16:** ANOVA result

![Tukey Simultaneous 95% CIs](image)

*If an interval does not contain zero, the corresponding means are significantly different.*

**Figure 5.17:** Plot for Tukey simultaneous data comparison
Figure 5.18: Plot the Hsu simultaneous data comparison
Chapter 6: Simulation Models and Results

6.1 Theory of ARENA and Methodology

A simulation model that involves running a simulation program is used to produce sample histories. A set of statistics computed from these histories are used to form the performance measures for the LTE-based MCC network investigated in this study. The working simulation tool for the models in this research is Arena. Arena is a simulation environment consisting of module templates, built around SIMAN language constructs and other facilities, and augmented by a visual front end [74]. Arena implements a programming paradigm that combines visual and textual programming. It has a graphical user interface (GUI) built around the SIMAN language. SIMAN, from which Arena has evolved, consists of two classes of objects [75]: blocks and elements. Blocks are basic logic constructs representing operations (or a process), and elements represent facilities such as resources and queues. The fundamental building blocks of Arena models are modules. For instance, a process module models the processing of an entity, and internally the module consists of a few SIMAN blocks such as ASSIGN, QUEUE, SEIZE, DELAY, and RELEASE. The details on modeling with Arena can be obtained in Arena User’s Guide by Rockwell Automation [76]. Based on the simulation approach used, the study tests different probability distributions for traffic generation and service times distribution cases. For all the cases of test, Lognormal for traffic generation / Lognormal service
distribution and Normal for traffic generation / Exponential distribution for service times cases are used to implement the proposed LTE-based MCC networks.

The performance metrics of interest in evaluation of the LTE- based MCC network is mainly based on the following criteria

- throughput
- average delay or average waiting time of incoming traffic
- resource utilization
- queue length

Delay denotes the time spent waiting for resources and alternatively is called waiting time. Number of finished traffic leaving the system per unit time characterizes throughput. The proportion of time that resources are busy relative to total time describes resource utilization. To estimate the requisite statistics, the LTE-based MCC scenarios is simulated for a period of 360 seconds.

6.2 LTE-based MCC System Design:

LTE is a fourth generation (4G) cellular wireless technology introduced by 3GPP as technology into the future. The estimated peak data rates possible with LTE system in an ideal condition are high data rates of 100 to 326.4 Mbps on the downlink and 50 to 86.4 Mbps on the uplink depending on the antenna configuration and modulation depth [77]. In this study, a single eNodeB is used to analyze mission critical service scenarios over LTE network as shown in Fig. 6.1. The figure
represents an incidence scene where the first responders- R₁, R₂, .., Rₙ’ user equipment (UE) transmitting (voice, video streaming and data) uplink to the eNodeB. The radio resource management is being performed by the eNodeB. The 3GPP allocates 50 physical resource blocks (PRB) for LTE-based MCC systems on 10 MHz bandwidth [78, 77]. A resource block is the smallest amount of resource that can be allocated in the uplink or downlink. The LTE air interface consists of physical signals and physical channels defined in [79]. There are three physical layer channels defined for the uplink in LTE. These are Physical Uplink Shared Channel (PUSCH), Physical Uplink Control Channel (PUCCH), and Physical Random Access Channel (PRACH). PUSCH carries user data and PUCCH is used for control signaling. PUCCH comprises the uplink data transmitted independently of traffic data. The PRACH carries the random access preamble that UE sends to access the network in non-synchronized mode. It is used to allow the UE to synchronize timing with the eNodeB. For LTE-based MCC systems, the PRACH will consist of 50 PRB. Consequently, to calculate the estimate or actual throughput of the proposed LTE-based MCC, firstly, the study determines the number of Resource Elements (RE) per 1msec subframe given as:

\[
RE = \text{Subcarriers} \times SC_{\text{FDMA symbol}} \times \text{Resource block} \times \text{Slots} \tag{1}
\]

Then, the data rate (DR) when assuming 64QAM with Single Input Single Output (SISO) antenna configuration and no coding is:
\[ DR = \text{Number of bits per 64QAM symbol} \times RE \] (2)

The overheads related to PUCCH, PRACH, pilot, random access, control plane, guard band overhead and other channels is approximately 71.55 % [77]. Therefore, the peak data rate or throughput is 71.55 % of \( DR \). Therefore, for 2x10 MHz bandwidth assigned for the public safety communications, there are 12 subcarriers, 7 SC-FDMA per symbol and 50 resource block for 2 slots [2, 14]. Hence, the LTE capacity is obtained analytically for the peak data rate as 37 Mbps.

\[ \text{Figure 6.1: LTE-based MCC network.} \]
6.3 Channel Scheduling Algorithm with priority levels:

The channel scheduling algorithm for the LTE-based MCC network is presented under this section.

6.3.1 Traditional uplink scheduling algorithm for LTE

The LTE uses single carrier frequency division multiple access (SC-FDMA) as the multiple access schemes for uplink communication. This means that the resources that the scheduler needs to distribute have both a time and a frequency component. The LTE radio scheduler is responsible for distributing a fixed number of available PRB (obtained from dividing the total system bandwidth) over a varying number of users/bearers in a fixed time interval, so-called for LTE, the Transmission Time Interval (TTI) which is set to 1ms [80]. There are several scheduling schemes used by the LTE schedulers such as Round Robin (RR), Blind Equal throughput (BET), Proportional Fair (PF), Dynamic Allocation (DA), Equal Resources (ER), Maximum Throughput (MaxT) and many others [81]. The schemes examine the achievements of using the different scheduling disciplines in terms of fairness, latency reduction, spectral efficiency, and system utilization. Some of these scheduling schemes maximize cell throughput and system performance but do not provide fairness among the users. They will not fit for MCC because, the schemes will deprive responder with poor SNR even if user/responder is highest priority defined in MCC. Some of schemes will waste resources, because all available resources are allocated to the present user irrespective of the user’s load capacity. The traditional MaxT scheduling
algorithm for LTE multicarrier is being used to enable user equipment (UE) to access available channel from the eNodeB [81].

6.3.2 Proposed uplink scheduling algorithm for MCC over LTE

The scheduler located at the eNodeB will receive the user signaling with the user buffer occupancy. Based on this, the scheduler will allocate the PRBs. In the uplink, the scheduler will schedule users and distributes the PRBs between its bearers. The proposed uplink scheduling and distribution algorithm for MCC over LTE is shown in Fig. 6.2. The description is illustrated as follows:

Mission critical user equipment (MCUE) will send signaling with load capacity $L_i$, and priority level, $P_i$, to eNodeB. The eNodeB scheduler checks for available PRB, and scheduler assigns number of resource blocks $N_{PRB}$ based on number of available resource block and the MCUE load. This study assumes suitable and stable physical layer. Once the link budget is maintained (i.e. 160.3 dB) and if a MCUE is at a distance within budget, it can access a base station, the algorithm assumes that MCUE has suitable SINR. Then, MCUE distributes the assigned the PRBs between its bearers. If scheduler does not find any available resource, for incoming MCUE, it checks $MCUE_i(t)$ holding on unto the PRBs, if it is pre-emptive user and if incoming- $MCUE_{i+1}(t)$ is also pre-emptive user, then, arrival user waits on the queue for predefined time $T_{q_{i+1}}$ usually less than 20s. However, if the $MCUE_i(t)$ holding on unto the PRBs is not pre-emptive user, the scheduler releases
off $MCUE_i(t)$ holding on unto the PRBs, and gives resources to $MCUE_{i+1}(t)$ -pre-emptive user. If $MCUE_i(t)$ holding on unto the PRBs, is not pre-emptive user and incoming call, $MCUE_{i+2}(t)$ is not pre-emptive user, then, the scheduler checks for which $MCUE$ has highest priority level and the scheduler assigns PRB based on first in first out (FIFO) while others wait in the queue with predefined time.

When the incoming $MCUE$ seizes or holds the resource, it distributes its load on the offered PRB at time to live (TTL). Although this causes overall accumulated time delay, however, the priority level is set with required holding time $T_r$ unto the resources, and holding time $T_q$ in queue. Once these periods are exceeded, the scheduler cuts off the current $MCUE$ and it releases the resource, and start over again if there is still more to do. It is assumed that the priority levels are predefined on the scheduler with appropriate indicator.

\[ P_i, \quad i = 1, 2, 3, ..., n \]

$P_1 \rightarrow$ pre-emptive user is set with service level requirement (SLR) of 5 s delay and probability of 5 %. It must not wait more than 5 s to get resource. The priority levels defined by real life users are based on type of MCC traffic.

The priority factor calculation:

\[ p_i^{\text{Emerg}}(t) = \arg \max_i[P_i(t)] \quad (3) \]

\[ i = 1, 2, 3, ..., n, \]
Figure 6.2: Uplink scheduling algorithm.
Figure 6.3: ARENA simulation of MCC load scheduling.

$E_{\text{mergL}}$ is the emergency level, $P_{k}^{\text{E}mergL}(t)$ is the time domain priority factor using the eNodeB scheduler, $i$ is the user number and $[P_i[t]]$ is the instantaneous priority level of bearer $i$. Then, evaluate the cell throughput and $MCUE$ delay probability and average waiting time.
6.4 Demonstration and simulation Results

In this study, ARENA software [76] is used to model and simulate the proposed MCC uplink resource acquisition as shown in Fig. 6.3. The simulator has a process module where the traffic generation is defined. The decide module decides what type of traffic and with what priority. The decide modules is also used to check for resource availability, type of ongoing and incoming traffic. Lognormal is assumed for heavy tail traffic generation and exponential distribution is used for service process. Table 6.1 shows ARENA module definitions and Table 6.2 shows the simulation parameters.

The study evaluates the cell throughput, user waiting time, and probability delay for various MCC users with various traffics. This study shows what quantity of traffic and number of users can be supported by 10 MHz LTE uplink with 50 PRBs, and 37 Mbps (reality) for MCC. Table 6.3 shows the outcomes of the simulation and they are compared with reality model and 3GPP proposed theory. Resource utilization as one of the metric of performance as seen from the results might be hard to say whether we want it to be high (close to 1) or low (close to 0). High values for resource utilization in the simulation results is good since it indicates little excess capacity. However, it can also be bad since it might mean a lot of traffic congestion in form of long queues and slow throughput. The results of the comparison are shown Table 6.4 and Fig. 6.4 shows the plot for the comparison. From figure 6.4, the proposed approach is similar to the reality or theoretical calculations.
Simulating 10 users with a traffic equal to 3.6 Mbps, from Fig. 6.4 and Table 6.3, a total traffic from all users, which is about 32Mbps will be uploaded successfully under 6 mins without bringing down the network and with overall system delay of 5.96 sec and 0.6 sec for individual delay. Moreover, the size and resolution of motion digital video will impact throughput on the LTE-based MCC uplink [82]. Table 6.5 shows an example of motion video size and resolution space occupied in disc. Using the simulation approach, a compressed video traffic less than 36 Mbps will successfully be delivered. These results are in line with the 3GPP standard for MC-Video. An MC-Video UE that is able to transmit video may support a video resolution from 320 x 240 at 10 frames per second up to and beyond 1280 x 720 at 30 frames per second [82].
Table 6.1: ARENA Module Block Symbol and Functions

<table>
<thead>
<tr>
<th>Module</th>
<th>Function</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Create module</td>
<td>Create module is where traffic generation is set</td>
<td>To make nth decision</td>
</tr>
<tr>
<td>Assign module</td>
<td>To assign simulation attribute</td>
<td>Allow user to take hold of resources</td>
</tr>
<tr>
<td>Queue</td>
<td>Queue #1 sets with 1 and #2 with 9 capacity</td>
<td>To get waiting information</td>
</tr>
<tr>
<td>Release module</td>
<td>Allow user to release resources</td>
<td>Allow setting processes</td>
</tr>
<tr>
<td>Record module</td>
<td>To record defined statistics</td>
<td>To mark exit for incoming traffic</td>
</tr>
</tbody>
</table>

Table 6.2: Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Type</td>
<td>Single cell</td>
</tr>
<tr>
<td>Channel Model</td>
<td>Okumura-Hata Urban</td>
</tr>
<tr>
<td>Traffic generation distribution</td>
<td>Lognormal</td>
</tr>
<tr>
<td>Traffic Service distribution</td>
<td>exponential</td>
</tr>
<tr>
<td>Discipline</td>
<td>Preemptive and FIFO</td>
</tr>
<tr>
<td>Traffic Service Time</td>
<td>20 s</td>
</tr>
<tr>
<td>MCUE Transmit power</td>
<td>23 dBm</td>
</tr>
<tr>
<td>MCUE-preemptive SLR</td>
<td>5% and 5 s delay</td>
</tr>
<tr>
<td>System Bandwidth</td>
<td>10MHz</td>
</tr>
<tr>
<td>Number of PRBs</td>
<td>50</td>
</tr>
<tr>
<td>PRB Bandwidth</td>
<td>200KHz</td>
</tr>
<tr>
<td>Capacity</td>
<td>37 Mbps</td>
</tr>
<tr>
<td>Channel link budget</td>
<td>160.3 dB</td>
</tr>
<tr>
<td>User distance from eNodeB</td>
<td>Within link budget</td>
</tr>
<tr>
<td>Traffic and user</td>
<td>10 users</td>
</tr>
<tr>
<td>Simulation time</td>
<td>360 sec</td>
</tr>
</tbody>
</table>
**Table 6.3:** Simulation Results

<table>
<thead>
<tr>
<th>Number of users</th>
<th>Total traffic (Mbps)</th>
<th>Waiting time (s)</th>
<th>Number in waiting</th>
<th>Work in progress</th>
<th>Resource utilization</th>
<th>Probability of delay (%)</th>
<th>Throughput (Mbps)</th>
<th>Used resources</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.60</td>
<td>0.00</td>
<td>0</td>
<td>5.40</td>
<td>0.11</td>
<td>0</td>
<td>3.38</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>7.20</td>
<td>0.00</td>
<td>0</td>
<td>10.52</td>
<td>0.21</td>
<td>0</td>
<td>6.66</td>
<td>9</td>
</tr>
<tr>
<td>3</td>
<td>10.80</td>
<td>0.00</td>
<td>0</td>
<td>15.25</td>
<td>0.30</td>
<td>0</td>
<td>10.24</td>
<td>14</td>
</tr>
<tr>
<td>4</td>
<td>14.40</td>
<td>0.00</td>
<td>0</td>
<td>20.06</td>
<td>0.40</td>
<td>0</td>
<td>13.48</td>
<td>19</td>
</tr>
<tr>
<td>5</td>
<td>18.00</td>
<td>0.00</td>
<td>0</td>
<td>26.06</td>
<td>0.52</td>
<td>0</td>
<td>16.74</td>
<td>23</td>
</tr>
<tr>
<td>6</td>
<td>23.40</td>
<td>0.00</td>
<td>0</td>
<td>31.58</td>
<td>0.63</td>
<td>0</td>
<td>22.05</td>
<td>30</td>
</tr>
<tr>
<td>7</td>
<td>25.2</td>
<td>0.00</td>
<td>0</td>
<td>36.64</td>
<td>0.73</td>
<td>0</td>
<td>23.98</td>
<td>33</td>
</tr>
<tr>
<td>8</td>
<td>28.80</td>
<td>2.00</td>
<td>5.06</td>
<td>48.50</td>
<td>0.87</td>
<td>0.61</td>
<td>27.09</td>
<td>38</td>
</tr>
<tr>
<td>9</td>
<td>32.40</td>
<td>3.37</td>
<td>8.25</td>
<td>55.80</td>
<td>0.95</td>
<td>0.90</td>
<td>30.94</td>
<td>42</td>
</tr>
<tr>
<td>10</td>
<td>36.00</td>
<td>5.96</td>
<td>18.36</td>
<td>66.60</td>
<td>0.96</td>
<td>1.82</td>
<td>32.18</td>
<td>47</td>
</tr>
</tbody>
</table>

**Table 6.4:** Maximum Parameter Comparison

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Approach</th>
<th>3 GPP proposed standard</th>
<th>Theory / Reality</th>
<th>Proposed approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity (Mbps)</td>
<td></td>
<td>50</td>
<td>37</td>
<td>36</td>
</tr>
<tr>
<td>PRBs</td>
<td></td>
<td>50</td>
<td>47</td>
<td>47</td>
</tr>
<tr>
<td>Number of user with = 3.6 Mbps</td>
<td></td>
<td>14</td>
<td>11</td>
<td>10</td>
</tr>
<tr>
<td>Waiting time (s)</td>
<td></td>
<td>7.88</td>
<td>6.26</td>
<td>5.96</td>
</tr>
<tr>
<td>Delay probability</td>
<td></td>
<td>2.41 %</td>
<td>1.91 %</td>
<td>1.82 %</td>
</tr>
</tbody>
</table>
Figure 6.4: Throughput vs number of users.

Table 6.5: Compressed Digital Video for Resolution of 320 X 240

<table>
<thead>
<tr>
<th>Time</th>
<th>Scale</th>
<th>None compressed</th>
<th>3:1</th>
<th>25:1 (JPEG)</th>
<th>100:1 (MPEG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 sec</td>
<td>6.75 Mb</td>
<td>2.25 Mb</td>
<td>270 Kb</td>
<td>68 Kb</td>
<td></td>
</tr>
<tr>
<td>1 min</td>
<td>400 Mb</td>
<td>133 Mb</td>
<td>16 Mb</td>
<td>4 Mb</td>
<td></td>
</tr>
<tr>
<td>1 hour</td>
<td>24 Gb</td>
<td>8 Gb</td>
<td>1 Gb</td>
<td>240 Mb</td>
<td></td>
</tr>
</tbody>
</table>
6.5 Channel Scheduling Algorithm without Priority levels:

What will be the impact of different traffic-data, voice, video and short messages on the performance of LTE uplink in emergency situations? The aim of this research is to tackle the challenges and propose solutions to the question above. The section looks at the performance of LTE-based MCC network in terms of channel utilization, throughput, delay, and message delivery ratio as the metrics of performance. The channel scheduling mechanism is done without priority levels. The simulation is done under various traffic load, different traffic generation, service distributions and different simulation time.

In order to achieve the aim of this study, a single eNodeB is considered because in MCC networks, the capacity is not distributed across wider area as it is experienced for commercial LTE networks. Here, emergency scenarios will normally happen in one location and one eNodeB will be sufficient for successful data transmission. This study uses ARENA as simulation tool to investigate the impact of heterogeneous traffic on the performance of LTE-based MCC networks. The simulation is based on different scenarios of different data applications on the air interface.

6.5.1 Demonstration and Simulation Results

In this study, ARENA software [76] is used to model and simulate different MCC traffics as shown in Fig. 6.5. Table 6.6 shows sample of ARENA modules. PMR traffic is being simulated in ARENA following first in first out (FIFO) discipline using queue theory [2]. In the create module of ARENA, the PMR traffic is generated
using different distributions.

Given a traffic arrival rate $\lambda$, (call or message/time), then the average inter-arrival time (average time between traffic), $\tau$ is

$$\tau = \frac{1}{\lambda}$$  \hspace{1cm} (4)

For instance, for motion video traffic of 320 x 240 resolution, 10 frames/s, 12 Mbps,

$$\lambda = 12 \times 10^6 \text{ bits/sec} \text{ or } 12 \times 10^6 \text{ bits} / 3600 \text{ hrs}$$

Therefore, the average inter-arrival time is:

$$\tau = \frac{1}{\lambda} = \frac{3600}{12 \times 10^6} = 0.0003 \text{ hrs.}$$  \hspace{1cm} (5)

The average inter-arrival time is used to set the traffic generation in the create module of ARENA using different probability distributions and simulations times as shown in Fig. 6.6.
Figure 6.5: ARENA simulation of MCC traffic model.

Table 6.6: ARENA Module Block Symbols and Functions

<table>
<thead>
<tr>
<th>Create module</th>
<th>Process module</th>
<th>Allow setting processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Create module is where traffic generation is set</td>
<td>Process module</td>
<td>Allow setting processes</td>
</tr>
<tr>
<td>Assign module</td>
<td>To assign simulation attribute (not used here)</td>
<td>To mark exit for incoming traffic</td>
</tr>
</tbody>
</table>
Figure 6.6: Traffic generation setting in the ARENA create module.
Figure 6.7: (a) Traffic processing setting in the ARENA process module (b) resource setting in the resource module of ARENA.

Figure 6.8: Processed traffic exit setting in ARENA.

Similarly, in the process module of the ARENA as shown in Fig. 6.7 a, seize-delay-release attribute is used in order for traffic to take hold of channel resources for processing or transferring of traffic and allow queue (delay) for other traffics. The
seized resources are released when processing is done. The service probability
distribution required for processing traffic is also set with different times required in
the process module (e.g EXP (20) in Fig. 6.7a). The capacity of resources is set to
50 according to 3GPP standard for MCC (Fig. 6.7 b). The dispose module (Fig. 6.8)
marked the exit for the processed traffics or users.

Figure 6.9: Traffic processing setting in ARENA
Furthermore, for running the simulation, the simulation time or replication length—represent the time that the LTE-MCC network can be up and transfer corresponding data (throughput), is configured in the set up window as shown in Fig. 6.9. This study evaluates the cell throughput, user waiting time, and resource utilization for various MCC users with various traffics for LTE-based MCC uplink network.

From the outcomes of the simulations, the throughput, \( T_p \) is calculated as:

\[
T_p = \frac{\text{no of traffics exit}}{\text{no of traffics generated}} \times \text{offered traffic (Mbps)} \quad (6)
\]

The number (no) of traffic that exit the model, number of traffic generated, resource utilization, and waiting or delay time given different offered traffic (Mbps), service times, and simulation times are obtained from the output of the ARENA software as shown in Figs. 6.10 and 6.11. Table 6.7 shows the simulation results when considering different probability distributions for traffic generation and service time. Tables 6.8, 6.9, and 6.10 show the outcomes of the simulations.
Figure 6.10: Outcomes of simulation from ARENA showing the resource utilization

Figure 6.11: Outcomes of simulation from ARENA showing traffic in, out and waiting time
### Table 6.7: Results for 5 Users, 7.2 Mbps each, 20 Secs Service Time, for Different Traffic Generation and Service Distributions

<table>
<thead>
<tr>
<th>Cases</th>
<th>Traffic generation distribution / Service distribution</th>
<th>Simulation time (s)</th>
<th>Traffic generated</th>
<th>Traffic exit</th>
<th>Resource utilization</th>
<th>Throughput (Mbps)</th>
<th>Waiting time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Lognormal / Lognormal</td>
<td>734</td>
<td>2028</td>
<td>1887</td>
<td>0.98</td>
<td>33.49</td>
<td>16.71</td>
</tr>
<tr>
<td>2</td>
<td>Lognormal / Exponential</td>
<td>326</td>
<td>926</td>
<td>983</td>
<td>0.95</td>
<td>30.44</td>
<td>10.73</td>
</tr>
<tr>
<td>3</td>
<td>Lognormal / Normal</td>
<td>359</td>
<td>975</td>
<td>832</td>
<td>0.96</td>
<td>30.72</td>
<td>16.38</td>
</tr>
<tr>
<td>4</td>
<td>Exponential / Lognormal</td>
<td>410</td>
<td>1166</td>
<td>1022</td>
<td>0.97</td>
<td>31.55</td>
<td>8.05</td>
</tr>
<tr>
<td>5</td>
<td>Exponential / Exponential</td>
<td>171</td>
<td>504</td>
<td>361</td>
<td>0.92</td>
<td>25.79</td>
<td>11.34</td>
</tr>
<tr>
<td>6</td>
<td>Exponential / Normal</td>
<td>238</td>
<td>670</td>
<td>528</td>
<td>0.95</td>
<td>28.37</td>
<td>11.15</td>
</tr>
<tr>
<td>7</td>
<td>Normal / Lognormal</td>
<td>432</td>
<td>1165</td>
<td>1021</td>
<td>0.94</td>
<td>31.55</td>
<td>5.03</td>
</tr>
<tr>
<td>8</td>
<td>Normal / Exponential</td>
<td>1775</td>
<td>4569</td>
<td>4425</td>
<td>0.99</td>
<td>34.87</td>
<td>17.31</td>
</tr>
<tr>
<td>9</td>
<td>Normal / Normal</td>
<td>292</td>
<td>784</td>
<td>643</td>
<td>0.95</td>
<td>29.53</td>
<td>12.97</td>
</tr>
</tbody>
</table>

### Table 6.8: Results for 5 Users, 7.2 Mbps each, Different Simulation Times, for Normal Traffic Generation and Exponential Service Distribution

<table>
<thead>
<tr>
<th>Category</th>
<th>Service time (s)</th>
<th>Simulation time (s)</th>
<th>Traffic generated</th>
<th>Traffic exit</th>
<th>Resource utilization</th>
<th>Throughput (Mbps)</th>
<th>Waiting time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>&gt;&gt; 2000</td>
<td>5124</td>
<td>5104</td>
<td>0.51</td>
<td>35.86</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>1775</td>
<td>4569</td>
<td>4425</td>
<td>0.99</td>
<td>34.87</td>
<td>17.31</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>131</td>
<td>339</td>
<td>195</td>
<td>0.91</td>
<td>20.70</td>
<td>13.41</td>
</tr>
<tr>
<td>4</td>
<td>40</td>
<td>92</td>
<td>236</td>
<td>92</td>
<td>0.88</td>
<td>14.03</td>
<td>5.45</td>
</tr>
<tr>
<td>5</td>
<td>50</td>
<td>80</td>
<td>201</td>
<td>59</td>
<td>0.86</td>
<td>10.57</td>
<td>4.02</td>
</tr>
<tr>
<td>6</td>
<td>60</td>
<td>77</td>
<td>196</td>
<td>52</td>
<td>0.86</td>
<td>9.55</td>
<td>3.91</td>
</tr>
<tr>
<td>7</td>
<td>120</td>
<td>65</td>
<td>159</td>
<td>19</td>
<td>0.85</td>
<td>4.30</td>
<td>0.12</td>
</tr>
<tr>
<td>8</td>
<td>360</td>
<td>61</td>
<td>145</td>
<td>6</td>
<td>0.85</td>
<td>1.49</td>
<td>0.04</td>
</tr>
</tbody>
</table>
Table 6.9: Results for 3 Users, 12 Mbps each, Different Simulation Times, for Normal Traffic Generation and Exponential Service Distribution

<table>
<thead>
<tr>
<th>Category</th>
<th>Service time (s)</th>
<th>Simulation time (s)</th>
<th>Traffic generated</th>
<th>Traffic exit</th>
<th>Resource utilization</th>
<th>Throughput (Mbps)</th>
<th>Waiting time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>&gt;&gt; 2000</td>
<td>5122</td>
<td>5103</td>
<td>0.51</td>
<td>35.87</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>1066</td>
<td>2782</td>
<td>2657</td>
<td>0.99</td>
<td>34.12</td>
<td>16.69</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>121</td>
<td>314</td>
<td>171</td>
<td>0.89</td>
<td>19.61</td>
<td>9.83</td>
</tr>
<tr>
<td>4</td>
<td>40</td>
<td>93</td>
<td>236</td>
<td>91</td>
<td>0.87</td>
<td>13.88</td>
<td>3.97</td>
</tr>
<tr>
<td>5</td>
<td>50</td>
<td>81</td>
<td>206</td>
<td>62</td>
<td>0.86</td>
<td>10.83</td>
<td>3.89</td>
</tr>
<tr>
<td>6</td>
<td>60</td>
<td>79</td>
<td>195</td>
<td>50</td>
<td>0.86</td>
<td>9.23</td>
<td>2.98</td>
</tr>
<tr>
<td>7</td>
<td>120</td>
<td>65</td>
<td>165</td>
<td>20</td>
<td>0.84</td>
<td>4.36</td>
<td>1.31</td>
</tr>
<tr>
<td>8</td>
<td>360</td>
<td>62</td>
<td>152</td>
<td>7</td>
<td>0.84</td>
<td>1.65</td>
<td>2.63</td>
</tr>
</tbody>
</table>

Table 6.10: Results for 1 User, 36 Mbps Different Simulation Times, for Normal Traffic Generation and Exponential Service Distribution

<table>
<thead>
<tr>
<th>Category</th>
<th>Service time (s)</th>
<th>Simulation time (s)</th>
<th>Traffic generated</th>
<th>Traffic exit</th>
<th>Resource utilization</th>
<th>Throughput (Mbps)</th>
<th>Waiting time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>&gt;&gt; 2000</td>
<td>5122</td>
<td>5102</td>
<td>0.51</td>
<td>35.86</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>1249</td>
<td>3217</td>
<td>3071</td>
<td>0.97</td>
<td>34.37</td>
<td>13.43</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>131</td>
<td>340</td>
<td>194</td>
<td>0.90</td>
<td>20.54</td>
<td>12.78</td>
</tr>
<tr>
<td>4</td>
<td>40</td>
<td>98</td>
<td>242</td>
<td>96</td>
<td>0.87</td>
<td>14.28</td>
<td>7.40</td>
</tr>
<tr>
<td>5</td>
<td>50</td>
<td>90</td>
<td>221</td>
<td>74</td>
<td>0.86</td>
<td>12.05</td>
<td>6.38</td>
</tr>
<tr>
<td>6</td>
<td>60</td>
<td>81</td>
<td>198</td>
<td>51</td>
<td>0.85</td>
<td>9.27</td>
<td>3.40</td>
</tr>
<tr>
<td>7</td>
<td>120</td>
<td>66</td>
<td>166</td>
<td>19</td>
<td>0.83</td>
<td>4.12</td>
<td>0.06</td>
</tr>
<tr>
<td>8</td>
<td>360</td>
<td>62</td>
<td>151</td>
<td>6</td>
<td>0.83</td>
<td>1.43</td>
<td>0.00</td>
</tr>
</tbody>
</table>
Table 6.11: Maximum Parameter Comparison

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Approach</th>
<th>3 GPP proposed standard</th>
<th>Theory / Reality</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity (Mbps)</td>
<td></td>
<td>50</td>
<td>37</td>
<td>36</td>
</tr>
<tr>
<td>Number of user with = 7.2 Mbps</td>
<td></td>
<td>7</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>PRBs</td>
<td></td>
<td>50</td>
<td>48</td>
<td>48</td>
</tr>
<tr>
<td>Waiting time (s)</td>
<td></td>
<td>22.89</td>
<td>18.17</td>
<td>17.31</td>
</tr>
<tr>
<td>Delay probability</td>
<td></td>
<td>7.00 %</td>
<td>5.55 %</td>
<td>5.29 %</td>
</tr>
</tbody>
</table>

The goal here is to test the probability distribution for the proposed network. This is done in order to get a suitable probability distribution that will provide efficient traffic flow (throughput) while minimizing delay problems. From Table 6.7, the results indicate closeness in the first case (Lognormal distribution for traffic generation and Lognormal for service distribution) and the eighth case (Normal distribution for traffic generation and Exponential for service distribution). Evidence of significance difference is carried out using T-statistics and the results obtained is highlighted in Table 6.12. The test parameters are chosen as highlighted below:

- null hypothesis: equal mean
- alter hypothesis: not equal
- significance value ,α = 0.05
t statistic = \frac{X - \mu}{\sigma/\sqrt{n}} \tag{7}

where \(X\) is the sample mean and \(\mu\) is the known mean

**Table 6.12:** Probability distribution comparison using t-statistics

<table>
<thead>
<tr>
<th>Probability distribution comparison</th>
<th>t statistic</th>
<th>critical value</th>
<th>decision</th>
</tr>
</thead>
<tbody>
<tr>
<td>sample mean 30.11</td>
<td>-4.6613</td>
<td>-1.86</td>
<td>• Reject null hypothesis</td>
</tr>
<tr>
<td>Normal/exponential distribution – <strong>case A</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>known mean 34.87</td>
<td></td>
<td></td>
<td>• 34.87 is significant</td>
</tr>
<tr>
<td>Lognormal/Lognormal – <strong>case B</strong></td>
<td>-1.543</td>
<td>-1.86</td>
<td>• Do not reject</td>
</tr>
<tr>
<td>i.e. next highest = 33.49</td>
<td></td>
<td></td>
<td>• 34.87 and 33.49 are statistically the same</td>
</tr>
<tr>
<td><strong>case A vs case B</strong></td>
<td></td>
<td></td>
<td>4 % increase</td>
</tr>
</tbody>
</table>
Both cases observed are significant and are used to implement the approach proposed in this study. It is also observed that the Normal distribution for traffic generation and Exponential for service times gives 4% more throughput with 1.38 bps throughput and 0.6s delay.

From Tables 6.8, 6.9, 6.10, and Figs. 6.12 and 6.13, it can be seen as the simulation time (i.e. More time to upload traffic) increases, the more the traffic throughput transferred. Also, using normal traffic generation distribution and exponential service distribution with a tolerable increase in waiting time gives more throughput than other probability distribution as seen in Fig. 6.14 and Table 6.7. According to Fig. 6.15, resource utilization is moderate for when there is one user and it is very high for when there are three or five users even with same total offered traffic (36 Mbps). Resource Utilization as one of the metric of performance might be hard to say whether we want it to be high (close to 1) or low (close to 0. High values for resource utilization in the simulations is good since it indicates little excess capacity. However, it can also be bad since it might mean a lot of traffic congestion in form of long queues and slow throughput. This is illustrated in the simulation results in Tables 6.8, 6.9 and 6.10 respectively for different MCC users.

From Figs. 6.16 and 6.17 and Tables 6.8, 6.9, and 6.10, the throughput is maximum when the service time is 20 sec and simulation time is around 1066 sec. Also, this is possible with the use of normal traffic generation distribution and exponential service distribution. Also, the waiting time is tolerable for MCC services.
Figure 6.12: Throughput vs simulation time categories.

Figure 6.13: Simulation time vs Throughput.
Figure 6.14: Throughput and waiting time vs different cases of probability distributions.

Figure 6.15: Resource utilization vs simulation time categories.
The results of the simulation are also compared with actual / reality model and 3GPP proposed theory in Table VI and the results of the comparison are shown in Fig. 6.18. From Fig. 6.18, the result of the simulation approach is similar to the reality
or theoretical calculations. Simulating ten users with a traffic equal to 3.6 Mbps each; and a total traffic from all users, which is about 32 Mbps will be uploaded successfully under 6 mins without bringing down the network and with overall system delay of 5.96 sec and 0.6 sec for individual delay. Based on the analysis discussed in this study, it is therefore recommended that one user should only be allowed to upload at a time if the user has traffic around 30 Mbps, and ten users can upload to the eNodeB at the same time if each has a traffic less than 3.6 Mbps. Also, three users with traffic less than 12 Mbps each and 5 users with traffic less than 7.2 Mbps each can simultaneously use LTE-Based MCC uplink network to connect to the dispatch center.

**Figure 6.18:** Throughput vs number of users.
The throughput obtained from the simulation is compared with the analytical / theoretical approach and 3GPP standard. This is shown graphically in Fig. 6.18. There is closeness in the results obtained from the simulation approach and theoretical approach. These two results are far from the 3GPP expectations on capacity. Erring on capacity expectations of a network has negative consequences. If we think LTE cell will provide 50 Mbps of throughput (standard value by 3GPP) while in reality can only provide 37 Mbps, the MCC users will be short by 26 % of capacity in the access network resulting in poor user experience (slow upload, blocking of traffic). This is why it is crucial to get capacity expectations right.

The statistics used for the final comparison is Mean Absolute Percentage Error (MAPE). It expresses accuracy as percentage of error. For accuracy of a model, it should be less than 10 [83]. The comparison result between the simulation and theoretical approach is less than 10 as shown in Table 6.13. This result indicates that the prediction in this study is accurate.

Also, Mean Squared Error of Mean Squared Deviation (MSE) is used as statistics measures of accuracy. It measures the average of the squares of the errors or deviations. It shows the difference between the estimator (3GPP standard) and what is estimated (theoretical values and simulation approach). Since values obtained for the comparison between theoretical and simulation are closer to zero. This indicates accuracy in the prediction.
\[
\text{MAPE} = \frac{1}{n_j} \sum_{k=1}^{n_j} \left| \frac{e_{M_k} - t_{M_k}}{e_{M_k}} \right| \times 100 \%, \quad (8)
\]

\[
\text{MSE} = \sum_{k=1}^{n_j} \frac{(e_{M_k} - t_{M_k})^2}{n_j - 1} \quad (9)
\]

**Table 6.13:** Probability distribution comparison using MAPE and MSE

<table>
<thead>
<tr>
<th></th>
<th>Reality</th>
<th>3GPP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Simulation</strong></td>
<td>MAPE= 4.7 %</td>
<td>MAPE= 28 %</td>
</tr>
<tr>
<td></td>
<td>MSE = 1.1</td>
<td>MSE = 66</td>
</tr>
</tbody>
</table>
Chapter 7: Conclusion and Future Work

7.1 Summary of Results

This study reports first the traffic analytical modeling for proposed deployment of LTE network for public safety communications. The study demonstrates that deploying public safety networks over conventional commercial LTE networks will improve traffic capacity of such network and also make mission-critical services available on real time. It also shows the likely number of trunks that will be required form LTE network to meet the SLA for public safety network and also likely delays. Finally, the study presents the effect of optimizing network in term of cost as a result of deployment over LTE. To optimize the transition, the OPEX has to go below certain level.

Secondly, the performance of LTE-based MCC network using simulation scenarios is investigated. It is demonstrated in this study that the realistic uplink capacity for LTE-based MCC network is 37 Mbps. Using the proposed scheduling approach for LTE-based MCC, delay will be minimized, MCC priority level implementation will be achieved. Also, the throughput and channel resources are optimized.

The results also demonstrate that the modeled LTE-based MCC cell provides enough capacity to simultaneously serve up to 10 users; each with traffic less than 3.6 Mbps data on the uplink of the LTE-based MCC network.

The performance of LTE-based MCC using heterogeneous traffics in simulation scenarios is investigated. It is demonstrated in this study that using Normal
distribution for traffic generation and exponential distribution for service times, delay will be minimized. Also, the throughput and channel resource are optimized.

The study shows that the lower the traffic volume per user, the more number of users can simultaneously use the LTE-based MCC uplink without causing congestion or bring down the network.

Moreover, the simulation results also show that LTE offers a significant improvement over the existing PMR technologies in terms of transmission capacity and performance.

As a recommendation based on the research in this dissertation:

- 1 user should only be allowed to upload at a time if the user has traffic around 36 Mbps
- 10 uses can upload at the same time if each has a traffic less than 3.6 Mbps
- 3 users with traffic less than 12 Mbps can upload simultaneously on the LTE-based MCC network.
- 5 users with traffic less than 7.2 Mbps each can simultaneously upload to the network.

This LTE-based MCC network dimensioning approach can help the network designers in the implementation of equipment and devices that could support broadband MCC systems.
7.2 Future Work

The study in this dissertation is based on 3GPP LTE standards which is presently available in many countries of the world. LTE standards keeps evolving with releases of higher data rates and higher performance. In the near future, the research focus will be on the newest releases of 3GPP technology and its standards for MCC and services.

In the meantime, the future study will be to investigate the traffic characteristic and performance of other deployment options including DMO and group communications through simulation and measurement. In addition, the future study will include repeating experiment by varying simulation time, service time, probability distribution, number of resources, and evaluate the performance. The future study will also test the effects of different traffic generation and service distribution on network performance using other simulation tools.

In the same vein, performance evaluation in terms of coverage area of LTE-based MCC networks could be important for future research.
Appendix: Statistical Analysis

A. Forecasting Statistics

Other statistics used in this study, that is, $MAPE$ (Mean Absolute Percentage Error) and $Ts$, are provided in equations (A) and (B) respectively. $MAPE$ expresses accuracy as a percentage of error [83].

$$MAPE = \frac{1}{n_k} \sum_{i=1}^{n_k} \left| \frac{em - tm}{em} \right| \times 100\% \quad (A)$$

In equation (A) and (B), $em$ represents the simulated model values, $tm$ represents the theoretical model values and $n_k$ is number of samples. According to [83], [84], $MAPE$ should be less than 10. The values are obtained by “rule of thumb” as approximation bound to test the significant of prediction.

Also,

$$MSE = \sum_{j=1}^{n_k} \frac{(em - tm)^2}{n_k - 1} \quad (B)$$

where $MSE$ is the means squared error.
B. Research Publications


Chapter 8: References


[65] 3GPP, "Proximity - Based Services (ProSe)," 3GPP TS 23.303.


[67] 3GPP, "Mission Critical Push to Talk MCPTT (Release 13)," 3GPP TS 22.179.


*IEEE Communications*, March 1994.


[78] 3GPP, "LTE; Evolved Universal Terrestrial Radio Access (E-UTRA);
Physical layer procedures (3GPP TS 36.213 version 10.10.0 Release 10 )," 2013.

[79] 3GPP, "LTE; Evolved Universal Terrestrial Radio Access (E-UTRA);
Physical Channels and Modulation (3GPP TS 36. 211 version 10.0.0 Release 10)," 2011.

[80] Y. L. Fang Liu, "Uplink Channel-aware Scheduling Algorithm for LTE-
Advanced System," in 7th International Conference on Wireless

[81] Y. Zaki, Future Mobile Communications: LTE Optimization and Mobile

[82] 3GPP TS 22.281 V15.0.0, "3rd Generation Partnership Project; Technical
Specification Group Services and System Aspects, Mission Critical Video
Services over LTE (Release 15)," June 2017.


[84] C. Bozarth, "Measuring Forecast Accuracy: Approaches to Forecasting : A

[85] G. J. Fernandez, I. Cuinas, M. G. Sanchez and V. A. Alejos, "Radio-Electric
Validation of an Electronic Cowbell Based on ZigBee Technology," Antennas


