PERFORMANCE ANALYSIS OF PRIORITISATION AND QOS CONTROL MECHANISMS IN LTE FOR PUBLIC SAFETY COMMUNICATIONS

Author: Bektaş ŞAHIN
Advisor: Prof. Ramon FERRUS

Abstract: Analysis of QoS mechanisms and prioritization in LTE environments with consideration of a public safety communication.

Keyword list: LTE, LENA, Prioritization, ns3, QoS, Public Safety, MAC Schedulers, QCI, PS.
Acknowledgements

The most challenging part of my 26 years of life is coming to an end and I would like to thank Department of Theory and Communications of Universitat Politecnica de Catalunya as a whole for giving me the opportunity to complete my thesis, it has been a great privilege.

My first debt of gratitude goes to my supervisor Prof. Ramon Ferrus for both his patience and helpfulness throughout my thesis process. His inputs were invaluable and made me complete my thesis in the way it is now.

Also, I would like to thank my family for making me who I am now and for their financial and emotional support during the last two years. Without them I would not have accomplished most of the things I accomplished now. My father Naci, my mother Nihal and my sister Hazal, I love all of you and I would like to thank you all for believing in me.

My friends and my beloved cousins who were always there when I needed them, I would like to take this opportunity to thank them. They were always a great influence on me and shaped me the way I am now.

Bektaş ŞAHIN

Barcelona, July 2014
Table of Contents

Table of Contents .................................................................................................................................................. iii
List of Figures ........................................................................................................................................................ iv
List of Tables .......................................................................................................................................................... vi

1. Introduction ...................................................................................................................................................... 1
2. Long Term Evolution (LTE) ........................................................................................................................ 3
   2.1 Requirements ............................................................................................................................................... 3
   2.2 Features ....................................................................................................................................................... 5
   2.3 LTE Network .............................................................................................................................................. 6
   2.4 MAC Schedulers........................................................................................................................................ 7
      2.4.1 Maximize Throughput Scheduler ...................................................................................................... 7
      2.4.2 Round Robin Scheduler ..................................................................................................................... 8
      2.4.3 Proportional Fair Scheduler ............................................................................................................... 8
3. Public Safety Communications .................................................................................................................... 10
   3.1 Scheduling Prioritization ........................................................................................................................ 11
   3.2 Prioritization Methods ............................................................................................................................. 12
      3.2.1 Pre-Emption and Pre-Emptability ..................................................................................................... 12
      3.2.2 Rate Limiting and Bandwidth Management ...................................................................................... 13
4. ns3 Simulator and LENA ............................................................................................................................. 14
   4.1 Concepts .................................................................................................................................................... 14
      4.1.1 Key Abstractions ............................................................................................................................... 14
      4.1.2 Simple ns3 Script .............................................................................................................................. 15
   4.2 Lena and LTE ............................................................................................................................................ 16
      4.2.1 Included Models and Shortcomings ................................................................................................ 17
      4.2.2 Simulation Outputs .......................................................................................................................... 19
5. Performance Analysis of Prioritization ....................................................................................................... 22
   5.1 Simulation Settings .................................................................................................................................. 22
   5.2 Only Bulk Send Application .................................................................................................................... 24
      5.2.1 Impact of the scheduling algorithm .................................................................................................. 26
      5.2.2 Impact of the system load ................................................................................................................ 30
   5.3 Only Streaming Application ..................................................................................................................... 33
      5.3.1 Impact of the Scheduler Algorithm .................................................................................................. 34
      5.3.2 Impact of the System Load ................................................................................................................ 38
   5.4 Both Applications Combined without Prioritization ............................................................................... 42
      5.4.1 Results .............................................................................................................................................. 42
   5.5 Prioritization ............................................................................................................................................. 44
      5.5.1 Single Application Prioritization ..................................................................................................... 45
      5.5.2 Both Applications ............................................................................................................................... 47
6. Conclusions ..................................................................................................................................................... 53
7. References ...................................................................................................................................................... 55
8. Appendix A ..................................................................................................................................................... 57
   8.1 2 Level Prioritization Results with Single Application ............................................................................... 57
   8.2 Mixed Application Extra Results .......................................................................................................... 59
9. Appendix B ..................................................................................................................................................... 66
List of Figures

Figure 2.1. Map of countries where LTE is deployed or planned to be deployed as of February 2014. [wik].............. 3
Figure 2.2. LTE network architecture[13]. ........................................................................................................ 7
Figure 3.1. System view of designated networks for PPDR and commercial services ........................................ 10
Figure 4.1. Lena model overview [11]. ............................................................................................................. 16
Figure 4.2. Lena end to end data plane [11]. ..................................................................................................... 17
Figure 4.3. Flow monitor sample output. .......................................................................................................... 20
Figure 5.1. Scenario configuration. .................................................................................................................. 22
Figure 5.2. Simulation area and the distribution of Nodes. .................................................................................. 24
Figure 5.3. Only TCP scenario configuration. .................................................................................................... 25
Figure 5.4. Node distribution for only TCP scenario. ........................................................................................ 25
Figure 5.5. CDF plot of throughput for only TCP PF scheduler scenario. .......................................................... 26
Figure 5.6. CDF plot for only TCP RR scheduler scenario. ................................................................................. 27
Figure 5.7. CDF plot for only TCP MT scheduler scenario. ............................................................................... 28
Figure 5.8. CDF plot of throughput for only TCP and all schedulers. ............................................................... 29
Figure 5.9. CDF plot of delay for only TCP and all schedulers. ..................................................................... 29
Figure 5.10. CDF plot of throughput with different no of users for only TCP PF scheduler scenario .............. 30
Figure 5.11. CDF plot of delay with different no of users for only TCP PF scheduler scenario.................... 31
Figure 5.12. Throughput vs Number of Users for only TCP PF scheduler scenario. .................................... 31
Figure 5.13. CDF plot of throughput with different no of users for only TCP MT scheduler scenario .......... 32
Figure 5.14. CDF plot of delay with different no of users for only TCP MT scheduler scenario ................. 32
Figure 5.15. Throughput vs Number of Users for only TCP MT scheduler scenario ..................................... 33
Figure 5.16. Scenario configuration for only UDP scenario. ......................................................................... 33
Figure 5.17. CDF plot for only UDP PF scheduler scenario. ......................................................................... 34
Figure 5.18. CDF plot for only UDP RR scheduler scenario. ......................................................................... 35
Figure 5.19. CDF plot for only UDP MT scheduler scenario. ......................................................................... 36
Figure 5.20. CDF plot of throughput for only UDP and all schedulers. .......................................................... 37
Figure 5.21. CDF plot of delay for only UDP and all schedulers. ................................................................. 37
Figure 5.22. CDF plot of throughput with different no of users for only UDP PF scheduler scenario .......... 38
Figure 5.23. CDF plot of delay with different no of users for only UDP PF scheduler scenario ................. 39
Figure 5.24. Throughput vs Number of Users for only UDP PF scheduler scenario. .................................... 39
Figure 5.25. CDF plot of throughput with different no of users for only UDP MT scheduler scenario .......... 40
Figure 5.26. CDF plot of throughput with different no of users for only UDP MT scheduler scenario .......... 41
Figure 5.27. Throughput vs Number of Users for only UDP MT scheduler scenario .................................... 41
Figure 5.28. Aggregate throughput of mixed application scenario with different number of UDP users ....... 42
Figure 5.29. Per user throughput of mixed application scenario with different number of UDP users ......... 43
Figure 5.30. Per user throughput for 3 levels of prioritization on TCP application and X=5......................... 45
Figure 5.31. Per user throughput for 3 levels of prioritization on TCP application and X=10 ..................... 46
Figure 5.32. Per user throughput for 3 levels of prioritization on UDP application X=5.............................. 46
Figure 5.33. Per user throughput for 3 levels of prioritization on UDP application X=10 ......................... 47
Figure 5.34. Per user throughput for PS officials on TCP application and X=5............................................. 48
Figure 5.35. Per user throughput for PS officials on TCP application and X=10........................................... 49
Figure 5.36. Per user throughput for PS officials on UDP application and X=5........................................... 50
Figure 5.37. Per user throughput for PS officials on UDP application and X=10........................................... 51
Figure 8.1. Per user throughput for TCP application 2 priority levels and X=5 ............................................. 57
Figure 8.2. Per user throughput for TCP application 2 priority levels and X=10 .............................................. 58
Figure 8.3. Per user throughput for UDP application 2 priority levels and X=5 ............................................. 58
Figure 8.4. Per user throughput for UDP application 2 priority levels and X=10 .......................................... 59
Figure 8.5. CDF plot for TCP (Prio 1) with X=5 ............................................................................................... 59
Figure 8.6. CDF plot for UDP (Prio 2) with X=5 ............................................................................................ 60
Figure 8.7. CDF plot for UDP (Prio 3) with X=5 ............................................................................................ 60
Figure 8.8. CDF plot for TCP (Prio 1) with X=10 .......................................................................................... 61
Figure 8.9. CDF plot for UDP (Prio 2) with X=10 .......................................................................................... 61
Figure 8.10. CDF plot for UDP (Prio 3) with X=10 .......................................................................................... 62
Figure 8.11. CDF plot for TCP (Prio 1) with X=5 ............................................................................................ 62
Figure 8.12. CDF plot for TCP (Prio 2) with X=5 ............................................................................................ 63
Figure 8.13. CDF plot for TCP (Prio 3) with X=5 ............................................................................................ 63
Figure 8.14. CDF plot for UDP (Prio 1) with X=10............................................................................................ 64
Figure 8.15. CDF plot for TCP (Prio 2) with X=10............................................................................................. 64
Figure 8.16. CDF plot for TCP (Prio 3) with X=10............................................................................................. 65
List of Tables

Table 3.1. QCI Characteristics .......................................................................................................................... 11
Table 3.2. ARP mapping table. .......................................................................................................................... 13
Table 5.1. Application parameters. .................................................................................................................... 22
Table 5.2. Simulation area parameters. .................................................................................................................. 23
Table 5.3. LTE default parameters. .................................................................................................................... 23
Table 5.4. Delay and Throughput statistics for only TCP PF scheduler scenario. ........................................... 26
Table 5.5. Delay and Throughput statistics for only TCP RR scheduler scenario. ........................................... 27
Table 5.6. Delay and Throughput statistics for only TCP MT scheduler scenario. ........................................... 28
Table 5.7. Delay and Throughput statistics for only UDP PF scheduler scenario. ........................................... 34
Table 5.8. Delay and Throughput statistics for only UDP RR scheduler scenario. ........................................... 35
Table 5.9. Delay and Throughput statistics for only UDP PF scheduler scenario. ........................................... 36
Table 5.10. Mean delay statistics of mixed application scenario with different number of UDP users. .......... 43
Table 5.11. Scenario settings for mixed application. ......................................................................................... 48
Table 5.12. Mean delay statistics for PS officials running TCP. ................................................................. 49
Table 5.13. Mean delay statistics for PS officials running UDP. ................................................................. 51
Table 8.1 Priority distribution ............................................................................................................................ 57
1. Introduction

This document presents analysis of QoS and prioritization mechanisms in Long Term Evolution (LTE) environments. The situation at hand is public safety communications and how can we prioritize these communications above commercial users.

In the last decade, communication technologies emerged to greater speeds and lower delay rates. In the past, a regular voice communication was considered enough for a public safety official however because of the technological improvements, the needs have increased. Now multimedia communications are considered necessary whereas it was impossible in the past. And this is where LTE comes in, with much higher speeds and lower latencies then its' predecessors.

However it is not enough as in a congested situation it is necessary for the public safety officials to have access to the resources so they can act and prevent further damage. In this paper, we consider the possibility of prioritizing public safety officials with their quality of service class identifier (Qci) values. Qci values have 9 different priority levels and they all have their own characteristics in regards of delay budget and packet error loss rate and these values are predefined on evolved packet service (EPS) bearers. We will consider the possibility of attaching a high priority bearer to public safety officials and observe the results in a congested environment to see if they can get the necessary resources.

This paper will consist of 5 different chapters after this one. In the second chapter, technological aspects of LTE will be explained. For this purpose, the requirements, features, LTE network architecture and our point of interest MAC schedulers will be explained.

Third chapter will be about public safety communications. In that chapter, a brief introduction to public safety communications will be given and then scheduling prioritization will be explained in context of public safety communications. Last point of interest will be prioritization methods.

The following chapter will be devoted on the simulation program, ns3. For the simulations, LENA module of ns3 is used and the results are obtained via that. After a brief introduction concepts of the simulation environment will be explained, followed by another explanation but this time about LENA. This program is an ongoing project and there is still some shortcomings and that will be our first point of interest, then simulation outputs and their interpretations will be given.

The last chapter is about the simulations. First part will explain the simulation environment and the following sub-chapters will consist of the results obtained. For the results part we considered 4 different scenarios. Firstly there will be only one type of application installed on all nodes and the results will be examined. The applications are one UDP and one TCP. So after these first two scenarios, the next one will be about combining the applications. We That part will be divided into two as well, one being without prioritization and the second one with prioritization. Prioritization will be held in two different branches as well, in one of them only one application will be installed on all nodes and in the following one both applications will be mixed.

The main objective of this work in all is to get familiar with ns3 simulator and LENA in particular. The simulation environment and how the results are being assessed is one of the most important parts of this paper.
Public safety communications is the key element in this paper as it is highly regarded as crucial in today's mobile communications industry. Public safety communications means to have access to resources for a group of public safety officials in a time of need. This topic is investigated in chapter 3 more deeply and our approach in how to prioritize them will be displayed. With the help of MAC schedulers, public safety officials will be given the resources they need even in a congested scenario.
2. Long Term Evolution (LTE)

Long Term Evolution, marketed as 4G LTE is a standard for wireless communication of high speed data for mobile phones and data terminals. It is based on GSM/EDGE and UMTS/HSPA network technologies, increasing the capacity and speed using different radio interfaces with some changes to the core network. The standard is developed by 3GPP and is described in release 8 with improvements and enhancements on the following releases. [1][2]

This technology was first adopted in Stockholm and Oslo by TeliaSonera on 2009 and later deployed in much more countries. [3] The map of LTE technologies being deployed or planned can be seen on Figure 2.1.

![Figure 2.1. Map of countries where LTE is deployed or planned to be deployed as of February 2014. [wik]](image)

The countries colored with red shows the ones that already has LTE deployed, dark blue ones being the ones that has LTE technology being deployed or planned and lastly light blue ones depict the countries with trial systems.

In the following sections the technology behind LTE will be further explained like the features and requirements of the system and how it works.

2.1 Requirements

In order for the LTE technology to be deployed and be operational, carriers needs to achieve certain characteristics regarding the performance of the system that are determined by the 3GPP organization. These aforementioned requirements will be further discussed below.

- Peak Data Rate Requirements
• Instantaneous peak data rate should be 100 mb/s within a 20 MHz downlink spectrum allocation. (5 bps/Hz)
• Instantaneous peak data rate should be 50 mb/s within a 20 MHz uplink spectrum allocation. (2.5 bps/Hz)

- Control Plane Latency Requirements
  • Transition time of less than 100ms from a camped cell, such as Release 6 Idle Mode, to an active state such as Release 6 CELL_DCH (cell dedicated channel).
  • Transition time of less than 50ms from a dormant cell, such as Release 6 CELL_PCH (cell paging channel) to an active state such as Release 6 CELL_DCH.

- User Plane Latency Requirements
  • Less than 5ms in unload condition (i.e. single user with single data stream) for small IP packet.

- User Throughput
  • Downlink: Average user throughput per MHz, 3 to 4 times of Release 6 HSDPA.
  • Uplink: Average user throughput per MHz, 2 to 3 times of Release 6 HSUPA.

- Spectrum Efficiency Requirements
  • Downlink: In a loaded network, target for spectrum efficiency 3 to 4 times of Release 6 HSDPA.
  • Uplink: In a loaded network, target for spectrum efficiency 2 to 3 times of Release 6 HSUPA.

- Mobility Requirements
  • E-UTRAN should be optimized for low mobile speed from 0 km/h to 15 km/h.
  • Higher mobility speed from 15 km/h to 120 km/h should be supported with high performance.
  • Mobility across the cellular network should be maintained between 120 km/h to 350 km/h.

- Coverage Requirements
  • Throughput, spectrum efficiency and mobility requirements described above should be obtained for 5km cells and with a slight degradation for 30km cells. Cells ranging to 100km should not be precluded.

- Further Enhanced Multimedia Broadcast Multicast Service (MBMS)
  • While reducing terminal complexity: Same modulation, coding, multiple access and UE bandwidth achieved like unicast operation.
  • Provision for simultaneous dedicated voice and MBMS services to the user.

- Spectrum Flexibility Requirements
  • E-UTRA should operate in spectrum allocation of different sizes, including 1.25 MHz, 1.6 MHz, 2.5 MHz, 5 MHz and 20 MHz for both the uplink and downlink. Operation in paired and unpaired spectrum should be supported.
  • The system should be able to support content delivery over an aggregation of resources including Radio Band Resources (as well as power, adaptive
scheduling etc) in the same and different bands, in both uplink and downlink and in both adjacent and non-adjacent channel arrangements. A "Radio Band Resource" is defined as all spectrum available to an operator.

- **Co-Existence and Inter-Networking with 3GPP Radio Access Technology (RAT)**
  - Co-Existence in the same geographical region and co-location with GERAN/UTRAN on adjacent channels.
  - E-UTRAN terminals supporting also GERAN and/or UTRAN operation should be able to support measurements of, and handover from and to, both 3GPP UTRAN and 3GPP GERAN.
  - The interruption time during a handover of real-time services between E-UTRAN and UTRAN should be less than 300msec.

- **Architecture and Migration Requirements**
  - Single E-UTRAN architecture.
  - The E-UTRAN architecture shall be packet based, although provisions should be made to support systems supporting real-time and conversational class traffic.
  - E-UTRAN architecture shall minimize the presence of "single points of failure".
  - E-UTRAN architecture shall support an end-to-end QoS.
  - Backhaul communication protocols should be optimized.

The previous requirements should be satisfied in order to deploy a functioning and ready to operate LTE system. LTE is actually a road step towards 4G network development as in the future it will ease the transition between 3G/3.5G networks to 4G networks thoroughly.

### 2.2 Features

LTE features better performance than its predecessors that are 3G and 3.5G. Some of the features that LTE has in order achieve this better performance are listed below.

- **LTE has higher spectral efficiency.**
  - Usage of OFDM (Orthogonal Frequency Division Multiplexing) in downlink makes the system robust against multipath interference and provides high affinity to advanced features such as frequency-domain channel-dependant scheduling and MIMO(multiple input multiple output).
  - Usage of DFTS-OFDM (Single-carrier FDMA) provides low PAPR(peak to average power ratio) and also opens the gate for user orthogonality in frequency domain.
  - It is a multi antenna application.

- **Both FDD and TDD modes are supported.**

- **Very low latency.**
  - Short TTI (Transmission time interval), fast RRC (Radio Resource Control) procedures and simple RRC states provides this behaviour.
• Simple Protocol Architecture.
  o LTE is based on shared channels.
  o Packet Switched mode is only available to VoIP applications.

• Simple Architecture
  o ENB is the only E-UTRAN node.

• Compatibility and Inter-Networking
  o Possible with earlier 3GPP releases.
  o Possible with other systems such as CDMA2000.

• Efficient Multicast/Broadcast Structure
  o Single frequency network with OFDM.

• Support for Self Organizing Networks (SON) operation.

These aforementioned features are what makes LTE a better and efficient system over its' predecessors. The improved performance and simplicity of the system provides better results in real time situations.

2.3 LTE Network

LTE network consists of two main parts [14], first one being the radio access network called as evolved UMTS radio access network (E-UTRAN) and the evolved packet core (EPC). EPC is mostly concerned about session and mobility management functions whereas E-UTRAN is more concerned about radio transmission function. The base stations in E-UTRAN are called evolved NodeB's (eNB's) [13]. Some of the things that EPC handles can be listed as:

• Mobility Management Entity (MME)
  o Handles location management.

• Serving Gateway (S-GW)
  o Handles traffic from and to E-UTRAN.

• Packet Data Network Gateway (P-GW)
  o Handles IP connectivity with other IP networks.

• Home Subscriber Server (HSS)
  o A database that contains user subscription related information.

The LTE IP connectivity service is established through Evolved Packet System (EPS) bearers. Users have an EPS bearer attached to them that defines the QoS that they will receive. These bearers are indicated with their QoS class identifier (Qci) values and assigned a QoS value. Following figure depicts the network architecture of LTE;
2.4 MAC Schedulers

One of the key elements in a LTE environment is the MAC schedulers. It has direct influence on how the system performs. There are several different MAC scheduler types, some of them focuses on generating maximum throughput whereas some of them prioritizes fairness among users. This paper focuses on 3 different schedulers as a start and continues working with Proportional Fair (PF) scheduler. These schedulers are, round robin (RR), maximize throughput (MT) and the aforementioned PF.

2.4.1 Maximize Throughput Scheduler

A scheduling algorithm for maximizing the throughput on the downlink of a multiuser Long Term Evolution (LTE) cellular communication system is studied in [4]. This scheduler can be obtained on both frequency domain and time domain. This paper will only include this scheduler in time domain. Maximize throughput (MT) scheduler [15] focuses on giving maximum possible throughput however if the user is at the edge of the cell then it may run into extreme delays and low resource allocation. This is due to the fact that for the scheduler, those nodes are more expensive than others. This behavior will be examined further in the simulation results part.

Mathematically, MT scheduler defines the achievable rate $R_i(k, t)$ as;

$$R_i(k, t) = \frac{S(M_{kk}(t), 1)}{T}$$  \hspace{1cm} (2.1)
Where $M_{i,k}(t)$ depicts, M being the MCS of user i on RB k and t being the subframe index. $\tau$ is the TTI duration. At the start of every subframe $t$, each RB is assigned to a certain user. In detail, the index $i_k(t)$ to which RB k is assigned at time t is determined as;

$$i_k(t) = \max_{j=1...N} R_j(k, t)$$  \hspace{1cm} (2.2)

When there are several users with same throughput, MT scheduler always selects the first node that is created. Fairness is never considered in MT scheduler.

### 2.4.2 Round Robin Scheduler

Round robin scheduler has a fairly simpler structure then the other two considered here. The main consideration done by round robin scheduler is that it does not take into account any kind of consideration. What it mainly does is allocate resources in a circular motion to all nodes equally. Round robin schedulers work by assigning a time slice or quantum to a data flow. It is pre-determined by a number and even if the flow does not end at the end of the flow, the slot is given to the next flow. The previous flow then will have to wait till the next time it is allowed to transmit.

### 2.4.3 Proportional Fair Scheduler

Proportional fair (PF) [16] scheduler will be the main scheduler for our simulations. PF scheduler is based upon maintaining a balance between network throughput and the minimum level of service a user has. This is mainly done by assigning each flow a data rate that is inversely proportional to its anticipated resource consumption. (6) . The mathematical expression of proportional fair scheduler starts similar to MT scheduler, first the achievable data rate $R_i(k, t)$;

$$R_i(k, t) = \frac{S(M_{i,k}(t), 1)}{\tau}$$  \hspace{1cm} (2.3)

The difference starts while obtaining the index as now fairness is included;

$$i_k(t) = \max_{j=1...N} \frac{R_j(k, t)}{T_j(t)}$$  \hspace{1cm} (2.4)

Where $T_j(t)$ is the perceived past throughput performance of user j. PF scheduler does not guarantee adjacent radio block groups (RBG). $T_j(t)$ is determined at the end of the subframe t with an exponential moving average approach like;

$$T_{j}(t) = \left(1 - \frac{1}{\alpha}\right) T_{j}(t-1) + \frac{1}{\alpha} T_{\bar{j}}(t)$$  \hspace{1cm} (2.5)

$\alpha$ represents the time constant of the exponential moving average. $T_{\bar{j}}(t)$ depicts the actual throughput of the user j in the subframe t and is calculated by first getting the actual $M_{\bar{j}}(t)$;

$$M_{\bar{j}}(t) = \max_{k: i_k(t) = j} M_{j,k}(t)$$  \hspace{1cm} (2.6)

then the total number of RBG's assigned to the user j is obtained by;

$$B_j(t) = |\{k: i_k(t) = j\}|$$  \hspace{1cm} (2.7)
Where \(|.|\) represents the cardinality of the set. Lastly to obtain \( T_j(t) \);

\[
T_j(t) = \frac{S(M_j(t), B_j(t))}{\tau}
\]  

(2.8)
3. Public Safety Communications

In the past, public protection and disaster relief (PPDR) was satisfied over Private/Professional mobile radio (PMR) technologies such as TETRA and TETRAPOL [13]. Although they had some advantages over that day's standards such as GSM they also had disadvantages. The biggest disadvantage of these technologies is that they are mostly voice centric. It was a solid solution to PPDR situations back in the day but in today's world, it is impossible to just stay with voice. This brings together the problem of more bandwidth, more speed and reliability. With the emerging LTE technology, now there is a possible solution to Public Safety concerns.

LTE has emerged as a high speed and low latency IP connection medium which allowed users to connect to external IP networks. This ability can be utilized by any application that relies on IP communication.

Nowadays due to the emerging technologies, the needs of PPDR operations are also increasing. They require access to more wider range of applications that can be textual, image or video applications. Some of these applications can be, video on demand, mobile office applications and online database enquiry [17].

Most of the PPDR service requirements are data traffic based and requires a client and server application with IP connectivity. Thus LTE is a suitable choice to implement these kinds of applications as it is ready for such. There are two ways to ensure connection to PPDR applications amongst others. One would be to have a dedicated network just for public safety and have another one for commercial usage. The other way would be to prioritize PPDR applications over others so in a situation where eNB is congested it would prefer PS officials over others. The following figure depicts the architecture with designated networks to PPDR and commercial;

![Figure 3.1. System view of designated networks for PPDR and commercial services.](image)

The other way to ensure connection to the PS officials by prioritization is the main scope of this document. In a given scenario, where there is no designated network for PS officials, we want to ensure that they are given a sufficient amount of bandwidth to have connection.
In general, to transmit something, a user has to pass 3 different areas in LTE. Those are access, admission and scheduling gates. Access gate determines if the user has the right to transmit whereas admission gate is where eNB checks if the user has the right to transmit and lastly, scheduling gate is concerned about bandwidth allocations.

In this paper, scheduling prioritization for public safety will be examined. Our scenario will start basic with simple application and one type node group and grow into more complex scenarios where there will be a couple different groups with different prioritization levels. The prioritization in the scheduling level is granted by the use of quality of service class identifier (QCI). As it will be examined in more detail in the following sections, the only important thing to know here is that granted a QCI value that has higher priority, the user will have firsthand access to resources. This might differ for scheduling algorithms but mainly the idea is like this.

### 3.1 Scheduling Prioritization

Scheduling priority starts working after the user is allowed to transmit/receive by both access and admission gates. After that it is queued and the place in the queue is determined by the Qci value. Mainly scheduling prioritization is concerned with packet latency and packet loss rate. At the time of this paper the following QCI value table is considered to be sufficient for scheduling prioritization applications[7];

<table>
<thead>
<tr>
<th>QCI</th>
<th>Resource Type</th>
<th>Priority</th>
<th>Packet Delay Budget</th>
<th>Packet Error Loss Rate</th>
<th>Example Services</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>GBR</td>
<td>2</td>
<td>100 ms</td>
<td>$10^{-2}$</td>
<td>Conversational Voice</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>4</td>
<td>150 ms</td>
<td>$10^{-3}$</td>
<td>Conversational Video</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>3</td>
<td>50 ms</td>
<td>$10^{-3}$</td>
<td>Real Time Gaming</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>5</td>
<td>300 ms</td>
<td>$10^{-6}$</td>
<td>Non Conversational Video</td>
</tr>
<tr>
<td>5</td>
<td>Non-GBR</td>
<td>1</td>
<td>100 ms</td>
<td>$10^{-6}$</td>
<td>IMS Signalling</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>6</td>
<td>300 ms</td>
<td>$10^{-6}$</td>
<td>Video TCP (www, e-mail, ftp etc)</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>7</td>
<td>100 ms</td>
<td>$10^{-3}$</td>
<td>Voice, Video, Interactive Gaming</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>8</td>
<td>300 ms</td>
<td>$10^{-6}$</td>
<td>Video, TCP Based</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>9</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Table 3.1. QCI Characteristics*

Note: GBR stands for guaranteed bit rate.
Apart from Qci values, EPS bearer's QoS can be parameterized with guaranteed bit rate (GBR) and allocation and retention priority (ARP). All of these are configured by policy and charging rules (PCRF) entity according to the operators policy. In this document the method that will be used for prioritization will be with Qci values.

### 3.2 Prioritization Methods

In this section, the methods that are used to give prioritized users, public safety users, their needed connection. There are several methods and it might differ with the situation at hand. For example if the situation is not life threatening, then dropping a connection in order to give it to a PS officer might not be needed.

The most popular methods will be discussed in this section and they are; pre-emption and rate limiting.

#### 3.2.1 Pre-Emption and Pre-Emptability

Pre-emption refers to immediate removal of the user without even serving a warning [7]. This means in a situation that requires attention from a PS official, if the node is congested that is, a user will be dropped in order to sufficiently fulfil PS officials requirements. However as it can be guessed, most of the operators does not like this method as it will result with loss of subscribers in the long run.

In a PS network though, it is crucial to have the required resources available to the officials. The network should be set to prioritize certain applications above others as it might be more important. Such as voice applications are almost always more crucial then multimedia applications so if there is a chance to prioritize voice over multimedia, then it should be done.

In LTE this is achieved by the usage of ARP. ARP gives a 15 level prioritization map that is used in a situation that concerns PS. In the following table, prioritization levels enforced by the ARP process is given.

<table>
<thead>
<tr>
<th>Priority</th>
<th>User Group</th>
<th>Non-GBR Bearer</th>
<th>GBR Bearer</th>
<th>Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>Can Pre-empt</td>
<td>Vulnerable</td>
<td>Reserved for Serving Network</td>
</tr>
<tr>
<td>2</td>
<td>1st responder at home (A)</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
</tr>
<tr>
<td>3</td>
<td>1st responder at home (B)</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
</tr>
<tr>
<td>4</td>
<td>1st responder at home (C)</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
</tr>
<tr>
<td>5</td>
<td>1st responder at home (D)</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
</tr>
<tr>
<td>6</td>
<td>PS support at home (A)</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>8</td>
<td>PS support at</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>
As it can be seen, pre-emption is defined for some of the levels as "can pre-empt" whereas some of them can only be "pre-empted" in a PS situation.

### 3.2.2 Rate Limiting and Bandwidth Management

Rate limiting is another way to prioritize certain users in a congested scenario. Rate limiting and bandwidth management enables PS users to have the required over the air bandwidth resources at times that is necessary. Rate limiting is implemented with the usage of non-GBR bearers [7]. This means that a user accessing the internet can be limited at times. This control is most of the times used as aggregate maximum bit rate and in LTE it is called access point name aggregate maximum bit rate (APN-AMBR). This approach limits the total resource usage in an APN to a limit and when this limit is exceeded the network will stop transmitting more traffic until AMBR drops below the limit again. One other approach is to define AMBR on user basis (UE-AMBR). This way it will be independent of the APN and all users will have a limit set on their equipments.

Bandwidth management on PS users is mostly set by GBR bearers. The bandwidth management on these users are mostly set by guaranteed bit rate (GBR) and maximum bit rate (MBR) for each LTE bearer. GBR determines the minimum resource that should be allowed to that specific PS official whereas MBR determines the maximum that is allowed for that user [7].
4. ns3 Simulator and LENA

ns3 is an open, extensible network simulator mainly designed for research and education[8]. The main reason behind using ns3 to simulate a network is that it is either too difficult, expensive or not even possible to conduct in a real environment or to study the behaviour of the network in a highly controlled scenario. Its main focus is internet protocols and how networks work but it can also be used to conduct non-internet simulations.

ns3 operates onlinux based systems however there are possible windows applications that can run it on windows such as Cygwin. ns3 works through a system of libraries that works together. User programs are written in either C++ or python. The simulations in this document will be done over C++. After downloading the libraries a user must build the libraries first before continuing with their program. This program runs over command prompt and you need to be first in the same directory, then build ns3 and after that you may run your program with a C++ or python extension. One of the possible methods to build is through ./waf. The command is shown below;

```
./waf clean
./waf -d optimized --enable-examples --enable-tests configure
```

There are other possible things to enable but this is the most basic and most of the times enough to build. Now after that one may run their program through;

```
./waf --run scratch/YourFile
```

But before going through and writing a script, first some of the concepts that are crucial will be explained.

4.1 Concepts

In this section some of the concepts that are related with ns3 and networking in general will be explained. Firstly some key abstractions will be given, then available applications and methods will be explained consequently.

4.1.1 Key Abstractions

- **Nodes**

  Instead of the usual internet jargon host, in ns3 node is used for the computing device. It is originated from the graph theory. Node in a ns3 script should be thought as a computer that you can add different functionalities. Some of the possible things that can be added are applications, protocol stacks and peripheral cards.

- **Applications**

  The idea of application in ns3 is to perform tasks in the simulated world on the nodes to drive simulations. This class provides the user program activities in a simulation. It is possible to create more applications that are not currently available but for this document it was not needed.
• Channel

Channel is the medium that connects a node to an object and it acts as a communication subnetwork. It might be just a simple wire such as point to point connection however it can also be described as a complex infrastructure like ethernet switches.

• Net Device

Net device contains the software needed to communicate as well as the hardware that are called as network interface controllers (NIC). A node can be connected to another node to communicate over a channel with the help of net device that is installed on it. Also a node can have multiple net devices installed on them to communicate in different ways.

4.1.2 Simple ns3 Script

To begin writing a simple script in ns3 one first needs to include the header files that would be necessary in their script. It is pretty similar with C++ with that matter. Some of the possible header files to include would be:

```c++
#include "ns3/core-module.h"
#include "ns3/network-module.h"
#include "ns3/ipv4-global-routing-helper.h"
#include "ns3/internet-module.h"
#include "ns3/mobility-module.h"
#include "ns3/lte-module.h"
#include "ns3/applications-module.h"
```

It depends on what you want to simulate but here it can be seen that in a simulation if one wants to simulate LTE then that header should be included, core and network modules are mandatory to any simulation as it is the basis of the script. There are a lot more headers depending on the scenario and applications to be considered and it is possible to have anything from wifi to lte.

Next step is to define a NS log component. This enables or disables the writer of the script to console message logging by reference to the name that is chosen. An example of such line would be the following:

```c++
NS_LOG_COMPONENT_DEFINE ("UdpTcpApplicationNoQci");
```

After doing both the main part of the script can be initiated with a line similar to C++ such as;

```c++
int main (int argc, char *argv[]) {
```

The main script depends on what is wanted. It should be noted that ns3 is highly dependent on helpers to do most of the work in the background. So for example if one decides to work on LTE related script, lte and epc helpers needs to be initiated. These will help throughout the script. Some of the parameters of LTE would then be written such as scheduler type, path loss model etc.

In ns3 applications run on remote hosts that act as servers. It can also be installed on a regular node but if the scenario includes a network like LTE or 3G or something similar, then installing applications on remote host is required. Remote hosts are created at first, then internet stack will be installed on them with a base IP address. Next step is to create the
routing between remote hosts and ENB through packet data network gateway (P-GW). This part is just for the LTE case but in our scenarios it will be necessary.

Now that routes are there to remote hosts it is time to decide mobility and the scenario settings in general. There are a lot of possible choices for mobility it can be randomly distributed in a disc statically or dynamically also it can be deterministic again static or dynamic.

Next step is to define use the routing tables defined earlier to connect remote hosts with the nodes. After that the applications will be installed on remote hosts as serving side and nodes as the client. Last section of any script will consist of output files or stats. One common and easy way is to use flow monitor which enables the user to see throughput and delay statistics on the command prompt which can also be written on a xml file to read.

4.2 Lena and LTE

LENA is an open source network simulation for vendors to design and test self organized network (SON) algorithms and solutions [9]. LENA was actually developed as an individual simulator by Centre Tecnològic de Telecomunicacions de Catalunya (CTTC) and it was included in ns3 simulator as a module to simulate LTE/EPC from 2011. Some of the possible target applications to simulate are;

- Downlink & Uplink Schedulers
- Radio Resource Management Algorithms
- Inter cell interference coordination solutions
- Load balancing and mobility management
- Heterogeneous solutions
- End to end QoE provisioning
- Multi RAT network solutions
- Cognitive LTE systems [10]

Lena model overview can be observed in the following figure;

![Figure 4.1. Lena model overview [11].](image)
As it was explained in the previous sections, in end to end data plane the user application is served on a remote host. This is done by passing ENB, SGW/PGW and to the remote host in the end. This end to end data plane protocol relationships can be seen on Figure X;

![End-to-End Data Plane Diagram](image-url)

Figure 4.2. Lena end to end data plane [11].

In the upcoming sections, some of the capabilities and limitations of the simulator will be described. Also it will be observed that all of the capabilities of LTE is currently not included and some might be missing.

**4.2.1 Included Models and Shortcomings**

- **Radio Propagation Model**
  - Buildings can be included with internal and external wall losses.
  - Several path loss models (Okumara Hata, ITU R P1411, P1238).
  - Isotropic and sectoral antennas are possible.

- **Physical Model**
  - Only frequency division duplexing (FDD) is modeled.
  - Frequency domain granularity is radio blocks (RB), for time domain it is transmission time interval (TTI).
  - CQI feedback is possible.
  - Gaussian interference models are used.
  - Single input single output (SISO) is used as propagation model.
  - Multiple input multiple output can be achieved by modeling SINR over SISO.
• Hybrid Automatic Repeat Request (HARQ) Model
  o Incremental redundancy type 2 model is adapted.
  o Asynchronous model for DL and synchronous for UL.
  o All the retransmissions are handled by the scheduler.

• MAC and Scheduler Model
  o Resource allocation model is adapted as Allocation type 0 defined in "3GPP TS 36.213 “E-UTRA Physical layer procedures”".
  o Two different adaptive modulation and coding models are available. One is described in [12] and is called as Piro, the other one is based on physical error model and can be called as Vienna.

  Piro model is based on analytical bit error rate (BER) which makes it quite conservative. Vienna on the other hand is based on block error rate (BLER).
  o Possible downlink schedulers are;
    ▪ Round Robin (RR) and Proportional Fair (PF) as part of LENA project.
    ▪ Maximum Throughput (MT), Throughput to Average (TTA), Blind Average Throughput (BET), Token Bank Fair Queue (TBFQ), Priority Set Scheduler (PSS) as a project from google summer of code 2012.
  o For uplink, all schedulers inherit round robin scheduling algorithms.

• Radio Link Control (RLC) Model
  o Transparent mode (TM), unacknowledged mode (UM) and acknowledged mode (AM) are all supported.
  o Protocol data units (PDU) and headers are modeled as real bits following 3GPP specs.
  o Segmentation, fragmentation and reassembly are available.

• Packet Data Convergence Protocol (PDCP) Model
  o Headers are modeled as real bits following 3GPP specs.
  o Transfer of data is featured as well as transfer of sequence number (SN) status.
  o Unsupported Features
    ▪ Header compression and decompression using ROHC.
    ▪ Chiphering and dechiphering user and control plane data.
    ▪ Integrity verification and protection.
    ▪ In sequence delivery of upper layer PDU’s.

• Radio Resource Control (RRC) Model
  o System information generation and ENB and reception and processing at user equipments.
  o RRC connection establishment and reconfiguration are featured.
These are the most important models included in the LENA and ns3 platform. By including lte and epc module in any script, one can simulate a scenario with the aforementioned models.

4.2.2 Simulation Outputs

In a given LTE simulation the outputs are almost always traces. These traces can be RLC, PDCP, MAC, PHY or using a flow monitor to capture the flows between nodes and servers in order to see application parameters. In our simulations flow monitor will be adapted as being more convenient for our needs. In the end of the simulation script adding these lines will give us the possibility to create trace files;

```c
lteHelper->EnablePhyTraces ();
lteHelper->EnableMacTraces ();
lteHelper->EnableRlcTraces ();
lteHelper->EnablePdcpTraces ();
```

After adding those lines and running our simulation, the trace files are created. All of these files will be divided as uplink and downlink to begin with. The contents, as columns, of the file are given below;

**RLC Trace File**

1) Start time of measurement interval  
2) End time of measurement interval  
3) Cell ID  
4) International mobile subscriber identity (IMSI)  
5) Radio network temporary identity (RNTI)  
6) Logical channel ID  
7) No of transmitted RLC PDU’s  
8) Total bytes transmitted  
9) No of received RLC PDU’s  
10) Total bytes received  
11) Average RLC PDU delay

And after that column the statistical values such as standard deviation, min and max of delays are given. Similarly, the PDCP trace file contains the same parameters in same columns but instead of RLC it contains the PDCP values.

The **MAC trace file contains**;

1) Simulation time  
2) Cell ID  
3) IMSI  
4) Frame number  
5) Subframe number
6) RNTI
7) Modulation and coding scheme (MCS) of transport block (TB)
8) Size of TB

The physical trace files are divided into 7 different files. Which are;
1) DlRsrpSinrFilename
2) UeSinrFilename
3) InterferenceFilename
4) DlTxOutputFilename
5) UlTxOutputFilename
6) DlRxOutputFilename
7) UlRxOutputFilename

These are smaller files then the others because of the division. First file contains the reference signal received power (RSRP) and average SINR of downlink radio blocks. Second file contains uplink SINR. Third file is for interference of radio blocks. Transmission files include layer of transmission, MCS's, size of the TB and redundancy version. Reception files on the other hands contain all the same as transmission and transmission mode, new data indicator flag and correctness of the reception of TB.

Due to simplicity and convenience of flow monitor module of ns3, the simulations described here are observed with it. In a given script to include flow monitor the first thing to do is to use include function of C++ in the beginning to add flow monitor module to the simulation.

Then the function void ThroughputMonitor is coded and inside, the lines for getting the bytes and time for all flows are coded. This function is called in the main function and installed on the nodes that is relevant. Also the servers should be running this function as otherwise the delay and loss of packets cannot be traced. A simple output to the command prompt can be seen on Figure 4.3.

![Flow monitor sample output](image-url)

Figure 4.3. Flow monitor sample output.
As it can be seen in this sample output, flow number 1 is from the remote host with IP address 10.1.1.2 to the node with the IP address 7.0.0.7. Transmitted and received packets are also observed and total received bytes can be seen through the end. With the help of duration and the bytes received, throughput is calculated and displayed.

This is convenient to observe how the simulation is going and to see if it is reasonable. Flow monitor can be scheduled to display these statistics every time period that is necessary. However the most important aspect that is used in the simulations that are displayed in this document is that one can have an output xml file that contains all the relevant information about every flow in the scenario. These informations will be manipulated in order to obtain performance statistics such as throughput and delay in section 5.
5. Performance Analysis of Prioritization

This section will be devoted to performance analysis of different scenarios. The performance measures will be throughput and delay throughout all simulations. The first part of this chapter will be devoted into explaining the simulation settings, the settings that does not change throughout the simulations. Whereas the next ones will consist of the results obtained from the simulations. Specific parameters regarding a certain simulation will be described in the corresponding section.

5.1 Simulation Settings

In this part, the simulation scenario will be described. The scenario consists of a single eNB that serves a number of nodes N. Two applications are considered: a streaming application, in this case UDP client server application, and an elastic application which is, in this case, a bulk send application that uses TCP. Details of these applications are provided in Table 5.1. Each node runs a single application. There are $N_1$ nodes running the streaming application and $N_2$ running the bulk traffic application ($N_1 + N_2 = N$).

<table>
<thead>
<tr>
<th></th>
<th>Bulk Send</th>
<th>Streaming</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Packets</td>
<td>Unlimited</td>
<td>1024</td>
</tr>
<tr>
<td>Packet Size</td>
<td>512 Bytes (Headers not included)</td>
<td>1024 Bytes (Headers not included)</td>
</tr>
<tr>
<td>Interval</td>
<td>-</td>
<td>15 ms</td>
</tr>
</tbody>
</table>

*Table 5.1. Application parameters.*

The simulation scenario looks roughly like Figure 5.1. Server 1 will be serving the TCP application whereas Server 2 will be responsible for UDP application. This is a sample figure because there will be simulations with only 1 application and without prioritization. In one application scenarios, there will be only one type of nodes and also one server to host the applications. These settings are permanent and will be static throughout the simulations. Also the ones described in Table 5.2 and 5.3 are also permanent.

![Figure 5.1. Scenario configuration.](image-url)
The nodes in the simulation area are distributed uniformly in a disc with the following parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>X position of the center</td>
<td>0</td>
</tr>
<tr>
<td>Y position of the center</td>
<td>0</td>
</tr>
<tr>
<td>Radius of the disc</td>
<td>250</td>
</tr>
</tbody>
</table>

*Table 5.2. Simulation area parameters.*

The simulation time is decided to be 10 seconds and the applications are started at 2 seconds mark. Friis propagation model is adapted and the MAC schedulers considered are Round Robin (RR), Maximize Throughput (MT) and Proportional Fair (PF). Some parameters of the ENB and the LTE channels are given in the following table;

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downlink Bandwidth</td>
<td>25 Resource Blocks</td>
</tr>
<tr>
<td>Uplink Bandwidth</td>
<td>25 Resource Blocks</td>
</tr>
<tr>
<td>E-UTRA Absolute Radio Frequency Channel Number (Downlink)</td>
<td>2120 MHz</td>
</tr>
<tr>
<td>E-UTRA Absolute Radio Frequency Channel Number (Uplink)</td>
<td>1930 MHz</td>
</tr>
<tr>
<td>ENB Transmit Power</td>
<td>30 dBm</td>
</tr>
<tr>
<td>ENB Noise Figure</td>
<td>5 dB</td>
</tr>
<tr>
<td>User Equipment Transmit Power</td>
<td>10 dBm</td>
</tr>
<tr>
<td>User Equipment Noise Figure</td>
<td>9 dB</td>
</tr>
</tbody>
</table>

*Table 5.3. LTE default parameters.*

To observe the behaviour of ENB, the applications will be run in the following order. Firstly TCP application will be examined. For this purpose two different behavioural issues will be simulated. First one examining the impact of the scheduler and the second one being the impact of the system load. For the first one, 3 different schedulers will be tested with 20 nodes each. The latter one will consist of nodes ranging from 5-30. Second part of the simulations will consist of only UDP application installed on the nodes and same tests will be evaluated. This time for some schedulers the nodes may range from 5 to 60 in order to see the effects more clearly.

Last part will consist of combining the applications. An $\alpha$ parameter will be defined which describes the ratio of TCP nodes to UDP nodes. In the first part, there will be no difference between the QCI parameters thus giving them the same priority. Holding TCP node number stable, the degradation in performance parameters through TCP and UDP nodes will be examined with a different number of TCP and UDP nodes.

Further simulations will take into consideration the QCI values which were explained earlier and again two tests to see the impacts will be evaluated. The following figure depicts an example of how the scenario will look like. The nodes are distributed randomly among an area that is described by the parameters given earlier. The example figure below consists of 20 nodes which is basically the positioning that is used for seeing the impact of the scheduler.

For TCP applications the simulation will be run 10 times with different initial positions for each node to aggregate the results in order to achieve more reliable outputs. For the UDP, it
has been observed that the node positions have little to no effect on throughput or delay thus every scenario will be run just for once to observe the results. Bear in mind that this display is just a sample as the nodes are assigned randomly, with a different number of users or a different run for TCP case, will result with another distribution of the nodes.

Moving on to the simulations, the first part will be single applications separately without prioritization. Then both applications will be combined without prioritization and lastly, prioritization will be considered and evaluated with separate applications and mixed applications.

### 5.2 Only Bulk Send Application

In this section, the simulation scenario will consist of an ENB connected to EPC (Evolved Packet Core) which is connected to a server that runs a Bulk Send Application. Also 20 nodes will be attached to the ENB with the same application. Simplifications done in this and the following scenarios are that the nodes are stationary, uniformly distributed and there is no buildings or height difference between nodes and ENB. The configuration explained here can be observed in the following figures;
Note that this node distribution is just representative as the nodes are uniformly distributed among this area and the simulation is run 10 times to achieve aggregate results. The reason to run the simulation 10 times and not more is that after 10 runs the results seems to cover enough possibilities.

After the scenario is set, the results will be obtained for 3 different MAC schedulers. Which are proportional fair, round robin and maximum throughput. In the next sections the results for these schedulers will be displayed.
5.2.1 Impact of the scheduling algorithm

5.2.1.1 Proportional Fair Mac Scheduler

Proportional fair scheduler will be the next one to be experimented. How this scheduler works was described on section 2.4 and now to see how this works in our environment, number of simulations will be run.

The simulation will run for 10 seconds and the application starts on 2nd second till the end. To gather reliable results, 10 different simulations with different node distributions will be aggregated. The results will be displayed in the following table whereas the cdf will be plotted on Figure 5.5.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Min Throughput</td>
<td>0.7473 mbps</td>
</tr>
<tr>
<td>Max Throughput</td>
<td>0.8095 mbps</td>
</tr>
<tr>
<td>Mean Throughput</td>
<td>0.7863 mbps</td>
</tr>
<tr>
<td>Standard Deviation of Throughput</td>
<td>0.0131 mbps</td>
</tr>
<tr>
<td>Median of Throughput</td>
<td>0.7862 mbps</td>
</tr>
<tr>
<td>Mean Delay</td>
<td>94 µs</td>
</tr>
<tr>
<td>Standard Deviation of Delay</td>
<td>5.9 µs</td>
</tr>
</tbody>
</table>

Table 5.4. Delay and Throughput statistics for only TCP PF scheduler scenario.

Figure 5.5. CDF plot of throughput for only TCP PF scheduler scenario.
5.2.1.2 Round Robin Mac Scheduler

As described in section 2.4, round robin schedulers just allocates resources to every node without any prioritization thus should result with little difference between nodes in performance.

For this purpose another set of simulations will be run on our simulation scenario. The difference between simulations is merely the position of the nodes in our disc with 250 metres radius. Aggregate results for throughput and delay will be displayed in the following table and the cdf plots for throughput and delay will be displayed on Figure 5.6.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min Throughput</td>
<td>0.7674 mbps</td>
</tr>
<tr>
<td>Max Throughput</td>
<td>0.8307 mbps</td>
</tr>
<tr>
<td>Mean Throughput</td>
<td>0.8145 mbps</td>
</tr>
<tr>
<td>Standard Deviation of Throughput</td>
<td>0.0072 mbps</td>
</tr>
<tr>
<td>Median of Throughput</td>
<td>0.8140 mbps</td>
</tr>
<tr>
<td>Mean Delay</td>
<td>108 μs</td>
</tr>
<tr>
<td>Standard Deviation of Delay</td>
<td>3.4 μs</td>
</tr>
</tbody>
</table>

*Table 5.5. Delay and Throughput statistics for only TCP RR scheduler scenario.*

![CDF plot for only TCP RR scheduler scenario.](image-url)
Maximize throughput scheduler tries to achieve the maximum throughput of the network with assigning higher priorities to the links that are least expensive. This results with some nodes having low throughput whereas the other ones can have much higher values. Again a number of simulations will be run in order to achieve reliable results. It can be seen from the following table and figure that MT scheduler can give a node much higher throughput than PF or RR scheduler.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Min Throughput</strong></td>
<td>0.005 mbps</td>
</tr>
<tr>
<td><strong>Max Throughput</strong></td>
<td>2.5795 mbps</td>
</tr>
<tr>
<td><strong>Mean Throughput</strong></td>
<td>0.7752 mbps</td>
</tr>
<tr>
<td><strong>Standard Deviation of Throughput</strong></td>
<td>0.6893 mbps</td>
</tr>
<tr>
<td><strong>Median of Throughput</strong></td>
<td>0.3643 mbps</td>
</tr>
<tr>
<td><strong>Mean Delay</strong></td>
<td>688 μs</td>
</tr>
<tr>
<td><strong>Standard Deviation of Delay</strong></td>
<td>2.1 ms</td>
</tr>
</tbody>
</table>

*Table 5.6. Delay and Throughput statistics for only TCP MT scheduler scenario.*

![CDF plot for only TCP MT scheduler scenario.](image)
5.2.1.4 All Schedulers Compared

In this section, all the schedulers will be compared with the performance parameters that are throughput and delay. The point is to see the fairness of round robin and proportional fair schedulers whereas maximize throughput scheduler should allocate resources more unfairly. As explained before, maximize throughput checks the channel quality and allocates resources according to that thus creating an unfair scenario where one node can receive good throughput and delay values whereas others may suffer.

Figure 5.8. CDF plot of throughput for only TCP and all schedulers.

Figure 5.9. CDF plot of delay for only TCP and all schedulers.
As it can be observed, by using PF and RR schedulers, a fair throughput and delay values are obtained on all the nodes. RR scheduler has slight advantage over the PF one. With MT scheduler some nodes achieve better throughput and delay values whereas some nodes simply are much worse than the others.

### 5.2.2 Impact of the system load

To see the impact of the system load, the previous scenarios will be run with different number of users. From 5 to 30 users will be considered and they will be again, uniformly distributed among our simulation area. Proportional fair and maximize throughput schedulers will be used to demonstrate results as it is expected that as the number of users increase, the throughput should increase and the delay should decrease. Also to obtain reliable results, yet again the simulations are run 10 times to obtain aggregate results.

#### 5.2.2.1 System Load with Proportional Fair Scheduler

In the previous sections, only 20 users were considered. Now a number of different users will be considered in order to see the effect it has on our performance parameters, throughput and delay.

![Empirical CDF of throughput with different number of users](image)

Figure 5.10. CDF plot of throughput with different no of users for only TCP PF scheduler scenario.
Lastly, to see the effect of increasing the number of nodes, maximum, minimum and means of the scenarios will be displayed in the following figure.

Figure 5.12. Throughput vs Number of Users for only TCP PF scheduler scenario.
5.2.2.2 System Load with Maximize Throughput Scheduler

Same scenario as before but now different scheduler will be considered. With proportional fair scheduler the change is somewhat linear whereas as it can be observed in the following figures, with maximize throughput scheduler it is not as linear due to the nature of the scheduler.

Figure 5.13. CDF plot of throughput with different no of users for only TCP MT scheduler scenario.

Figure 5.14. CDF plot of delay with different no of users for only TCP MT scheduler scenario.
Last figure will be about the maximum, minimum and the mean of throughput and to observe the effect of system load.

![Figure 5.15. Throughput vs Number of Users for only TCP MT scheduler scenario.](image)

### 5.3 Only Streaming Application

Like the bulk send application scenario, this scenario will consist of same number of nodes in the same positions as before just with a streaming application instead. Same simplifications are considered. Average throughput and delay is calculated. Scenario configuration, similar to the one with TCP application can be seen below.

![Figure 5.16. Scenario configuration for only UDP scenario.](image)
Again like it was done for TCP scenarios, first the impact of the scheduler algorithm will be examined and after that impact of the system load will be checked. For this purpose, same simplifications will be done.

5.3.1 Impact of the Scheduler Algorithm

5.3.1.1 Proportional Fair MAC Scheduler

Same scenario will be run with 20 nodes to get results for schedulers. First is the proportional fair one. Unlike TCP application, the UDP application, by nature, assigns same resources to every node. Because of this, aggregating the results does not increase the reliability so all scenarios will be run just once. Below is the CDF of the throughput of the system and also some important performance parameters of the system will be given on Table 6.4.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min Throughput</td>
<td>0.5361 mbps</td>
</tr>
<tr>
<td>Max Throughput</td>
<td>0.5364 mbps</td>
</tr>
<tr>
<td>Mean Throughput</td>
<td>0.5363 mbps</td>
</tr>
<tr>
<td>Standard Deviation of Throughput</td>
<td>1.65*10^(-4) mbps</td>
</tr>
<tr>
<td>Median of Throughput</td>
<td>0.5364 mbps</td>
</tr>
<tr>
<td>Mean Delay</td>
<td>22.33 μs</td>
</tr>
<tr>
<td>Standard Deviation of Delay</td>
<td>1.37 μs</td>
</tr>
</tbody>
</table>

*Table 5.7. Delay and Throughput statistics for only UDP PF scheduler scenario.*

![Figure 5.17. CDF plot for only UDP PF scheduler scenario.](image)
There is almost no difference between node throughput values and also delays as it is only
affected by the connection time. They all receive same amount of data due to the nature of
UDP.

5.3.1.2 Round Robin MAC Scheduler

Same scenario will be run with the usage of Round Robin scheduler. The scheduler was
described in TCP part and it is the same as that. The only difference of this scenario is the
application. The resulting throughput CDF and the relevant performance parameters are
displayed below.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Min Throughput</td>
<td>0.5360 mbps</td>
</tr>
<tr>
<td>Max Throughput</td>
<td>0.5362 mbps</td>
</tr>
<tr>
<td>Mean Throughput</td>
<td>0.5361 mbps</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>4.36*10^(-5)</td>
</tr>
<tr>
<td>Median of Throughput</td>
<td>0.5361 mbps</td>
</tr>
<tr>
<td>Mean Delay</td>
<td>21.34 μs</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.14 μs</td>
</tr>
</tbody>
</table>

Table 5.8. Delay and Throughput statistics for only UDP RR scheduler scenario.

Figure 5.18. CDF plot for only UDP RR scheduler scenario.
5.3.1.3 Maximize Throughput MAC Scheduler

This scheduler tries to maximize the throughput. However it is a little different than the TCP scenario as in UDP if a node gets connection, it will receive the data till max packet number is achieved. So this scheduler actually cannot maximize the throughput like it does in TCP. What it does instead is, thinking it can maximize throughput, if the number of nodes are increased (i.e like 20-25) it drops some of the connections. This scheduler takes into account the user channel conditions and assigns radio blocks according to that. If there are several users with same channel conditions (same SNR) the scheduler assigns all the radio blocks to the first user in the queue. This results with some nodes having no connection. This behaviour was not observable in TCP scenario due to TCP being connection oriented. The effect of number of nodes will be observed in the following section, Impact of the System Load. Below are the performance parameters and throughput CDF plots.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Min Throughput</td>
<td>0 mbps</td>
</tr>
<tr>
<td>Max Throughput</td>
<td>0.5361 mbps</td>
</tr>
<tr>
<td>Mean Throughput</td>
<td>0.4021 mbps</td>
</tr>
<tr>
<td>Standard Deviation of Throughput</td>
<td>0.2382 mbps</td>
</tr>
<tr>
<td>Median of Throughput</td>
<td>0.5361 mbps</td>
</tr>
<tr>
<td>Mean Delay</td>
<td>14.97 μs</td>
</tr>
<tr>
<td>Standard Deviation of Delay</td>
<td>9.58 μs</td>
</tr>
</tbody>
</table>

Table 5.9. Delay and Throughput statistics for only UDP PF scheduler scenario.

Figure 5.19. CDF plot for only UDP MT scheduler scenario.
As it can be observed from the CDF, some nodes (around 25%) does not have any connection at all.

5.3.1.4 All Schedulers Compared
Throughput and delay of the schedulers are compared in the following figures.

Figure 5.20. CDF plot of throughput for only UDP and all schedulers.

Figure 5.21. CDF plot of delay for only UDP and all schedulers.
Again like the TCP application it can be observed that MT scheduler in average has worst fairness with respect to PF and RR schedulers. Although the difference is lower with UDP, still RR scheduler performs slightly better for delay whereas for throughput they are equal.

5.3.2 Impact of the System Load

5.3.2.1 System Load with Proportional Fair Scheduler

To see the effect of the system load, the same simulation will be run with 5 to 60 nodes with 5 increments each. For this purpose, min max and mean throughputs will be plotted and CDF of the delays will be displayed. The reason for using 60 instead of the usual 30 is that the system starts getting saturated after 30 users.

![Figure 5.22. CDF plot of throughput with different no of users for only UDP PF scheduler scenario.](image)

The drop in throughput and also the increase in delay that can be observed on the next plot are due to the buffer overflow. Some of the packages needs to be discarded in order to get rid of the buffer overflow thus the increase in delay gets more significant as the number of nodes are increased.
With proportional fair scheduler, max, min and mean values for throughput remains almost the same. It can be seen a slight change when the number of users are increased however it can be overlooked. The delay CDF plot is to be expected and also the throughput CDF plot is understandable as the values for the throughput are too close to each other the plot basically is equal for different number of nodes.
5.3.2.2 System Load with Maximize Throughput Scheduler

Now the same scenarios with Maximize Throughput scheduler. As it was mentioned in section 5.3.1.3 with UDP application, some nodes does not get any connection with the increasing number of nodes. The effect of this can be observed better in the following plots.

The first plot will depict the CDF of throughput, and in that plot it can be observed that as the number of nodes increase, i.e for 30 nodes, the probability of 0 throughput is almost 0.5 and decreases as the number of nodes decrease. Also the same behaviour can be observed for the CDF plot of delay. Last plot will be of min max and mean of the throughput. With that plot one can see the effect of increasing number of nodes to the throughput more clearly.

![Figure 5.25. CDF plot of throughput with different no of users for only UDP MT scheduler scenario.](image)

Figure 5.25. CDF plot of throughput with different no of users for only UDP MT scheduler scenario.
Figure 5.26. CDF plot of throughput with different no of users for only UDP MT scheduler scenario.

Figure 5.27. Throughput vs Number of Users for only UDP PF scheduler scenario.
5.4 Both Applications Combined without Prioritization

This section will examine the behaviour of ENB and the applications in a mixed application environment. A number of nodes will run TCP application and this number will be fixed while UDP node number will vary from 5-40. The point of this is to see when UDP nodes gets degraded in terms of aggregate and per user performance measures. This is the first part of mixed application scenarios where there is no consideration of prioritization and every node will be assigned same Qci value.

The nodes will be randomly initialized as before with no difference between UDP and TCP. Proportional Fair scheduler is the scheduler of choice for this and the next section as it is a common scheduler and the fairness of it makes it a good choice to observe this behaviour. Again our scenario will have a radius of 250m and ENB will be on the center of it. Same assumptions as the previous sections are considered.

5.4.1 Results

The observations of this section will consist of seeing the degradation of TCP and UDP nodes' performance parameters. As before these parameters will be throughput and delay. TCP node number will be changed between 5-10 and 20 and held while changing UDP from 5-40. The following plot depicts TCP and UDP aggregate and per throughput statistics where the legend will describe number of TCP users and x axis will display number of UDP users.

![Graph showing aggregate throughput of mixed application scenario with different number of UDP users](image)

Figure 5.28. Aggregate throughput of mixed application scenario with different number of UDP users
From the previous plot it can be observed that UDP application is not as degraded as TCP and also it takes a significant amount of users to be active in order to decrease UDP throughput. It can also be seen that as aggregate throughput increases for UDP, it decreases the TCP throughput drastically. Which can be observed on the per user throughput with 5 TCP users, although starting at over 1 mbps throughput rates, in the end it is around 0.2 mbps. Also both plots shows us that if there are more TCP nodes in the scenario, UDP throughput decreases earlier then other scenarios. For example with 20 TCP nodes, UDP throughput decreases at 15 nodes but with 10 TCP nodes it did decrease only at 20 UDP nodes and once more 25 but still higher than 20 TCP scenario.

Now let's look at the mean delay statistics in μs on the following table;

<table>
<thead>
<tr>
<th>TCP Nodes</th>
<th>5 UDP</th>
<th>10 UDP</th>
<th>15 UDP</th>
<th>20 UDP</th>
<th>25 UDP</th>
<th>30 UDP</th>
<th>35 UDP</th>
<th>40 UDP</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 TCP Nodes</td>
<td>TCP</td>
<td>32.5</td>
<td>42.62</td>
<td>73.27</td>
<td>104.87</td>
<td>116.53</td>
<td>133.68</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>UDP</td>
<td>15.37</td>
<td>19.4</td>
<td>22.18</td>
<td>24.66</td>
<td>27.53</td>
<td>139.54</td>
<td>X</td>
</tr>
<tr>
<td>10 TCP Nodes</td>
<td>TCP</td>
<td>42.49</td>
<td>67.77</td>
<td>76.4</td>
<td>100.47</td>
<td>127.8</td>
<td>X</td>
<td>109.35</td>
</tr>
<tr>
<td></td>
<td>UDP</td>
<td>18.37</td>
<td>22.7</td>
<td>24.59</td>
<td>27.33</td>
<td>134.16</td>
<td>X</td>
<td>178.66</td>
</tr>
<tr>
<td>20 TCP Nodes</td>
<td>TCP</td>
<td>102.35</td>
<td>106.6</td>
<td>123.83</td>
<td>X</td>
<td>91.01</td>
<td>103.78</td>
<td>81.91</td>
</tr>
<tr>
<td></td>
<td>UDP</td>
<td>24.4</td>
<td>28.46</td>
<td>130.22</td>
<td>X</td>
<td>147.69</td>
<td>172.13</td>
<td>186.05</td>
</tr>
</tbody>
</table>

*Table 5.10. Mean delay statistics of mixed application scenario with different number of UDP users.*
Also from the previous delay statistics table, it can be observed that when the UDP application gets degraded, the delay values increase significantly. The degradation is consistent with the throughput statistics. TCP application on the other hand, most of the times has increased delay values as the total number of nodes is increased till the point where UDP application starts to degrade. Then it is more or less fluctuating around similar values.

### 5.5 Prioritization

In this section, prioritization will be discussed. Prioritization is achieved by changing the proportional fair metric in the PF scheduler to reflect the QCI values. In ns3, none of the schedulers currently takes QCI into account. The new PF metric is influenced from the metric described in [18]. This new metric is then introduced into the source code of PF scheduler. The following formulas describe how the metric is obtained and used:

First we define an alpha value which is to refine our metric and in our experiments it is set to be 0.7. This value is also employed from the PF metric described in [18] original PF metric calculation did not take this into account at all. After that each QCI level is given a priority factor which is inversely proportional to their corresponding priority level. In our experiments we will be using:

- Priority One -> QCI 1 -> Priority Level 2 -> Priority Factor 8
- Priority Two -> QCI 4 -> Priority Level 5 -> Priority Factor 5
- Priority Three -> QCI 7 -> Priority Level 7 -> Priority Factor 3

These priority levels are picked from the original 9 values described in Table 3.1. It was considered to give QCI 1 to PS officials as conversational voice is one of the most important application that is required in a given situation. The other two groups are chosen to display a different type of application. Where priority group 2 is a guaranteed bit rate bearer and group 3 will have non guaranteed bit rate bearers.

The previous PF metric, that was in the scheduler used the following formula to obtain it which did not consider any QCI levels at all:

$$ PF_{\text{metric}} = \frac{\text{achievableRate}}{\text{lastThroughput}} \quad (5.1) $$

The scheduler that is developed here, obtains QCI values of the flows as a start. A flow is the data stream on either uplink or downlink. After obtaining QCI, scheduler labels the flow with the priority factor and then the PF metric is calculated with the following formula:

$$ PF_{\text{metric}} = \frac{\text{Priority Factor}}{\alpha \ast \text{lastThroughput} + (1-\alpha) \ast \text{achievableRate}} \quad (5.2) $$

This metric gives flows a priority over others if their respective priority factor is more or less. After the scheduler is set and ready, simulations are done to see how this works in a given situation.
5.5.1 Single Application Prioritization

First part of the simulations are based on single application. For this purpose, the users are divided into 2 or 3 different QCI values and the effect of prioritization is observed. QCI levels used are the same as the ones described in the previous section. The results of UDP and TCP are given below;

For three levels, priority group 1 and 2 node number will be held as 5 and 10 whereas group 3 will have increased number of users in order to see the results in a congested scenario. The number of priority 1 and 2 users will be called as X and number of priority 3 users can be obtained by the alpha formula below;

$$\text{Alpha} = \frac{\text{Priority 1 or 2}}{\text{Priority 3}}$$

(5.3)

For the sake of simplicity only 3 different level versions are displayed below and the two level results are displayed on appendix A.

![Figure 5.30. Per user throughput for 3 levels of prioritization on TCP application and X=5.](image-url)
The results for TCP application were rather interesting as it can be seen that for high values of alpha prioritization is more efficient whereas when alpha is lower it doesn't really prioritize but rather allocate resources depending on channel quality.

Figure 5.31. Per user throughput for 3 levels of prioritization on TCP application and X=10.

Figure 5.32. Per user throughput for 3 levels of prioritization on UDP application X=5.
Figure 5.33. Per user throughput for 3 levels of prioritization on UDP application X=10.

The effect of prioritization can be observed more clearly on the UDP application as with the increased number of nodes we can see the degradation of the lower priority groups more clearly. In the first scenario it can be observed that priority 1 and 2 are getting resources to the max level, max being the achievable throughput in our scenarios 0.53 mbps. In the second scenario, priority 1 still gets the most possible resources whereas the other groups get degraded.

5.5.2 Both Applications

In the mixed application part, PS officials will be given a higher QCI value and the scenario will consist of 3 groups of users. PS officials, priority 2 users and priority 3 users.

<table>
<thead>
<tr>
<th>Priority Group 1</th>
<th>Priority Group 2</th>
<th>Priority Group 3</th>
<th>Alpha (Prio1(X)/Prio3(Y))</th>
<th>Simulation No</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 TCP</td>
<td>5 UDP</td>
<td>5 UDP</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>5 TCP</td>
<td>5 UDP</td>
<td>10 UDP</td>
<td>0.5</td>
<td>2</td>
</tr>
<tr>
<td>5 TCP</td>
<td>5 UDP</td>
<td>20 UDP</td>
<td>0.25</td>
<td>3</td>
</tr>
<tr>
<td>10 TCP</td>
<td>10 UDP</td>
<td>10 UDP</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>10 TCP</td>
<td>10 UDP</td>
<td>40 UDP</td>
<td>0.25</td>
<td>5</td>
</tr>
<tr>
<td>5 UDP</td>
<td>5 TCP</td>
<td>5TCP</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>5 UDP</td>
<td>5 TCP</td>
<td>10 TCP</td>
<td>0.5</td>
<td>7</td>
</tr>
<tr>
<td>5 UDP</td>
<td>5 TCP</td>
<td>20 TCP</td>
<td>0.25</td>
<td>8</td>
</tr>
<tr>
<td>10 UDP</td>
<td>10 TCP</td>
<td>10 TCP</td>
<td>1</td>
<td>9</td>
</tr>
<tr>
<td>--------</td>
<td>--------</td>
<td>--------</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>10 UDP</td>
<td>10 TCP</td>
<td>40 UDP</td>
<td>0.25</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 5.11. Scenario settings for mixed application.

Alpha is defined like equation 5.3 and priority 1 is used since priority 1 and 2 users will always have the same number of nodes.

Application parameters are as described before and the scenario range and positions are also the same. For the first part, PS officials will be thought as using TCP application whereas in the second set of applications, they will be considered as using UDP. Extra results can be seen in Appendix A part 2 and here, per user throughput and delay statistics will be evaluated.

5.5.2.1 PS Officials on TCP Application

The first 5 simulations described in Table 5.10 will be done in this chapter. Our performance measures, throughput and delay, will be evaluated in the following figures and table where X being the number of priority 1 and 2 users individually.

![Figure 5.34. Per user throughput for PS officials on TCP application and X=5.](image-url)
With a low load in the first scenario priority 2 and 3 are barely losing any resources. In the previous sections it was determined that the eNB can allocate around 15mbps of throughput in a 30 node UDP scenario and this is not achieved in the first part of experiments. TCP traffic starts to decline after passing Alpha=0.5 and the declination is not that big. In the second part of experiments, with a bigger load, it can be seen that priority 3 group declines a lot by decreasing alpha whereas TCP traffic does not change that much. In addition to that, priority 2 group also declines which we did not observe in the first set of experiments. In the following table, delay statistics for the scenarios can be seen;

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Priority Level</th>
<th>Mean Delay (μs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 TCP Scenario 1</td>
<td>Prio 1 (5 TCP)</td>
<td>28.12</td>
</tr>
<tr>
<td></td>
<td>Prio 2 (5 UDP)</td>
<td>16.58</td>
</tr>
<tr>
<td></td>
<td>Prio 3 (5 UDP)</td>
<td>23.22</td>
</tr>
<tr>
<td>5 TCP Scenario 2</td>
<td>Prio 1 (5 TCP)</td>
<td>26.16</td>
</tr>
<tr>
<td></td>
<td>Prio 2 (5 UDP)</td>
<td>16.52</td>
</tr>
<tr>
<td></td>
<td>Prio 3 (10 UDP)</td>
<td>26.16</td>
</tr>
<tr>
<td>5 TCP Scenario 3</td>
<td>Prio 1 (5 TCP)</td>
<td>25.14</td>
</tr>
<tr>
<td></td>
<td>Prio 2 (5 UDP)</td>
<td>22.8</td>
</tr>
<tr>
<td></td>
<td>Prio 3 (20 UDP)</td>
<td>83.6</td>
</tr>
<tr>
<td>10 TCP Scenario 1</td>
<td>Prio 1 (10 TCP)</td>
<td>25.79</td>
</tr>
<tr>
<td></td>
<td>Prio 2 (10 UDP)</td>
<td>23.81</td>
</tr>
<tr>
<td></td>
<td>Prio 3 (10 UDP)</td>
<td>97.36</td>
</tr>
<tr>
<td>10 TCP Scenario 2</td>
<td>Prio 1 (10 TCP)</td>
<td>29.14</td>
</tr>
<tr>
<td></td>
<td>Prio 2 (10 UDP)</td>
<td>159.4</td>
</tr>
<tr>
<td></td>
<td>Prio 3 (40 UDP)</td>
<td>302.2</td>
</tr>
</tbody>
</table>

Table 5.12. Mean delay statistics for PS officials running TCP.
Looking at the delay table it is fair to say that priority one users are guaranteed a delay of below 30 μs whereas as the traffic increases in eNB, the other groups gets degraded. In an event that concerns public safety, delay is extremely crucial and this prioritization algorithm delivers.

5.5.2.2 PS Officials on UDP Application

On this part, PS officials will be on UDP application whereas the other nodes will be running TCP application. The node numbers and scenario settings are the same as last section. Again first per user throughput plots will be displayed and then mean delay of all levels of users will be examined.

UDP application, due to its' characteristics, gets the resources if possible and tries to maintain the most possible throughput. Since our prioritization group will be UDP users, it can be observed in the following plots that UDP nodes tend to stay around 0.53-0.54 mbps which is the possible maximum achievable rate.

Figure 5.36. Per user throughput for PS officials on UDP application and X=5.
With the UDP application as priority 1 installed on PS users, it can be observed that in both cases the required resources are allocated on them without losing any throughput whatsoever. The other nodes do decline after a certain number of nodes and the declination is more in the \( x=10 \) scenarios. The following table will display mean delay statistics of all groups considered in this scenario.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Priority Level</th>
<th>Mean Delay (μs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 UDP Scenario 1</td>
<td>Prio 1 (5 UDP)</td>
<td>15.57</td>
</tr>
<tr>
<td></td>
<td>Prio 2 (5 TCP)</td>
<td>39.01</td>
</tr>
<tr>
<td></td>
<td>Prio 3 (5 TCP)</td>
<td>55.79</td>
</tr>
<tr>
<td>5 UDP Scenario 2</td>
<td>Prio 1 (5 UDP)</td>
<td>15.68</td>
</tr>
<tr>
<td></td>
<td>Prio 2 (5 TCP)</td>
<td>40.88</td>
</tr>
<tr>
<td></td>
<td>Prio 3 (10 TCP)</td>
<td>64.74</td>
</tr>
<tr>
<td>5 UDP Scenario 3</td>
<td>Prio 1 (5 UDP)</td>
<td>15.86</td>
</tr>
<tr>
<td></td>
<td>Prio 2 (5 TCP)</td>
<td>32.75</td>
</tr>
<tr>
<td></td>
<td>Prio 3 (20 TCP)</td>
<td>53.78</td>
</tr>
<tr>
<td>10 UDP Scenario 1</td>
<td>Prio 1 (10 UDP)</td>
<td>19.24</td>
</tr>
<tr>
<td></td>
<td>Prio 2 (10 TCP)</td>
<td>67.8</td>
</tr>
<tr>
<td></td>
<td>Prio 3 (10 TCP)</td>
<td>167.54</td>
</tr>
<tr>
<td>10 UDP Scenario 2</td>
<td>Prio 1 (10 UDP)</td>
<td>20.5</td>
</tr>
<tr>
<td></td>
<td>Prio 2 (10 TCP)</td>
<td>80.17</td>
</tr>
<tr>
<td></td>
<td>Prio 3 (40 TCP)</td>
<td>169.82</td>
</tr>
</tbody>
</table>

*Table 5.13. Mean delay statistics for PS officials running UDP.*
Similarly with prioritizing TCP, in these scenarios priority 1 users are kept below 20 μs and it is something that is wanted. The other users also has lower priority then UDP users in the first part of simulations. In an optimal scenario where delay is more important prioritizing UDP traffic on PS officials give better results for both prioritized users and regular users.
6. Conclusions

Public safety communication is a major concern in today's societies and new ways to ensure public safety is being researched every day. In this paper we considered PS communications over the new 3GPP standard for mobile communications, LTE. After a brief introduction and introducing how LTE and our simulation program works, we passed to the part about the simulations.

First consideration was to see how eNB reacts under several considerations. We decided to go with 3 well known schedulers and examined their performance in our simulation environment. Proportional fair and round robin schedulers were the ones that gave a better and more fair performance whereas maximize throughput scheduler was all about giving more resources to the one with better channel conditions. For these simulations and the ones after these, two different application types were considered, UDP and TCP.

The differences between these applications were observed. UDP, if eNB is not congested, can reach up to 0.53-0.54 mbps and does not differentiate between users. All users gets the pre-determined number of packets. In TCP however, channel conditions do take effect and some users might get slight degradation in terms of throughput and delay. By increasing the number of nodes, we tried to congest eNB and see the behaviour of our schedulers and applications.

Regarding prioritization, which is the main topic of this paper, we considered to use QCI (QoS Class identifiers) levels to prioritize group of nodes from the others. There are 9 different levels of QCI and every level has a different priority ranking which is used in our algorithm to change PF metric in the PF scheduler to allocate more resources in a time of congestion.

First we considered the applications separately and gave 2-3 priority levels to our groups of nodes. In all applications, we held the nodes with priority 1 (and 2 in 3 level simulations) and increased the number of users in lesser prioritized group of nodes. This was to simulate in a given scenario how will eNB allocate resources to PS officials who are a given number of users whereas the commercial users might be 10 or 50 so we tried to determine alpha values which is the number of priority 1 users to number of priority 2 users (or 3 in 3 level simulations).

It was observed that in TCP prioritization, for a large alpha the system performed well and prioritized whereas for a lower value of alpha, the difference is not that big and even at some points lesser priority groups performed slightly better. However for UDP prioritization it was observed that priority group 1 hardly lost any resources even though the number of users did increase a lot.

Last part of our simulations was to consider both applications running simultaneously on different user groups. At first we considered PS officials to run TCP applications and in the second part, we considered PS officials to run UDP. In both applications, the other priority groups did run the other application, like if priority 1 is TCP the other groups run UDP and vice versa.

For TCP application on PS officials, it was observed that for low number of TCP users (5), other groups did not lose any resources and also TCP users also did not really suffer. This is due to the fact that eNB was not that congested and it could support other priority groups simultaneously. If we increased the number of TCP users, we observed that both UDP groups
did lose their resources whereas TCP was not that effected. Also it is clear on this part of the simulations how priority group 2 and 3 were also differentiated in the scheduler.

For UDP application on PS officials, for both parts of the simulations, priority group 1 did not lose any of their resources. This result is parallel to the one with single application prioritization. The other groups did suffer as alpha decreased and it is to be expected, also in these applications it is easy to see how group 2 and 3 were differentiated.

In conclusion, using QCI levels to achieve prioritization seems to be efficient in different types of scenarios. In any given PS communications environment, it is necessary to have access to resources because the situation might be extremely important. It was seen in these simulations that delay and throughput for both applications are satisfied for different number of priority groups. In real life, there might be more groups than our proposed 3 however the scheduler and the algorithm is capable of prioritizing between more groups of users.

For the future, the simplifications like area of simulations and the nodes being fixed can be eased and also different applications might be considered. And the upmost challenge would be to put prioritization with QCI to other schedulers or even creating a new scheduler that is based on QoS and QCI values.
7. References


8. Appendix A

8.1 2 Level Prioritization Results with Single Application

Simulation results for 2 different levels of priority for both UDP and TCP application. First part will be on TCP application whereas the second part will be on UDP. Simulations that are done in this section can be seen on the following table;

<table>
<thead>
<tr>
<th>Priority 1 Nodes (TCP or UDP)</th>
<th>Priority 2 Nodes (TCP or UDP)</th>
<th>Alpha (Priority 1/Priority 2)</th>
<th>(Priority 1/Priority 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
<td>0.25</td>
<td>0.5</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>20</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>10</td>
<td>40</td>
<td>0.25</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Table 8.1 Priority distribution.

Figure 8.1. Per user throughput for TCP application 2 priority levels and X=5

per Throughput TCP Prio 1 with 5 Nodes
per Throughput TCP Prio 2
Figure 8.2. Per user throughput for TCP application 2 priority levels and X=10.

Figure 8.3. Per user throughput for UDP application 2 priority levels and X=5.
Similarly to the 3 level scenarios, with 2 levels it is possible to observe how priority 2 nodes have degraded traffic as the number of nodes increase whereas priority 1 suffers less for both applications.

### 8.2 Mixed Application Extra Results

Here the cdf plots of throughput for different priority groups can be seen. First 6 plots correspond to TCP being the priority 1 group and the next 6 will belong to UDP being priority 1.
Figure 8.6. CDF plot for UDP (Prio 2) with X=5.

Figure 8.7. CDF plot for UDP (Prio 3) with X=5.
When TCP is the priority 1 group in the previous plots, due to the low number of nodes other priority groups does not get degraded at all. Whereas there is a slight degradation in TCP nodes even though they are priority 1 but that is due to the characteristics of TCP and UDP applications.

Figure 8.8. CDF plot for TCP (Prio 1) with X=10.

Figure 8.9. CDF plot for UDP (Prio 2) with X=10.
When the number of nodes is increased, X being 10, it can be observed that both priority 2 and 3 suffers greatly. It is more clear by checking the priority group 3 as it decreases from 0.53 to somewhere near 0.23 mbps. Priority 1 group also has some degradation but it is acceptable and it can be seen from part 5.5.2.1 that the delay is still below 0.3 μs.
Figure 8.12. CDF plot for TCP (Prio 2) with X=5.

Figure 8.13. CDF plot for TCP (Prio 3) with X=5.
When priority 1 is UDP application it can be observed that there is no degradation with X=5, which is both because of UDP characteristics and the low load on eNB. The other groups running TCP does get degraded and it can be observed from the previous plots.

Figure 8.14. CDF plot for UDP (Prio 1) with X=10.

Figure 8.15. CDF plot for TCP (Prio 2) with X=10.
Figure 8.16. CDF plot for TCP (Prio 3) with X=10.

With UDP on priority 1 group increasing the load does not effect the first priority group at all. These plots are similar to X=5 scenarios but with a lower throughput for TCP groups.
9. Appendix B

In this appendix, the changes that are made to the code of pf scheduler will be described. The names of the files are pf-ff-mac-scheduler.h and pf-ff-mac-scheduler.cc. These files are found in ns3-directory/src/lte/model. The changes and their respective lines are listed below;

In the header file only a single change is made on line 61 we add the qci value to the pfsFlowPerf_t function with;

```
int qci;
```

In the code file starting with the following codes are added between 388-396

```
uint8_t Dlqci = params.m_logicalChannelConfigList.at (i).m_qci;
Dlqci=int(Dlqci);

if (Dlqci==9) {
    m_flowStatsUl[(*it).first].qci = Dlqci;
}
else {
    m_flowStatsDl[(*it).first].qci = Dlqci;
}
```

These lines obtains the QCI value of the given flow and attaches it to the flowStats of the given flow. The thing about the if clause is because all the UL flows are given the same, 9, QCI values due to no uplink schedulers currently being available in ns3.

Next step is to calculate the PF metric given a QCI value, for that purpose the following lines are added between 1118 to 1164

```
int prioFactor=0;
//int prio=0;
if ((*it).second.qci==1) {
    // prior= 2;
prioFactor=8;
}
else if ((*it).second.qci==2) {
    // prior= 4;
prioFactor=6;
}
```
else if ((*it).second.qci==3) {
    // prio= 3;
    prioFactor=7;
}
else if ((*it).second.qci==4) {
    // prio= 5;
    prioFactor=5;
}
else if ((*it).second.qci==5) {
    // prio= 1;
    prioFactor=10;
}
else if ((*it).second.qci==6) {
    // prio= 6;
    prioFactor=4;
}
else if ((*it).second.qci==7) {
    // prio= 7;
    prioFactor=3;
}
else if ((*it).second.qci==8) {
    // prio= 8;
    prioFactor=2;
}
else if ((*it).second.qci==9) {
    // prio= 9;
    prioFactor=1;
}
else {
    // prio= 9;
    prioFactor=1;
};

double alpha=0.7;
// double rcqi = achievableRate / (*it).second.lastAveragedThroughput;
    double rcqi = prioFactor/(alpha*(it).second.lastAveragedThroughput+(1-alpha)*achievableRate);

These lines first obtain the QCI value and assign a prioFactor value to that QCI with respect to the value. After that, an alpha is defined and our own PF metric calculation, here called as rcqi, is calculated. Also the old version of the metric can also be seen here. This concludes the changes that are done to PF scheduler code in general.