Service-Class Based Scheduling for Long Term Evolution (LTE) Networks

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Approval

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Abstract

LTE (Long Term Evolution) is a wireless communication standard providing support for IP-based traffic as well as end-to-end Quality of Service (QoS) with description of strict margins as to how QoS for different service classes should be maintained. These service quality related requirements including delay budgets and packet loss rates are listed in a standard service class table for LTE. Due to the stringent QoS requirements, simplest schedulers adopted from literature like Proportional Fair, Maximum Throughput and Exponential Rule cannot be applied directly to LTE Networks. Moreover if these schemes are used as such, the non guaranteed traffic is bound to suffer from resource scarcity whilst a number of best effort flows are always present in the network for major scenarios.

To achieve a minimum resource level guarantee for service classes, specifically the best effort traffic while satisfying the delay budget requirements, we propose a service delay-budget and channel quality aware LTE network scheduler. The scheduler is implemented for the downlink with a bound on the number of resources that can be assigned to each class. These bounds are dynamically tested for delay budgets and packet loss rates to determine the number of accommodated and sustainable users of different service types. For example in a 10MHz spectrum usage, the number of accommodated users in a 7:3 resource ratio for Guaranteed (Video, VoIP and CBR tested individually) and Non-Guaranteed (Best Effort) traffic came out to be ~ 14, 280, 33 and 480 using theoretical model with delay budget of 100ms. These were validated using simulations with close approximations of ~ 12, 244, 27, and more than 400 users for each category while running Video at 242kbps, VoIP at 12kbps, CBR at 100kbps and BE at 3kbps. Moreover the data rate of best effort is sustained within specific levels corresponding to the assured resources even when the system is loaded with guaranteed users. The throughput of best effort using normal schedulers goes down to zero after the resources get mostly occupied by guaranteed service. Using delay budget parameters, the delay for services is also maintained within margins. Admission Controller for LTE Network forms one of the direct applications of this work. Capacity based Admission Controller design is also discussed in terms of the resource calculations needed to accommodate and sustain specific number of QoS subscribed users.

Certificate of Originality

I hereby declare that this submission titled "**Service-Class Based Scheduling for Long Term Evolution (LTE) Networks**" is my own work and to the best of my knowledge it contains no materials previously published or written by another person, nor material which to a substantial extent has been accepted for the award of any degree or diploma at NUST SEECS or any other education institute, except where due acknowledgment has been made in the thesis. Any contribution made to the research by others, with whom I have worked at NUST SEECS or elsewhere, is explicitly acknowledged in the thesis.

I also declare that the intellectual content of this thesis is the product of my own work, except to the extent that assistance from others in the project's design and conception or in style, presentation and linguistic is acknowledged.

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Salman Ali

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List of Abbreviations

Abbreviation	Description
BE	Best Effort
CBR	Constant Bit Rate
CQI	Channel Quality Index
DL	Downlink
eNB	Evolved Node B
EPC	Evolved Packet Core
FDD	Frequency Division Duplex
GBR	Guaranteed Bit Rate
HOL	Head of Line
IMS	IP Multimedia System
LTE	Long Term Evolution
LTE-A	LTE-Advanced
MME	Mobility Management Utility
NGBR	Non Guaranteed Bit Rate
OFDMA	Orthogonal Frequency Division Multiple Access
PCRF	Policy Control and Charging Function
PDCP	Packet Data Convergence Protocol
PLR	Packet Loss Rate
PRB	Physical Resource Block
QoS	Quality of Service
RAT	Radio Access Technology
RNC	Radio Network Control
ROHC	Radio Header Compression
TDD	Time Division Duplex
TTI	Transmission Time Interval
UE	User Equipment
UL	Uplink
UTRA	Universal Terrestrial Radio Access
UTRAN	Universal Terrestrial Radio Access Network

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Chapter 1

Introduction

Long Term Evolution (LTE) is a wireless communication standard supporting high speed data transmission. It is maintained by 3GPP (3rd Generation Partnership Project). LTE is an evolution of UMTS (Universal Mobile Terrestrial System) network and currently in its version 10 called LTE-Advanced. The chain of UMTS begins with HSPA (High Speed Packet Access) which was later modified as HSPA+ and then under LTE releases. LTE's radio access side is called Evolved UMTS Terrestrial Radio Access Network (E-UTRAN) and is designed to improve end-user throughputs up to 100Mbps in the downlink and 50Mbps for uplink. Sectored capacity and reduction of user plane latency at less than 5ms time enhances user experience. LTE also provides support for IP-based traffic with end-to-end Quality of service (QoS). Voice traffic is carried as Voice over IP (VoIP) integrating other multimedia services as well [1]. LTE uses Enhanced Packet Core (EPC) network architecture integrated with E-UTRAN through reduced and simplified network elements and functionality. LTE allows seamless hand-over and mobility support. Aggressive performance requirements, based on physical layer technologies including Orthogonal Frequency Division Multiplexing (OFDM) and Multiple-Input Multiple-Output (MIMO) use makes LTE ideal for high system throughput. The use of flexible spectrum use with predefined bandwidths is also defined in the standard.

The Evolved NodeB (eNB) station in LTE networks controls time and frequency domain related resources for uplink and downlink corresponding to different User Equipments (UEs). The time and frequency resources constitute resource blocks on which data is transmitted. A scheduler in eNB allocates Physical Resource Blocks (PRBs) to users for a predetermined Transmission Time Interval (TTI). The scheduling method is implemented by service provider since there are no guidelines by 3GPP in this regard. Basic scheduling features may include the selection of best multiplexing methods for UE based on channel conditions and some form of integrated fairness criteria in resource allocation. Scheduling may also require information about buffer condition and flow priorities of different services including interference statistics. UE continuously coordinates with eNB the channel conditions reflecting the instantaneous channel quality. Interference coordination that controls the inter-cell interference can also form a part of scheduler implementation. Downlink scheduling in LTE can be done with schemes such as Frequency Selective Scheduling (FSS), Frequency Diverse Scheduling (FDS) or Proportional Fair Scheduling (PFS) etc. However, these schemes are suited for one type of network condition and not ideal for major scenarios.

1.1 Motivation

LTE standard does not provide any documented scheduler to be used with the eNB station. This is also true for WiMAX and other major cellular networks. However LTE defines more strict limitations as compared to others to how QoS for different service classes should be maintained. Due to the strict requirements in the form of delay budget and error rates defined in the service class tables, simplest schedulers adopted from other technologies like Proportional Fair, Maximum Throughput and Exponential Rule cannot satisfy these conditions. If such simple schedulers are used with strict priorities of service classes, this would result in either the best effort class suffering from resource starvation or some users in the guaranteed class themselves not getting sufficient chances of scheduling due to less favorable channel conditions. We therefore need to define some mechanism that would allow only limited guaranteed and best effort users in the system such that the service class requirements are satisfied for majority of the network users. This can be done if we define an admission controller functionality with system capacity perspectives that calculates how much users of a particular class can be admitted and then decide for user admission or rejection policy. Moreover once the users are admitted in the system in different service class categories it is beneficial to use flexible prioritization in terms of resource allocation rather than strict prioritization to limit the resource starvation for lowest ranked flows.

1.2 Research Statement

We define our thesis problem statement as:

"*To design a service delay and channel quality aware LTE network scheduler with a minimum guarantee of available resources for service classes"*

1.2.1 Service Delay Awareness

Service delay awareness corresponds to the delay budget standardized for LTE service classes. The scheduler must make sure that none of the user packets in the queue for a specific class exceed this delay budget.

1.2.2 Channel Quality Awareness

Since use of Channel Quality Index (CQI) measurements is an available feature in LTE Networks to regulate Automatic Modulation and Coding (AMC) scheme, the scheduler must use the channel quality measurements to enable channel diversity for users.

1.2.3 Resource Availability

Resource availability relates to the accessibility of Physical Resource Blocks (PRBs) of LTE networks for different service classes that need to be guaranteed in some relative percentage or ratio.

1.3 Research Contributions

Research objectives set in accordance with the research statement and later achieved are summarized below:

- Incorporation of Packet Delay Budget parameter from LTE service class standards specification in traffic scheduling
- Controlled Allocation of Physical Resource Block for service classes

- Use of a modified theoretical model to calculate accommodated user capacity keeping in view the data rates or type of service.
- Verification of theoretical model via simulations with close approximations
- We also maintained minimum resource guarantee for Best Effort class while in typical schedulers the Best Effort does not get resources when guaranteed class users are exceeded.
- Finally we presented guidelines using theoretical and simulated users of different traffic types that can be accommodated in LTE Network via Tabular form.

1.4 Thesis Organization

There are five chapters in this thesis dissertation which are organized as follows:

In Chapter 2, an introduction to Resource Allocation, Scheduling and LTE Service Classes is given along with the related work.

In Chapter 3, we discuss the delay based LTE scheduler design with specification and research methodology.

In Chapter 4, the simulation and implementation results are given and explained in detail. Also, comparison with previous methods is given and discussed.

Chapter 5 summarizes the work and concludes our thesis with proposals of some possible extensions to this work.

References of the work done by different people in this field are provided at the end in Bibliography section.

Chapter 2

Literature Review

LTE promises wireless broadband technology with fulfillment of user's demands for various applications under different scenarios. LTE is also a candidate for 4th generation cellular technology, with support for mobility and higher demand of multi-media data traffic. In this section, we discuss the important features of LTE physical and MAC layers respectively. We restrict ourselves and discuss the topics related to our research work only. Resource Allocation in LTE Networks is also discussed.

2.1 LTE Architecture

LTE is a radio access technology implemented by the E-UTRAN (Evolved Universal Terrestrial Radio Access Network). It also integrates non-radio details in the form of System Architecture Evolution (SAE) and Evolved Packet System (EPS). At a much higher level, the network comprising the core network part is called Evolved Packet Core (EPC). In LTE, a user flow is called bearer and is defined as an IP packet flow with an associated QoS level between the UE and gateway [1]. CN takes the responsibility for the overall management of UEs and the related bearers. EPC also integrates Home Subscriber Server (HSS) along with a Policy Control and Charging Rules Function (PCRF). EPS handles the bearer with certain QoS level while the management of multimedia applications is the done by the IP Multimedia Subsystem (IMS). E-UTRAN also houses a powerful terminal called eNB which is similar to a base station in cellular networks but much more capable.

2.2 LTE Physical

LTE Physical Layer is build upon OFDMA method with a cyclic prefix in the downlink, and on SC-FDMA with a cyclic prefix for the uplink. The LTE PHY layer does coding and decoding, modulation and demodulation in addition to multi-antenna mapping. Three duplexing methods are implemented namely full duplex FDD, half duplex FDD, and TDD. There are two frame structure types in LTE namely

1. Type-1 shared by both full-duplex and half-duplex FDD
2. Type-2 applicable only for TDD

An LTE Type-1 radio frame spans 10ms containing 20 slots with single slot duration of 0.5ms. Two adjacent slots of 1ms length constitute a LTE subframe. Modulation schemes supported in LTE are the QPSK, 16QAM and 64QAM. Broadcast related channels only uses QPSK modulation scheme. The maximum size of information block is 6144 bits and a CRC-24 error detention method is used. The LTE type-2 frame is also similar in terms of the subframe and slot duration. The Type-2 frame of 10ms is divided into 2 half frames each containing five 1ms slots corresponding to the TTI of LTE in TDD. The two types of frames are depicted in Figure 2.1 and Figure 2.2 [13][14].

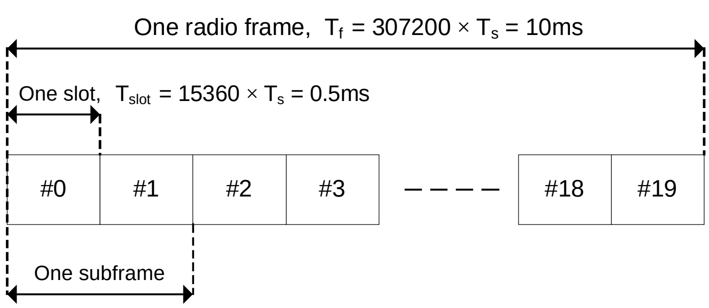

Figure 2.1: LTE Type-1 Frame

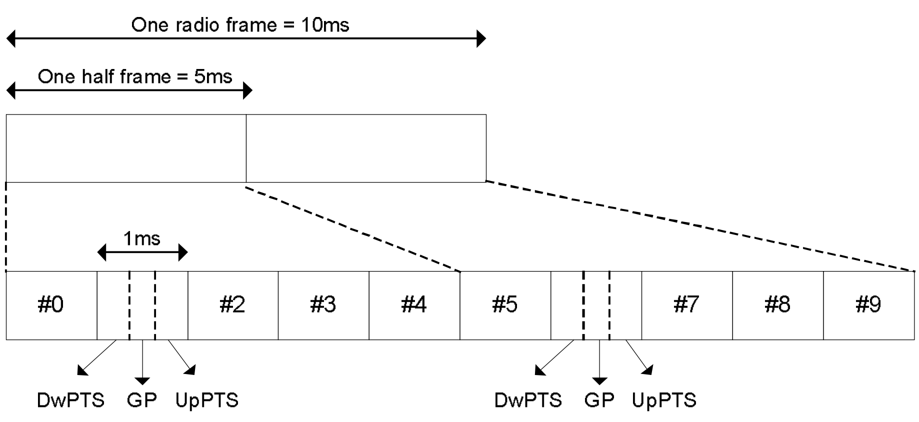

Figure 2.2: LTE Type-2 Frame

2.3 LTE Radio Interface

The eNB and UE both have data and control plane protocol layers. Data enters LTE network as IP packets in the form of SAE bearer. Packets are passed through protocols inlcuding Packet Data Convergence Protocol (PDCP) used for IP header compression via Robust Header Compression (ROHC). There is also a Radio Link Control (RLC) entity that is used for concatenation and segmentation, handling retransmission and for management of in-sequence data delivery.

2.3.1 LTE Radio Link Control (RLC) Layer

Depending on scheduler decisions, certain size of data is selected for transmission in the form of RLC PDU (Protocol Data Unit). In LTE the size of RLC PDU varies dynamically according to network conditions. Each RLC PDU incorporates a header that includes sequence number used for proper ordered data delivery and for retransmissions. A retransmission protocol works between RLC functions in both the transmitter and receiver sides.

2.3.2 LTE Communication Channels

The LTE RLC function offers support to PDCP level in the radio bearer form. LTE MAC offers services to RLC as logical channels while transport channels work between LTE Physical layer and LTE MAC layers. A logical channel is distinguished by the information content type and generally classified as control channel, used for carrying control information necessary for LTE system configuration. A user data traffic channel represents the information transmitted over radio interface side. The different LTE channels are described in Table 2.1.

Table 2.1: Physical Channels in LTE [13]

	Channel	Purpose
Downlink	PDSCH	Carry user data (DL)
	Physical broadcast channel (PBCH)	Carry broadcast information
	Physical Multicast channel (PMCH)	Carry multicast services
	PCFICH	Indicate the size of the control region in number of OFDM symbols
	PHICH	Carry ACK/NACK associated with UL transmission
	PDCCH	Carry DL scheduling assignments and UL scheduling grants
Uplink	PUSCH	Carry user data (UL)
	PUCCH	Carry ACK/NACK associated with DL transmission, scheduling request, and feedback of DL channel quality and pre-coding vector
	Physical Random Access Channel (PRACH)	Carry random access transmission

2.4 LTE Bearers

To identify different service level data flows, network needs to categorize them in the form of “data profile”. In LTE networks this flow classification is called “bearer” which is a user connection between the gateway and UE. This service flow is accompanied with QoS treatment in scheduling, data queue management and rate shaping in the core network by mapping of QoS Class Identifier (QCI). LTE standard describes two basic types of bearer connection, namely Guaranteed Bit Rate (GBR) and Non-Guaranteed Bit Rate (NGBR) [1]. GBR bearers require guaranteed network resource while NGBR bearer is related to best effort class. All default LTE bearers are categorized in NGBR class. An additional dedicated bearer is further classified as GBR or NGBR. The default bearer is to remain associated with the network though it may or may not send any data. Further there are flows related to signaling that are given intermediate priority. The different LTE Bearer categories are described in Figure 2.3.

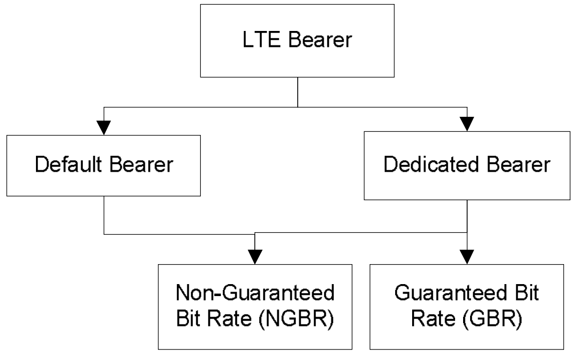

Figure 2.3: LTE Flow Categorization

In order to provide QoS, all network elements have to operate in a synchronous manner including the IP packet filters associated with the gateway and related to Admission Controller. Also there is a need for proper QCI parameters mapping and robust scheduling at the eNB station. We however limit ourselves to the Scheduling and Resource Block Allocation at the eNB station for downlink. Also the effect of Admission Controller functionality is simulated and tested at the eNB station instead of gateway. The main areas of thesis are highlighted in Figure 2.4.

In a technical report by Pedersen et al. [19], various LTE network entities related to radio resource management have been summarized. Different protocols involved between the eNB station, Gateway and air interface for data transmission have been explained. The report also provides guidelines as to how network planning and dimensioning should be prepared for proper QoS providence.

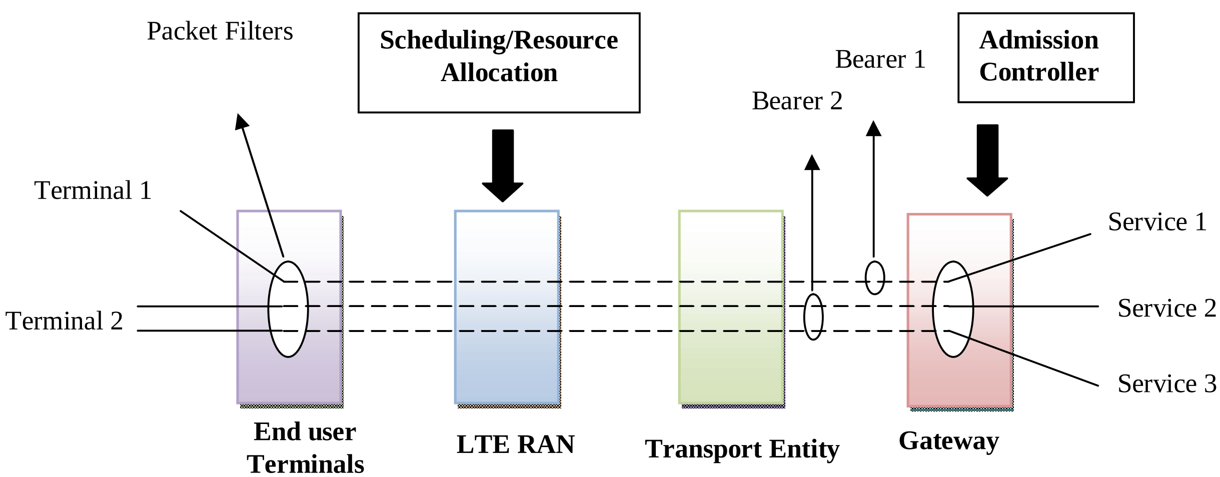

Figure 2.4: LTE Scheduling and Admission Control Region

2.4.1 LTE Admission Control

Admission Control Policy plays an important part in maintaining QoS in the network. Its main function is to allow only a limited number of users in the network for which resources are sufficient. The admission control can should take into account network conditions and channel conditions to handle new requests intelligently. In general policy implemented in admission control can consider statistics and parameters like power of the terminals, throughput requested, total network capacity and user traffic related bandwidth or delay constraints. For heterogeneous network support, parameters like sessions sensitivity, Radio Access Terminal (RAT) capabilities, previously queued and handover sessions can also be checked.

Several approaches for the design of admission controller have been presented in literature. In the game theoretic work of Niyato et al. [8], bandwidth allocation for 4G networks has been modeled by Game Theoretic framework. Since 4G networks require backward compatibility and co-existence, a resource allocation method for distributing network resources using a utility function and cooperative game involving mutual information sharing is used. In the research contribution by Elias et al. [9], an admission control mechanism is used to limit the network traffic according to channel conditions and network capacity. Similarly in the work of Qian et al. [13], a novel radio admission control functionality is described that supports treatment of service classes following QoS. The method checks user priorities, traffic types and the network load in order to admit users.

2.4.2 Quality of Service and LTE Service Class

The QoS parameters involved in the bearer connection and the transportation of bearer traffic between Gateway and UE with associated QoS is described in Table 2.2. The table defines nine classes in total with four in guaranteed and 5 in non-guaranteed category. The main QoS attributes include the Packet Delay Budget and Packet Error Loss Rates.

Table 2.2: QCI Priority MAP [1]

QCI	Resource Type	Priority	Packet Delay Budget	Packet error loss rate	Example services
1	GBR	2	100 ms	10^{-2}	Conversational voice
2		4	150 ms	10^{-3}	Conversational video (live streaming)
3		3	50 ms	10^{-3}	Real time gaming
4		5	300 ms	10^{-6}	Non-conversational video (buffered stream)
5	Non-GBR	1	100 ms	10^{-3}	IMS signaling
6		6	300 ms	10^{-6}	Video (buffered streaming) TCP-based (e.g., www, e-mail, chat, ftp, p2p sharing, progressive video etc.)
7		7	100 ms	10^{-6}	Voice, Video (live streaming, Interactive Gaming)
8		8	300 ms	10^{-3}	Video (buffered streaming), TCP-based (e.g., www, e-mail, chat, ftp, p2p sharing, progressive video, etc.)
9		9		10^{-6}	

The QCI is a scalar quantity that links each service flow with scheduling priorities, admission thresholds, queue management and other QoS related configurations. Other standard parameters include Allocation and Retention Priority (ARP), Maximum bit rate (MBR), Aggregate MBR (AMBR) and Guaranteed bit rate (GBR). ARP parameter is used to choose admitted and rejected users in the network. MBR defines the highest bit rate a GBR bearer must not surpass. GBR defines the bare minimum bit rate that is assured for a GBR bearer. AMBR defines the combined NGBR bit rate to which a set of users be limited to. Different classes can be run under different LTE service categories depending upon service provider taking into account the delay and tolerable loss rates. Some recommended data rates for different service types are defined in Table 2.3.

Table 2.3: Recommended Bandwidth for different Traffic Types

No.	Application	Recommended Data rates
1	Mobile voice call	6 kbps to 12 kbps
2	Text-based e-mail	10 to 20 kbps
3	Low-quality music stream	28 kbps
4	Medium-quality music stream	128 kbps
5	High-quality music stream	300 kbps

6	Video conferencing	384 kbps to 3 Mbps
7	Entry-level, high-speed Internet	1 Mbps
8	Minimum speed for responsive Web	1 Mbps
9	Internet streaming video	1 to 2 Mbps
10	Telecommuting	1 to 5 Mbps
11	Gaming	1 to 10 Mbps
12	Enterprise applications	1 to 10 Mbps
13	Standard definition TV	2 Mbps
14	Distance learning	3 Mbps
15	Basic, high-speed Internet	5 Mbps
16	High-Definition TV	7.5 to 9 Mbps
17	Multimedia Web interaction	10 Mbps
18	Enhanced, high-speed Internet	10 to 50 Mbps, 100 Mbps

Several research contributions have been made in the QoS domain for LTE. An initial work by Sadiq et al. [6] in this regard proposes a dynamic prioritization scheme utilizing fast computations for scheduling and resource allocation. The PHY and MAC layers are modeled using network abstractions. The scheduler uses the queue and channel statistics in a dynamic manner and various tradeoffs are studied in this perspective. Similarly, in the research by Iana et al. [10], the impact of mixed traffic type on end user satisfaction is evaluated. A mix of streaming video, VoIP, best effort and interactive gaming was used to monitor the end user satisfaction impact of with parameters like jitter and delay. Results show that light data traffic does not suffer much when mixed with similar priority traffic. However, with different priority levels, degradation in end user satisfaction becomes common. In the work done by Huang et al. [11], a method for provisioning differentiated services in 4G networks is proposed. Some level of proportional differentiation is maintained by a model that prioritizes user's data according to previous data history in addition to the relative priority among different flows. The method allows for improved user satisfaction and high levels of Quality of Experience (QoE).

2.5 LTE Medium Access Control (MAC) Layer

Data on LTE transport channel is transmitted as a transport block. At each Transmission Time Interval (TTI), a transport block is transmitted over the radio interface to or from eNB station. Each transport block follows Transport Format (TF) specifying the details of block size and structure. This includes in addition to the size, the modulation scheme and antenna orientation. By varying TF, different data rates are implemented. The LTE Medium Access Control (MAC) layer also manages hybrid-ARQ retransmission mechanism.

2.5.1 LTE Resource Allocation

A Scheduler in eNB allocates Physical Resource Blocks (PRB) to UE for different TTI. The PRB consist of either 6 (with long cyclic prefix) or 7 (with short cyclic prefix) OFDM symbols. Longer cyclic prefix are required to cater longer fading channels. The number of subcarriers per PRB and sub-channel spacing is fixed in LTE but the operating bandwidth varies constituting different number of allocatable PRB at each TTI. For channel estimations in OFDM communication, known reference symbols are placed in the OFDM frequency-time grid. The PRB structure with subcarrier placing and OFDM symbols are described in Figure 2.5.

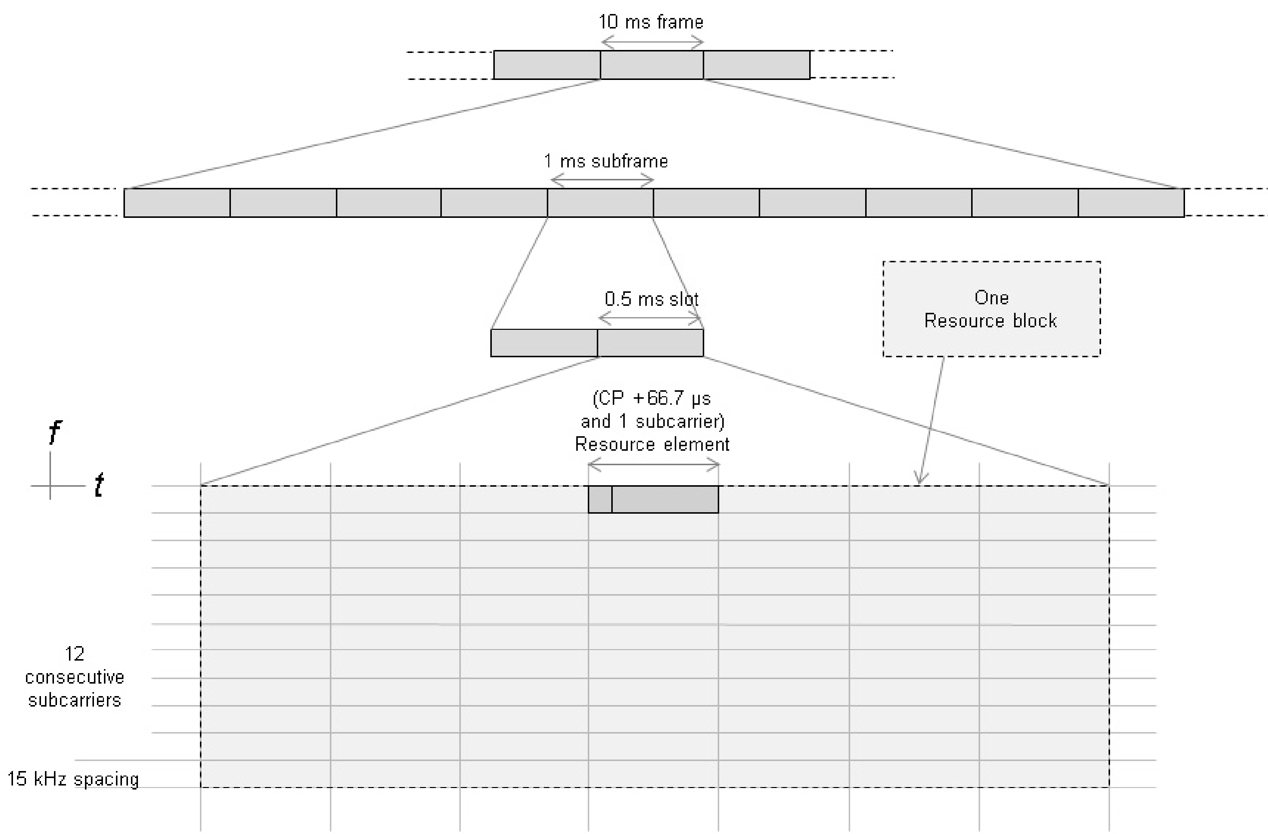

Figure 2.5: LTE Resource Block Structure

2.5.2 LTE MAC Scheduler

The MAC scheduler in eNB station controls time and frequency domain related resources for uplink and downlink corresponding to different User Equipments (UEs). The time and frequency resources constitute resource blocks on which data is transmitted. A LTE downlink scheduler allocates Physical Resource Blocks (PRBs) to users for a predetermined Transmission Time Interval (TTI). The scheduling method is implemented by service provider since there are no guidelines by 3GPP in this regard. Basic scheduling features may include the selection of best multiplexing methods for UE based on channel conditions and some form of integrated fairness criteria in resource allocation. Scheduling may also require information about buffer condition and flow priorities of different services including interference statistics. UE continuously coordinates with eNB the channel conditions reflecting the instantaneous channel quality. Interference coordination that controls the inter-cell interference can also form a part of scheduler implementation. Downlink scheduling in LTE can be done with schemes such as Frequency Selective Scheduling (FSS), Frequency Diverse Scheduling (FDS) or Proportional Fair Scheduling (PFS) etc. However, these schemes are suited for one type of network condition and not ideal for major scenarios.

Scheduling and queue management are also essential for service prioritization implemented at the access portion of the eNB station. Scheduling is implemented according to service provider requirements. Many general scheduling schemes are also available in this regard. These methods comprise ‘Round Robin’ scheme in which users are served with network resources on the basis of turns, ‘Maximal Signal to Interference Noise Ratio’ (MaxSIR) in which users that can establish high SIR values are served first, ‘Proportional Fair’ scheme in which users that allow relatively higher data rates are provisioned with resource. Other schemes include ‘Fair Throughput’ following fairness in terms of resource allocation and finally ‘Exponential Rule’ in certain decision parameters like delay and data rate are sustained in an exponential way. These classical scheduling schemes are listed below:

- Proportional Fairness
- Fair Throughput
- Round Robin
- Max SIR
- Opportunistic Scheduling
- Exponential Rule
- Delay Based

2.6 Related Work

Now we discuss the research contributions by different people related to scheduling and resource allocation in LTE domain. A lot of important contributions have been made in this regard over the past few years since the launch of LTE in 2008. In one of the research contributions by Mauricio et al. [2], a two level resource allocation and scheduling scheme has been proposed. At the first step, resources in the form of Physical Resource Blocks are distributed among different type of traffics according to the load requirements of flows. A game theory with shapely value fairness metric is used for this purpose. In the second step, an exponential scheduler is applied. The method has been compared with other conventional schemes to for performance evaluation. The results show improved delay, fairness and throughput characteristics as compared to Proportional Fair and M-LWDF Algorithm.

In the research work by Kumbesan et al. [3], a head of line delay based scheduling scheme has been proposed for LTE Networks. The delay is measured as a function of packet head of line time in the scheduling queue. The user with highest utility for delay is selected for scheduling at the access. SINR is also used to perform scheduling where the Resource Block that can achieve the highest SNR value is allocated. Performance analysis against other schemes suggests improved performance in terms of throughput, delay and fairness.

In the survey for 3GPP LTE schedulers [4], several key schedulers have been recognized with different network characteristics. These include the basic Proportional Fair, Round Robin, Maximal Signal to Interference Ratio and Fair Throughput. Other complex schemes include exponential rule, intra-class and inter-class schedulers. The main theme of the survey is the suggestion for a balance between user and network side perspectives when designing scheduling in LTE systems for proficient results.

In the work by Pham et al. [5], a scheduling scheme tailored to cope the service class priorities is mentioned. The priority of service class along with target bit error rates from LTE specifications are used to perform scheduling. Channel quality statistics in addition to the user's earlier data rates and channel occupancy statistics are also calculated for scheduling. When compared to Maximum Throughput and Proportional Fair, the proposed method depicted increased overall system throughput.

In the research paper by Basukalaet al. [7], performance analysis of Proportional Fair, Exponential rule and M-LWDF has been analyzed for LTE downlink. Proportional Fair distributes resources to flows on the basis of channel quality measures. The users that maintain maximum SNR on physical resources are scheduled first. In Exponential method and M-LWDF, indirect delay measures are used to schedule users flow. The users having highest delay measure is selected and given access to physical channel. However both are different in terms of basic delay calculation. In general Exponential and M-LWDF perform better than basic Proportional Fair and can be used with LTE service class constraints. Similarly in the thesis by Zhiqiang [12], different possible methods for scheduling data traffic on LTE networks has been identified. The major ones include Proportional Fair, Delay measuring based, Maximum Throughput and Exponential delay method. These schedulers have been altered to cope up with frequency and as time domain scheduling. A hybrid for simultaneous frequency and time scheduling is also mentioned. Simulation results suggest the need for proper resource distribution addition to scheduling of resources. The schedulers that include basic delay parameters are proposed for use with LTE standard.

In the theory based evaluation of packet scheduling in [18], a range of relationships have been proposed to find the best packet scheduler features that may support a variety traffic with different priorities, channel statistics, queue sizes and traffic loads while improving the QoE for end users. The most superior packet schedulers have been identified to be the ones incorporating delay budgets while sustaining a stable relationship between traffic loads and channel statistics.

In the research work by Giuseppe Piro in [22] and [23], a multi level scheduling scheme that supports some basic QoS requirements in LTE networks has been proposed. At an initial level, flows are sorted out according to the traffic load following the user scheduling. This reduces the complexity of scheduler where it is required to sort various traffic mixes of users with different priorities. A video streaming model has been tested to check the QoS levels obtained. It was observed that the scheme performs well even for basic schedulers are used at the last scheduling step with good level of user satisfaction. In the work related to opportunistic scheduling [16], a mechanism that exploits channel statistics and user traffic loads to define opportunities related to resource allocation and scheduling while improving overall throughput of the network is presented. While such an exploitation scheme for scheduling is valid for utilization of resources but having an overall impact of starvation for some user flows that never experience favorable channel or network characteristics. In the work presented in [17], another dynamic packet scheduling has been introduced that takes several input parameters for users flows to allocate resources. Relationships involving user priorities, queue sizes and network conditions have been exploited to schedule user data. A Mixture of VoIP and best effort has been studied to analyze different user satisfaction levels. It is observed that the proposed dynamic scheme results in improved user satisfaction even with heavy flows while best effort users get relatively more scheduling opportunities compared to basic classical methods. Finally in the research findings in [20] and [21], widely adopted scheduling schemes including Proportional Fair, Exponential method, M-LWDF and Max Throughput have been analyzed in terms of capacity and throughput in different LTE cell sizes. It is observed that all schemes keep their associated benefits as well as demerits but none can is suited for major network scenarios and QoS requirements.

Chapter 3

LTE Service Class Based Scheduler Design

This chapter deals with the Resource Allocation strategy, the scheduling of LTE service class traffic using delay budget parameters and admission control strategy for LTE users. The theoretical models, implementation details and related algorithms are discussed with details in relevant sections.

3.1 Research Methodology

The complete thesis objectives for service class based scheduling can be classified into three distinct parts. First of these is the Admission Controller part that is used to admit or reject LTE users in the network depending upon the criteria of available system capacity or the accessible resources set aside for each class. The details of the admission control mechanism would be discussed in the relevant section later. Once the users enter the system the next step is to properly distribute Physical Resource Blocks among different service classes. The number of Physical Resource Blocks would vary depending upon the operating system bandwidth. For the six specific categories of bandwidth on which LTE can operate; the number of allocatable Physical Resource Blocks is mentioned in Table 3.1.

Table 3.1: LTE Resource Blocks corresponding to different Operating Bandwidths

System Bandwidth (MHz)	1.4	3.0	5	10	15	20
Physical Resource Blocks	6	15	25	50	75	100

The physical resource called Resource Block (RB) stretches across frequency and time dimensions. Each RB lasts for 0.5ms time slot and consists of 6 or 7 symbols according to the prefix involved and containing 12 sub-carriers in frequency domain. An LTE subchannel is 180KHz wide and downlink allocation is done on a RB-pair corresponding to 1ms subframe or a single TTI.

After the resource allocation next step is to perform the actual scheduling of users for transmission. This step involves use of delay metric from LTE service class specifications. The users that meet the delay requirements are transmitted and the packets that fail to follow the delay budget in a specific class are dropped from the MAC queue. The Resource Block distribution and packet scheduling parts can be distinguished as being inter-class and intra-class related sorting methods. Hence we achieve complexity reduction by following a 'divide and conquer' strategy in which first the service classes are sorted for resource allocation and then users in a class are sorted for packet scheduling. The three steps in the service class based scheduling are reflected in Figure 3.1.

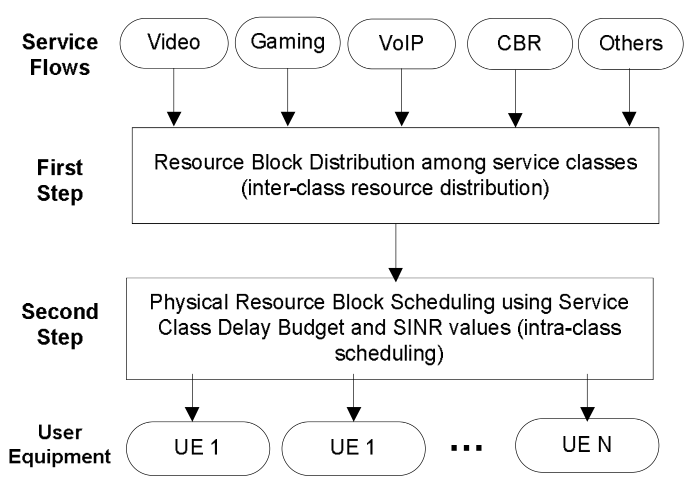

Figure 3.1: Resource Allocation and Scheduling steps in LTE

3.1.1 System Capacity Estimation

The classical approach for system capacity estimation in literature uses spectral efficiency and the bandwidth of operation in addition to the parameters like busy hour loading and the sector into which the operating cell site is divided into. This is described in equation

$$capacity\_of\_cell\_site = no\_of\_sectors \times spetral\_efficiency \times bandwidth \times busy\_hour\_loading \quad (3.1)$$

In a communications system, the sliding period of 60 minutes during which occurs the maximum total traffic load in a given 24-hour period is called busy hour loading while spectral efficiency defines the number of bits per second that are transmitted on average in 1 Hz of bandwidth. The simultaneous subscribers of a specific class that can be accommodated in a cell site is thus

$$simultaneous\_subscribers = \frac{capacity\_of\_cell\_site}{QoS\_data\_rate} \quad (3.2)$$

Here QoS_data_rate represents the data ate of a traffic type, e.g. VoIP traffic type might have the requirement of 12kbps or streaming video might be required to maintain a steady 300kpbs data rate. For more than one type of traffic type the capacity can be split into the percentage by which we want to accommodate each type of traffic. At each transmission interval, UE reports their instantaneous downlink SNR to eNB station. This value varies because of frequency and time selective fading from multi-path and mobility. It is used to calculate the data rate in number of bits for the allocatable RB-pair. A user i's achievable data rate for jth RB at time t is calculated as:

$$R_{i,j}(t) = \frac{n\_bits}{symbol} \times \frac{n\_symbols}{slot} \times \frac{n\_slots}{TTI} \times \frac{n\_subcarrier}{RB} \quad (3.3)$$

where n_bits, $n\_symbols$, n_slots and $n\_subcarrier$ are the number-of-bits, number-of-symbols, number-of-slots and number-of-subcarriers respectively [19].

3.1.2 Admission Controller

Since we are considering the capacity of LTE networks in the downlink only we need to modify the theoretical model to be more specific as to how much users of different traffic types can be accommodated by the eNB station. Moreover we want to consider only the users that are active meaning that they always have data to send and the flows are readily available at the eNB MAC scheduler for transmission in the downlink.

The classical method for subscriber capacity calculation cannot be used here because we are considering the downlink and we need to calculate only the goodput for different traffic type considering their QoS requirements. Hence we need to remove the uplink portion from the capacity equation and consider only the symbols that carry the actual data and not the control information. In addition the calculation of QoS data rate should be done corresponding to the delay budget, i.e. how many bits per second should be transmitted within the delay budget period. For this the specific model would then be

$$\text{subscriber\_capacity} = \frac{\frac{\text{n\_bits}}{\text{symbol}} \times \frac{\text{n\_symbols}}{\text{TTI}} \times \frac{\text{n\_subcarrier}}{\text{RB}} \times \frac{\text{n\_RB}}{\text{slot}} \times \frac{\text{n\_dl\_slots}}{\text{frame}} \times \frac{\text{n\_frames}}{\text{TTI}}}{\text{QoS\_data\_rate (per delay budget period)}} \quad (3.4)$$

Where n_dl_slots represents the number of downlink slots. The number of downlink slots may vary in LTE networks according to switch point periodicity specified by LTE specifications. The reason for variation of downlink and uplink slots is to cater the traffic load and provide some balance in traffic scheduling. The different switch point periodicity and corresponding configurations of uplink and downlink slots are given in Table 3.2.

Table 3.2: Switch-Point Periodicity table for LTE

Configuration	**Switch-Point Periodicity**	**Subframe Number**									
		0	1	2	3	4	5	6	7	8	9
0	5ms	D	S	U	U	U	D	S	U	U	U
1	5ms	D	S	U	U	D	D	S	U	U	D
2	5ms	D	S	U	D	D	D	S	U	D	D
3	10ms	D	S	U	U	U	D	D	D	D	D
4	10ms	D	S	U	U	D	D	D	D	D	D
5	10ms	D	S	U	D	D	D	D	D	D	D
6	5ms	D	S	U	U	U	D	S	U	U	D

The data rate also needs to be calculated according to the delay budgets. Mostly the delay budgets are specified in milliseconds, so we need to determine the QoS rate in this setting. The details of Admission Controller algorithm are highlighted in Figure 3.2 where the admission controller checks initially the GBR or NGBR service category. Next if the resources are available in corresponding category considering the user as active client then it is allocated resources, otherwise it is rejected. The NGBR is allowed to take up resources from GBR class if available but the opposite is not allowed. So an additional check is required to free up GBR resources in case the NGBR occupies the GBR resource pool. For another user request, the RB Allocation is again checked for underutilized resources following GBR and NGBR traffic verification. If however we want to make the resource division flexible then Resource Allocation method explained in 3.1.3 is used. The user admission or rejection is further explained by Example 3.1.

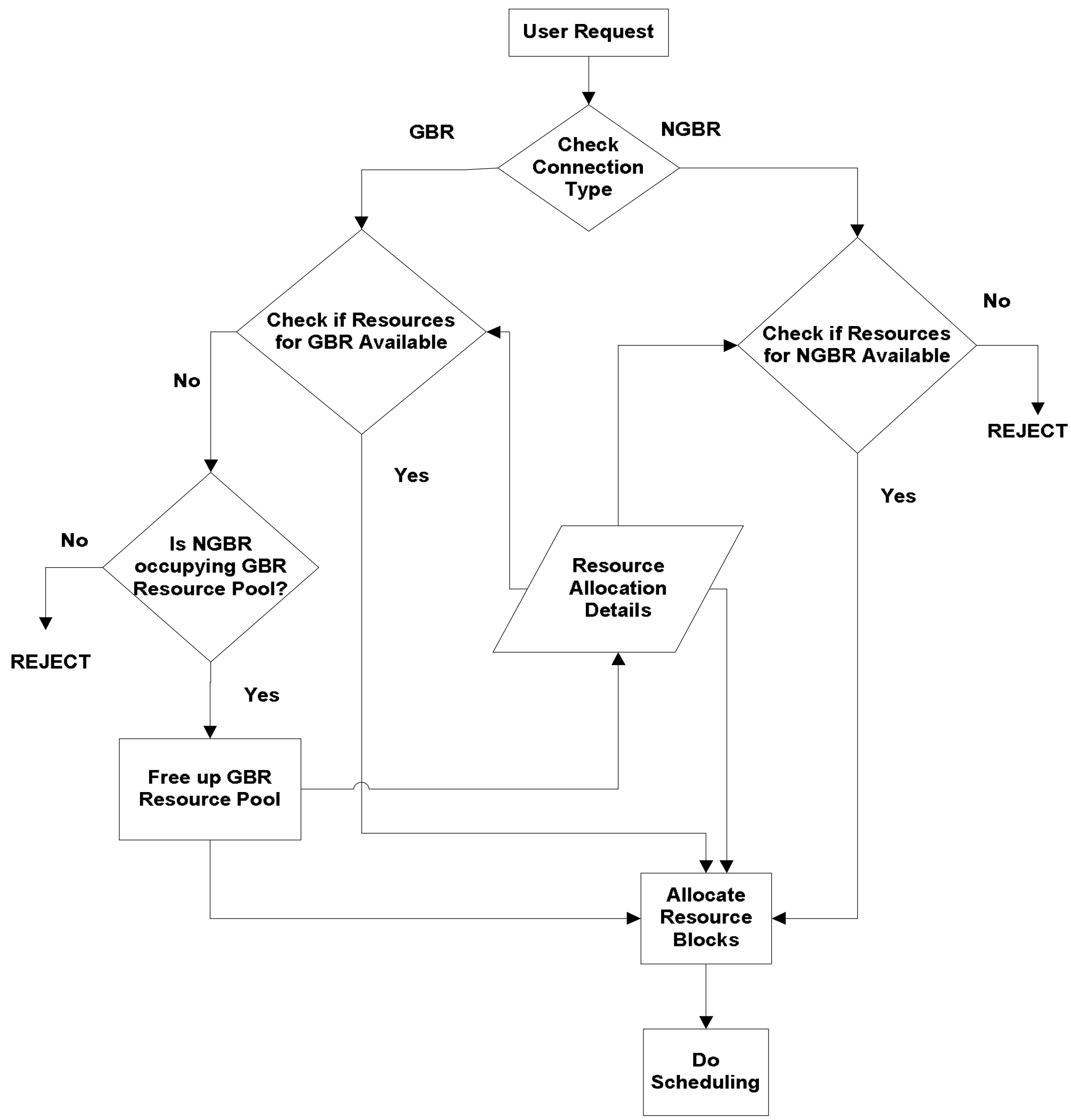

Figure 3.2: Admission Controller Design for LTE

Example 3.1

Let's suppose we want to run the network for two types of active traffic flows; Video at 300kbps and CBR at 100kbps. The two guaranteed classes are required to be scheduled at a fixed 7:3 ratio for Resource Blocks. Let's suppose further the network runs at 10MHz bandwidth, the average user SNR is 7.2dB (16QAM modulation scheme used), the switch point periodicity configuration used is 1 (4 downlink slots per frame) and we want to check how many users will be accommodated when there is a request of 25 users for Video and 30 users for CBR.

Using equation 3.4

$$\text{subscriber\_capacity} = \frac{\frac{\text{n\_bits}}{\text{symbol}} \times \frac{\text{n\_subcarrier}}{\text{sRB}} \times \frac{\text{n\_symbols}}{\text{TTI}} \times \frac{\text{n\_dl\_slots}}{\text{frame}} \times \frac{\text{n\_RB}}{\text{slot}} \times \frac{\text{n\_frames}}{\text{TTI}}}{\text{QoS\_data\_rate (per delay budget period)}}$$

Video Users Accommodated:

$$= \frac{4 \times 12 \times 10 \times 4 \times 35 \times 100}{300000} = 22.4$$

CBR Users Accommodated:

$$= \frac{4 \times 12 \times 10 \times 4 \times 15 \times 100}{100000} = 28.8$$

Hence the admission controller will allow 22 users for Video and 29 users for CBR, rejecting 3 and 1 user in each category.

3.1.3 Resource Block Allocation

Resource Block Allocation to service classes is done to provide minimum level of guarantee for the active service classes. We also allow Best Effort (the NGBR LTE class) to have a minimum level of guarantee in the network. While in a typical scheduling approach, best effort may not be provided any guarantee in the network and resource are only allocated when the guaranteed class in fully satisfied. The typical approach of only allowing best effort to take up only left over resources results in starvation when the network is loaded with guaranteed traffic. Best effort flows are also assumed to be present in considerable amount for majority of cellular networks. So for LTE network with 5 sub-classes of best effort (NGBR), it is beneficial to maintain some level of resource block guarantee in the network. The resource blocks that should be allocated to a specific QoS class with a specific number of users can be calculated as:

$$\text{RB\_allocate} = \frac{\text{QoS\_data\_rate} \times \text{no\_subscribers}}{\frac{\text{n\_bits}}{\text{symbol}} \times \frac{\text{n\_symbols}}{\text{TTI}} \times \frac{\text{n\_subcarrier}}{\text{RB}} \times \frac{\text{n\_dl\_slots}}{\text{frame}} \times \frac{\text{n\_frames}}{\text{TTI}}} \qquad (3.5)$$

where RB_allocate is rounded off to the nearest integer value to obtain the minimum allocatable resource blocks. The number of subscribers with different QoS rates allocated in the network is bounded by the downlink network capacity using the following equation

$$\{\text{data\_rate}_{\text{typ 1}} \times \text{no\_subscribers}_{\text{typ 1}}\} + \{\text{data\_rate}_{\text{typ 2}} \times \text{no\_subscribers}_{\text{typ 2}}\} + \ldots\ldots\ldots$$
$$\{\text{data\_rate}_{\text{typ n}} \times \text{no\_subscribers}_{\text{typ n}}\} \leq \text{downlink\_capacity}_{\text{total}} \qquad (3.6)$$

Example 3.2

Let's suppose we allow 10 Video users at 300kbps and 20 CBR users at 100kbps in the network. Let's suppose further the network runs at 10MHz bandwidth (50 RBs), the average user SNR is 7.2dB (16QAM modulation scheme used), the switch point periodicity configuration used is 3 (6 downlink slots per frame) and we want to check how many Resource Block each class should get. Alternatively we want to find out the Resource Block Allocation Ratio with which the scheduler should work.

Using equation 3.5

$$\text{RB\_allocate} = \frac{\text{QoS\_data\_rate} \times \text{no\_subscribers}}{\frac{\text{n\_bits}}{\text{symbol}} \times \frac{\text{n\_subcarrier}}{\text{RB}} \times \frac{\text{n\_dl\_slots}}{\text{frame}} \times \frac{\text{n\_symbols}}{\text{slot}} \times \frac{\text{n\_frames}}{\text{TTI}}}$$

RB Allocated to Video Class

$$= \frac{300000 \times 10}{4 \times 12 \times 4 \times 10 \times 100} = 15.6$$

RB Allocated to CBR Class:

$$= \frac{100000 \times 20}{4 \times 12 \times 4 \times 10 \times 100} = 10.4$$

Hence the ratio with which the scheduler should allocate resource Blocks is

$$\frac{\text{Video Users}}{\text{CBR Users}} = \frac{15}{10} = \frac{3}{2}$$

For 10MHz bandwidth usage, video class should get 30 RBs and CBR should get 20 RBs in each time slot.

3.1.4 Packet Scheduling

After the inter-class resource allocation step, next we need to select users of a specific class for scheduling on access interface. This intra-class user selection is derived from delay calculations as a function of the delay budget described in LTE table for service class. To implement the scheduler, a Head of Line (HOL) packet delay is measured which is defined as the time difference between the recent packet serving time and the time when the packet was stamped on its arrival in service queue. This time is then directly compared with the service class delay budget the user packet belongs to. The user whose difference in the HOL delay and budget difference is the lowest should be scheduled first. If the difference crosses zero and represents a negative value this means that the delay threshold is exceeded and packet needs to be dropped from the queue. In addition to this since LTE architecture mandates the use of CQI for proficient access interface utilization; we have also incorporated recent SNR values in the scheduling decision. The mathematical model for the scheduler is described below:

Let the user packet delay budget parameter for a class i be denoted by σ_i. Then for any use represented by j in the class i; the HOL delay measure at a time instant t is described as

$$\text{HOL}_j(t) = T_{current}(t) - T_{stamp} \tag{3.7}$$

where T_{stamp} denotes the time record of the packet since it arrived at the service scheduling queue and $T_{current}$ represents the current packet processing time. The delay or the remaining scheduling time for transmission is then presented as a function of HOL as:

$$\text{delay}_j(t) = \sigma_i - \text{HOL}_j(t) \tag{3.6}$$

The difference $\sigma_i - \text{HOL}_j(t)$ is only valid for positive values, corresponding to the fact that any packet that exceeds the budget is discarded. For final RB allocation, the user with the lowest $\text{delay}_j(t)$ metric should be selected.

$$u = \min\{\text{delay}_j(t)\} \qquad j \forall \text{user} \in \text{Class } i \tag{3.7}$$

Once the user u is chosen for transmission on RB, the SNR values conveyed by that user to eNB station are also analyzed and the greatest of these is picked up to decide the RB on which user should carry out the data transmission. A flow chart describing various stages in step 2 of intra-user selection is presented in Figure 2.

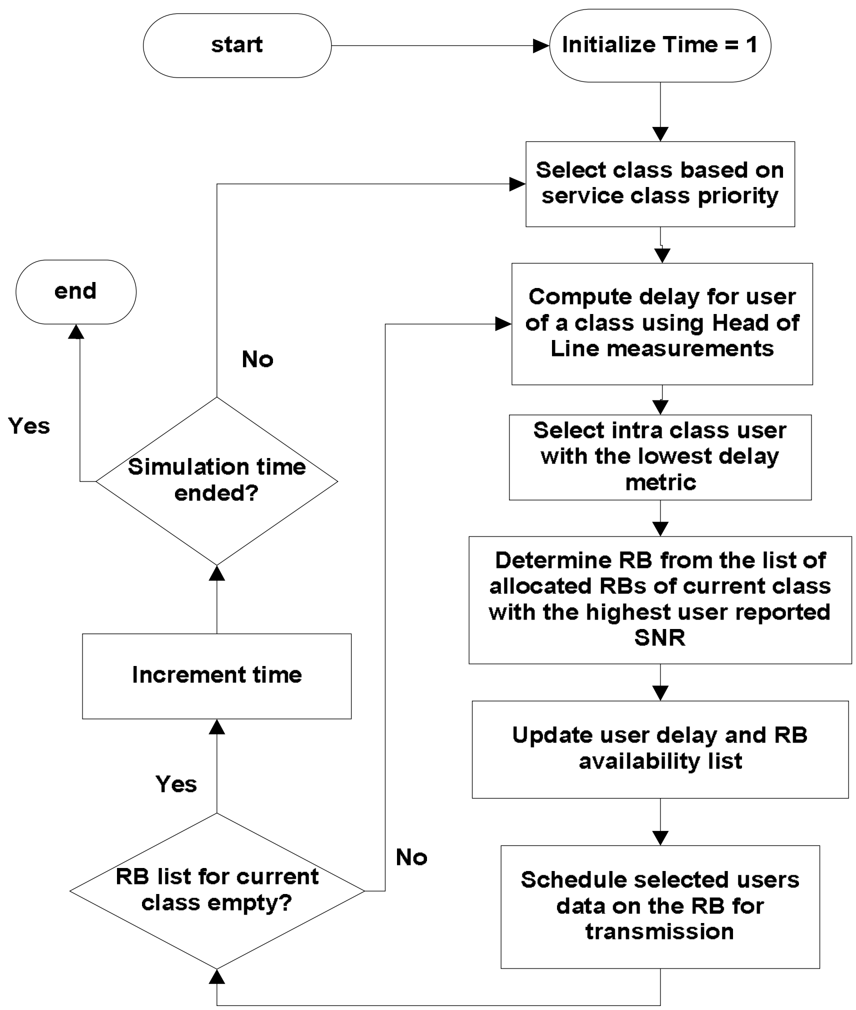

Figure 3.3: LTE Delay Based Scheduling Algorithm

3.2 Summary

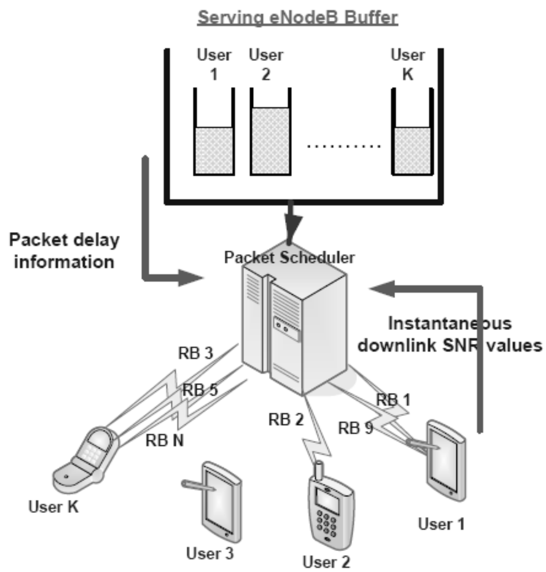

Figure 3.4: Resource Allocation and Delay based scheduling for LTE Networks

In this section we discussed the delay based scheduling design for LTE networks along with Resource Block Allocation and Admission Controller implementation. Examples with calculation for resource block and user capacity were also provided. It is necessary to limit the users in the network by admission controller so that the delay budget for majority of the users can be satisfied. It is also essential to include the SNR values in the scheduling RB scheduling process to achieve good throughputs for LTE users.

Chapter 4

Results and Discussion

This chapter deals with the simulation results, performance analysis and evaluation based on the results for service class based scheduling scheme. The simulator used is also explained with some preliminary calculations and examples.

4.1 Preliminary Calculations

The parameters used for evaluation of service class based scheduling scheme and for finding the accommodated or sustained users include the total system throughput, system delay, Packet Loss Ratio and Signal to Noise Ratio (SNR). The SNR of UE is obtained for different channels corresponding to different Resource Blocks. These analysis parameters are defined below:

4.1.1 System Throughput

The aggregated throughput of system is defined as the summation of packets transmitted in a simulation time from from eNB to all UE. Since we consider downlink only therefore we have not taken the UE to eNB transmissions. A certain amount of the total packets is the control portion and considered overhead reducing the overall goodput. But for general throughput measurements, we consider the aggregate of all packets. In mathematical form, the aggregate throughput of the system is:

$$\text{system throughput} = \frac{1}{T}\sum_{i=1}^{K}\sum_{t=1}^{T} p_{size_i}(t) \tag{4.1}$$

where T represents the total time is taken for simulation and p_{size} depicts the packet size in bits transmitted from eNB to a particular user i aggregated for the simulation time. K represents here the total number of active users in the system.

4.1.2 System Delay

Since we have designed the scheduler based on delay measurements, it is essential to determine the overall system delay experienced by the proposed scheme. The delay of the system is computed as an average of the total time delay difference between the packet arrival time in queue and the time instant it is transmitted to UE from the service queue. This calculation accounts for the HOL packet delay and is finally averaged over all transmitted packets. In mathematical terms we write

$$\text{system delay} = \frac{1}{T}\sum_{t=1}^{T}\frac{1}{K}\sum_{i=1}^{K}\mathrm{HOL}_i(t) \qquad (4.2)$$

Here HOL is described in the same way as mentioned previously while K represents the total number of users in a particular service flows and T being the total simulation time.

4.1.3 Packet Loss Ratio

The packet loss ratio is calculated as the ratio of aggregation of the packets discarded for not meeting the delay budget to the sum of all the packets arriving at eNB station buffer over the simulation time T

$$\mathrm{PLR} = \frac{\sum_{i=1}^{K}\sum_{t=1}^{T} p_{\mathrm{discard}_i}(t)}{\sum_{i=1}^{K}\sum_{t=1}^{T} p_i(t)} \qquad (4.3)$$

4.1.4 Signal to Noise Ratio

The path loss experienced by users is measured for each allocated RB. The gain of channel at time t for a user i on jth RB is then calculated as:

$$C_{Gain_{i,j}}(t) = 10^{\left(\frac{path\_loss}{10}\right)} \quad (4.4)$$

where path_loss is measured in dB scale. From the channel gain measures UE calculates instantaneous downlink SNR and report it to eNB. The final SNR value is calculated as:

$$SNR_{i,j}(t) = \frac{P_{total} \times C_{Gain_{i,j}}(t)}{N(N_o + I)} \quad (4.5)$$

P_{total} is the aggregated power with which eNB station does the transmission in the downlink direction, N represents total available RBs, I determines the neighboring cell interference and N_o is a measure of thermal noise. Since we consider only one un-sectored cell, therefore I is set to zero. The SNR derives the modulation scheme according to the Table 4.2

Table 4.1: Downlink SNR values and Modulation Scheme mapping for LTE

Minimum Instantaneous Downlink SNR Value (dB)	**Modulation Scheme**
1.7	QPSK
3.7	QPSK
4.5	QPSK
7.2	16QAM
9.5	16QAM
10.7	16QAM
14.8	64QAM
16.1	64QAM

4.2 System Characteristics

4.2.1 LTE-Sim

We use a discrete time event simulator LTE-Sim [24] build in C++ with LTE Release-8 specifications. LTE-Sim is an open source simulator including several dimensions of LTE networks, incorporating the E-UTRAN and the EPS. It provides support for single and multi-cell network, management of QoS parameters, multi bearer settings, bearer mobility, handover scenarios and reuse of frequency methods. Four main network entities including UE and eNB have been modeled. Four application level traffic generators have been included. Finally, well-known scheduling methods like Proportional Fair, MLWDF, Exponential Rule and Log-Exp rules have been developed.

4.2.2 System Parameters

System Bandwidths used for our simulation purpose is 5, 10 and 20 MHz which includes 100, 50 and 25 physical Resource Blocks in the downlink. The propagation loss model incorporates shadowing with 0dB mean and 8dB standard deviation. The loss model also takes into account the penetration loss with 12dB setting, multipath used as Jakes model and simple path loss determined as a function of distance form eNB terminal. The delay budget used for test purpose is 100ms or 0.1s corresponding to the tightest delay budget in the LTE service table. The UEs are placed with uniform distribution throughout the area and move around with Random Walk Mobility Model at an average speed of 3km/hr. The cell radius is fixed to 1km and the switch point periodicity is set to 1 (4 DL subframes in each 10ms frame). Users vary from unity to the level where Packet Loss Ratio (PLR) is not met. The simulation system parameters are listed in Table 4.3

Table 4.2: System Parameters used for Simulation

System Parameters	Values
System Bandwidth	20, 10 and 5 MHz
Number of Resource Blocks	100, 50 and 25
Sub-Carriers per Resource Block	12
Sub-Carrier Spacing	15KHz
Sub-Channel Bandwidth	180KHz
Slot Duration	0.5ms
Scheduling Time (TTI)	1ms
OFDM Symbols per RB	6

4.2.3 Scheduling Scenarios

The simulation setup consists of a single cell network with interference noise. There are four types of service flows in the network with requirements of 242kbps for trace based video data, 3kbps for best effort, 12 kbps for VoIP service and CBR traffic at 100kbps. The packet loss ratios for the four types of traffic are fixed to 0.01 except the trace based video which is fixed to 0.001. Each TTI in the simulator is of 1 ms length composed of two time slots of 0.5ms duration. An LTE frame is formed by 10 consecutive TTIs and within each 1ms subframe, 12 OFDM symbols are used.

4.3 Results

4.3.1 Theoretical vs. Simulated Users

For evaluation purpose, theoretical users that can be accommodated in different resource distributions and bandwidths are calculated first and then these are verified with simulations of the proposed scheduling approach. For simulation purpose LTE-Sim is used and the settings used and resource distribution ratios are explained in details.

4.3.1.1 Simulation with 20MHz Bandwidth

First set of simulation is conducted with 20MHz corresponding to 100 Physical Resource Blocks. The four service flows of VoIP, Video, CBR and Best Effort are taken at 12kbps, 242kbps, 100kbps and 3kbps data rate respectively. The delay budget is set to 100ms for all classes except the Best Effort class. The 100ms delay budget is considered the most stringent in the LTE service class table excluding the real time gaming service. The Best Effort class is scheduled with First in First out FIFO method and no packet is dropped for Best Effort even if 100ms delay budget is passed. The Guaranteed classes are scheduled with time delay measurements and the SNR values are maintained corresponding to 16QAM modulation scheme. The switch point periodicity of 5ms is used with configuration 0 (Table 3.2). First experiment within

20MHz bandwidth is done with constant resource ratio of 7:3 for Guaranteed and Best Effort. The guaranteed are tested individually against Best Effort in Table 4.3.User extrapolation is used where the users become too large for simulation. The gap between the simulated and Theoretical users is more for large number of users while the approximations tend to be close enough for less number of users.

Table 4.3: Theoretical and Simulated user capacity for 20MHz with 7:3 Resource Ratio

Traffic Type	Data Rate (kbps)	Resource Ratio GBR:NGBR	Resource Blocks Allocated	Resource Percent	Simulation Users	Theoretical Users
Video	242	7:3	70	70%	24	27.76
VoIP	12	7:3	70	70%	~400	560
CBR	100	7:3	70	70%	55-58	67.2
BE	3	7:3	30	30%	~550-600	960

Table 4.4: Theoretical and simulated mixed user capacity for 20MHz with 3:2:2:3 Resource Ratio

Traffic Type	Data Rate (kbps)	Resource Ratio GBR:NGBR	Resource Blocks Allocated	Resource Percent	Simulation Users	Theoretical Users
Video	242	3:3	30	30%	9	11.9
VoIP	12	2:3	20	20%	~130	160
CBR	100	2:3	20	20%	17-18	19.2
BE	3	7:3	30	30%	~550-600	960

Next we take simultaneous mixed traffic for guaranteed class with resource ratios of 3:2:2:3 for Video VoIP, CBR and Best Effort respectively. The simulated and theoretical users are listed in Table 4.4. Again the simulated and theoretical users for less number of users are in close approximations.

4.3.1.2 Simulation with 10MHz Bandwidth

Simulation set 2 is carried out with 10 MHz bandwidth corresponding to 50 Physical Resource Blocks and 100ms delay budget. The data rates requirement for the three classes are taken the same Constant resource ratio of 7:3 is maintained for Guaranteed and Best Effort for individual testing of guaranteed against best effort. The Resource Blocks are taken as an integer values for allocation at 35:15 ratio from 50 total resource pool. The simulated users are again in close approximation with the theoretical users.

Table 4.5: Theoretical and simulated user capacity for 10MHz with 7:3 Resource Ratio

Traffic Type	Data Rate (kbps)	Resource Ratio GBR:NGBR	Resource Block Allocated	Resource Percent	Simulation Users	Theoretical Users
Video	242	7:3	35	70%	12	13.88
VoIP	12	7:3	35	70%	244	280
CBR	100	7:3	35	70%	27	33.6
BE	3	7:3	15	30%	~400	480

Next mixed simultaneous traffic flows for guaranteed as well as best effort class is taken with resource ratios of 3:2:2:3 for Video VoIP, CBR and Best Effort respectively. The simulated and theoretical users are listed in Table 4.6. Since for 10MHz the resource blocks are half as compared to 20MHz case, correspondingly the number of users accommodated in each class are also less but more accurate to the theoretical values.

Table 4.6: Theoretical and simulated mixed user capacity for 10MHz with 3:2:2:3 Resource Ratio

Traffic Type	Data Rate (kbps)	Resource Ratio GBR:NGBR	Resource Blocks Allocated	Resource Percent	Simulation Users	Theoretical Users
Video	242	3:3	15	30%	6	5.9
VoIP	12	2:3	10	20%	70-73	80
CBR	100	2:3	10	20%	10	9.6
BE	3	7:3	15	30%	~400	480

4.3.1.3 Simulation with 5MHz Bandwidth

Next we further decrease the operating bandwidth of the LTE network and test the same traffic flows of VoIP, Video, CBR and Best Effort. The bandwidth is taken at 5MHz corresponding to the 25 Physical Resource Blocks. The delay budget is again taken at 100ms because we want to test the maximum limits to which the user can be accommodated. The guaranteed classes are tested against best effort individually with a constant ratio of 7:3 corresponding to 17 and 8 Resource block from a total pool of 25. It is observed that the simulated and theoretical values are much closer than the settings with higher operating bandwidth.

Table 4.7: Theoretical and simulated user capacity for 5MHz with 7:3 Resource Ratio

Traffic Type	Data Rate (kbps)	Resource Ratio GBR:NGBR	Resource Blocks Allocated	Resource Percent	Simulation Users	Theoretical Users
Video	242	7:3	17	70%	6	6.77
VoIP	12	7:3	17	70%	98-104	136
CBR	100	7:3	17	70%	13	16.32
BE	3	7:3	8	30%	~220	256

Finally the four types of flows are again tested simultaneously with 3:2:2:3 ratio for Video, VoIP, CBR and Best Effort class. The simulated and theoretical values are listed in Table 4.8.

Table 4.8: Theoretical and simulated mixed user capacity for 5MHz with 3:2:2:3 Resource Ratio

Traffic Type	Data Rate (kbps)	Resource Ratio GBR:NGBR	Resource Blocks Allocated	Resource Percent	Simulation Users	Theoretical Users
Video	242	3:3	9	30%	3	3.57
VoIP	12	2:3	4	20%	25	32
CBR	100	2:3	4	20%	4	3.84
BE	3	7:3	8	30%	~220	256

4.3.1.4 Simulation with 10ms Switch Point Periodicity

Different switch point periodicity configurations can be used for LTE frames as described in Table 3.2. These switch point periodicities are used to handle traffic load in the uplink and downlink direction. If the load in the downlink direction increases, a switch point periodicity with more downlink slots can be used. A switch point periodicity with higher downlink slots will increase the downlink data rate and more users can be accommodated. The number of accommodated users in 5MHz bandwidth and switch point periodicity configuration of 5 with 8 downlink slots per frame is described in Table 4.9 and Table 4.10 for different GBR to NGBR Resource Ratios.

Table 4.9: Theoretical and simulated user capacity for 5MHz and Switch Point Periodicity configuration 5 (8 DL slots per frame) with 7:3 Resource Ratio

Traffic Type	Data Rate (kbps)	Resource Ratio GBR:NGBR	Resource Blocks Allocated	Resource Percent	Simulation Users	Theoretical Users
Video	440	7:3	70	70%	55	61.09
VoIP	64	7:3	70	70%	~400	420
CBR	500	7:3	70	70%	50	53.75
BE	200	7:3	30	30%	52	57.6

Table 4.10: Theoretical and simulated user capacity for 5MHz and Switch Point Periodicity configuration 5 (8 DL slots per frame) with 3:2:2:3 Resource Ratio

Traffic Type	Data Rate (kbps)	Resource Ratio GBR:NGBR	Resource Blocks Allocated	Resource Percent	Simulation Users	Theoretical Users
Video	440	3:3	30	30%	24	26.18
VoIP	64	2:3	20	20%	120	108
CBR	500	2:3	20	20%	15	15.36
BE	200	7:3	30	30%	52	57.6

4.3.1.5 Simulation with Variable SNR

Downlink SNR plays a key role in driving the Automatic Modulation and Coding scheme. With higher SNR values, higher data rate can be achieved in the downlink direction with higher order Modulation Schemes. The minimum SNR values with corresponding Modulation schemes for LTE Networks are described in Table 4.2. Users near the eNB station tend to achieve higher SNR values while the users at the end of the cell usually suffer from lower SNR values. With constant placement of UEs in the cell with target SNR values, the maximum number of accommodated users in the cell is described in Table 4.11 for Modulation Schemes of 16QAM (4 bits per symbol) and 64QAM (6 bits per symbol).

Table 4.11: Theoretical and simulated user capacity for 5MHz and Switch Point Periodicity configuration 3 (6 DL slots per frame) with Variable downlink SNR

Traffic Type	Data Rate (kbps)	Resource Blocks	Average DL SNR (dB)	Bits per Symbol	Simulation Users	Theoretical Users
CBR	100	25	>7.2 & <10.7	4	64	72
CBR	200	25	>7.2 & <10.7	4	31	36
CBR	500	25	>7.2 & <10.7	4	13	14.4
CBR	100	25	>14.8	6	90	108
CBR	200	25	>14.8	6	45	54
CBR	500	25	>14.8	6	18	21.6

4.3.2 Comparison

4.3.2.1 System Delay

The proposed approach allows for minimum resource block guarantee hence a minimum level of data rate can be maintained (e.g. for Best Effort) while maintaining specific delay budget. There is however a compromise on the data rate of other classes since resources are borrowed for best effort from the guaranteed class. The delay characteristics are compared with Proportional Fair, Exponential Rule and Modified Largest Weighted Delay First (MLWDF). The delay measurement is taken as explained in section 4.1.2. The Proportional Fair algorithm performs the worst because it does not take into account any form of delay characteristics. It assigns radio resources taking into account both the experienced channel quality and the past user throughput. The goal is to maximize the total network throughput and to guarantee fairness among flows. Only MLWDF and Exp Rule take into account the delay characteristics indirectly. The exponential rule is designed to increase the priority of real time flows with respect to non real time ones when the exponential delay function accounts for a higher value for real flows. The MLWDF is used to improve the QoS of different flows by defining a probability function that represents the urgency for data transmission corresponding to higher time spent in the buffer queue.

Our proposed scheme directly includes the delay parameter from service class table and it is used to drop packets for guaranteed class when the delay budget is exceeded so as to avoid any load on the queue of other traffic. From the comparison it is visible from Figure 4.1 that PF performs the worst while MLWDF scoring the closest. The Exponential rule performs in between. It should be noted that the delay is maintained below 100ms or 0.1s for less than 60 users on average but it reaches 100ms after that showing that some or much of the flows have now started to cross delay budget and the average is close to the delay budget itself. This comes with a compromise of more packet loss as compared to other schemes. This can be catered by limiting the traffic by an admission controller to the level where delay thresholds can be satisfied for majority of the users.

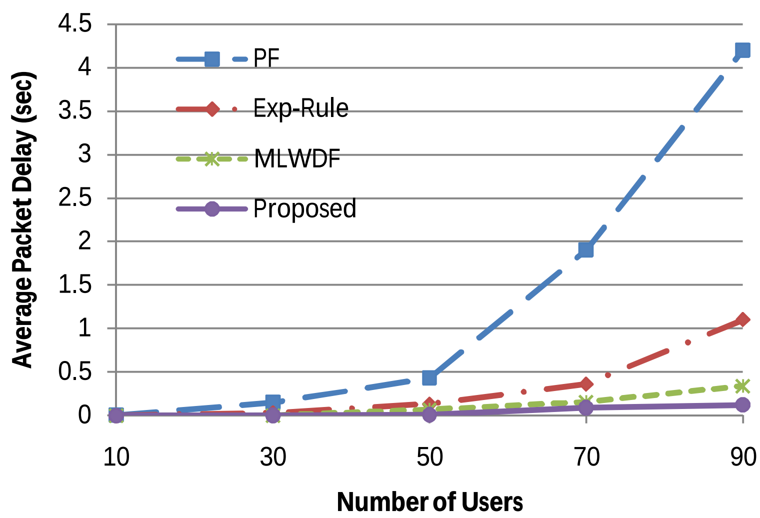

Figure 4.1: System Delay comparison for Proposed Scheduler

4.3.2.2 System Throughput

The through put for the network is measured according to the measurements explained in 4.1.1. Since we initially allocate Resource Blocks to different flows rather than having a flexible approach of different higher classes taking up other flows resource, therefore we have tried to maintain a minimum level of guarantee for different service classes. The throughput results for CBR and BE class are given in Figure 4.2 and Figure 4.3 where both traffic are simulated individually and allowed to take up all Resources. The setup is run at 10MHz for CBR and at 5MHz for BE. The data rate of CBR is maintained at 150kbps while the BE is taken at 50kbps. In the guaranteed traffic case of CBR, the proposed scheme suggests results similar or near to MLWDF scheme while the EXP-Rule achieves the highest throughput. The PF scheme results in the lowest comparative throughput for CBR. In the BE case, the minimum resource guarantee approach results in higher throughput for the proposed scheme while other methods show lower throughput with loaded users since they treat BE as lowest priority for resource allocation (Figure 4.3).

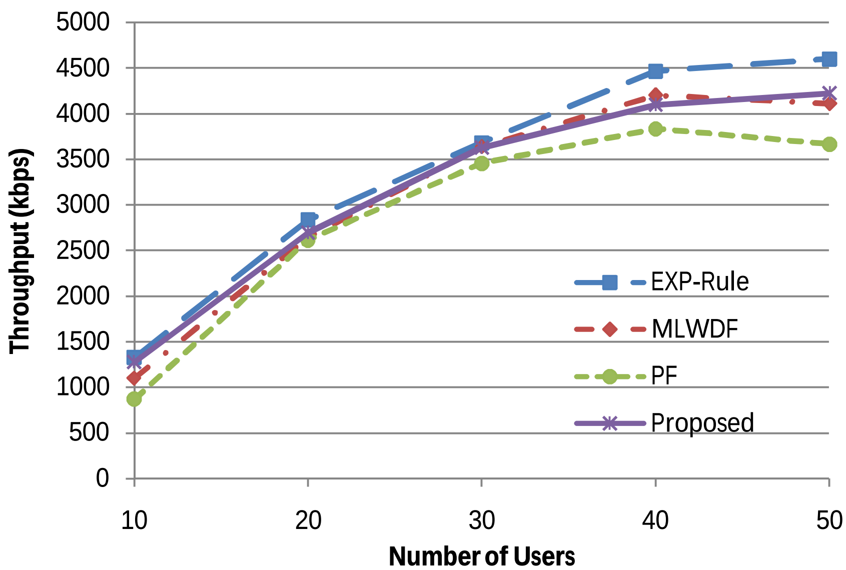

Figure 4.2: Throughput comparison for proposed scheme with CBR traffic at 150kbps and Resource Allocation of 100% in 10MHz Bandwidth

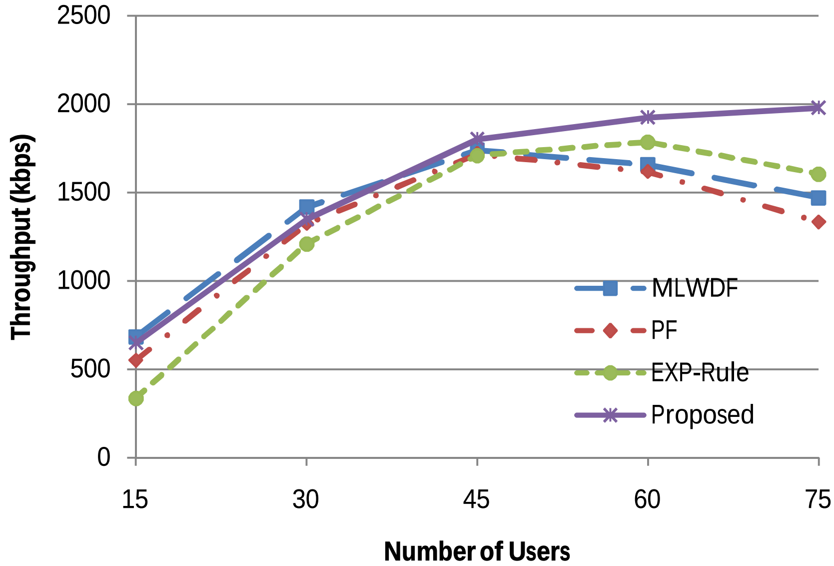

Figure 4.3: Throughput comparison for proposed scheme with BE traffic at 50kbps and Resource Allocation of 100% in 5MHz Bandwidth

In a mixed traffic case with GBR as well as NGBR services, the best effort is allowed to take resources from the guaranteed pool when there are free resources from the guaranteed resource section but the other is not true. This is because if some guaranteed user is admitted in the network then the best effort can be limited to its resource block pool without much compromise but if guaranteed traffic is allowed to take resources from the best effort resource pool and needs to limit to its own resource allocated ratio then the guaranteed class would suffer, For a 100ms delay budget comparison for CBR and Best effort at 150kbps and 200kbps respectively the results are depicted in Figure 4.4 and Figure 4.5.

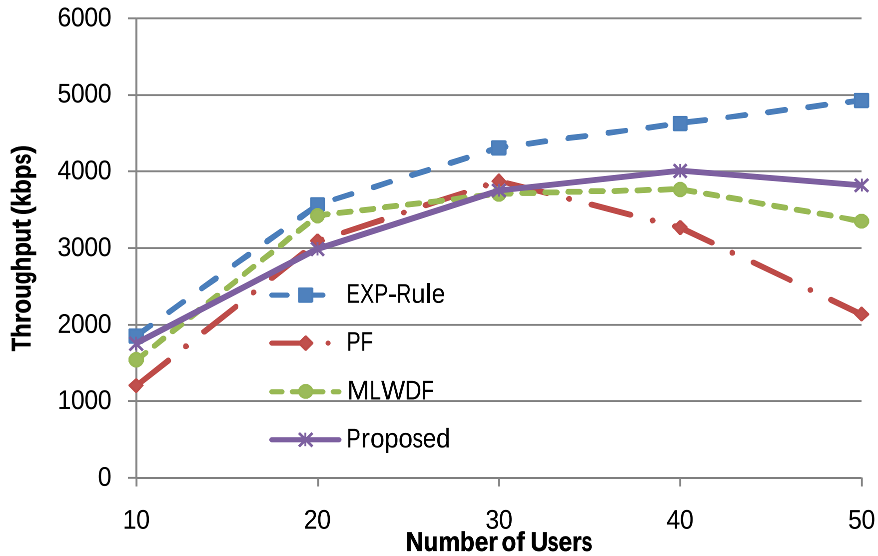

Figure 4.4: Throughput comparison for proposed scheme with CBR traffic at 150kbps and Resource Allocation of 70% in 10MHz Bandwidth

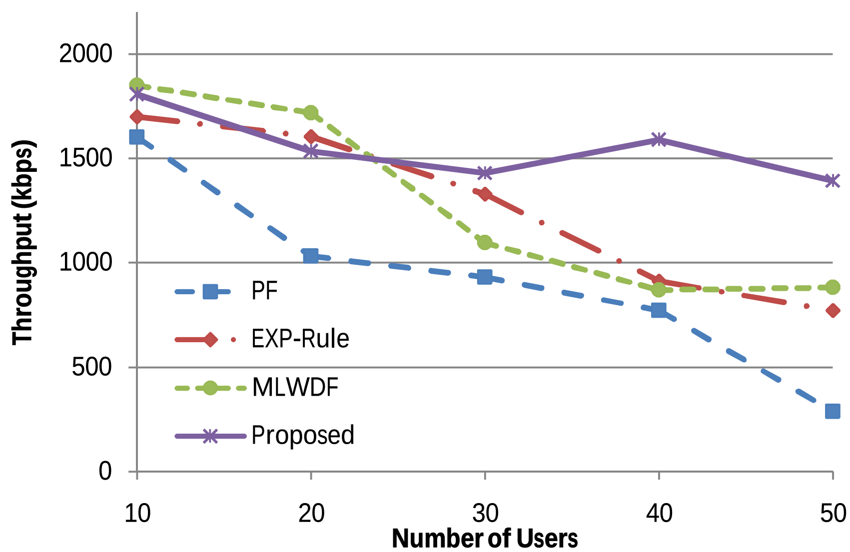

Figure 4.5: Throughput comparison for proposed scheme with BE traffic at 200kbps and Resource Allocation of 30% in 10MHz Bandwidth

The mixed GBR and NGBR traffic results show that when the number of users in the network increases, resources are taken away from the best effort class to fulfill the requirements of guaranteed traffic. But this is not the case with proposed scheme since we have maintained a minimum level of guarantee for the two traffic types by defining different resource pool ratio for both. For CBR traffic case the EXP-Rule algorithm performs the best because it take into account the buffer queue with an exponentially growing delay priority for user packets. The proposed method performs in between the EXP-Rule and other approaches. The PF performs worst for high load in the network corresponding to more than 40 users in the network on average.

For the best effort case the proposed scheme performs much better than other three schemes which deprive best effort class from resources when the users in the guaranteed class increase. Here again the PF perform worst, the MLWDF and Exp Rule in between but the proposed scheme maintains an appreciable gap with some stability and consistency in the throughput. This consistency in throughput is also visible in the CBR case which validates the minimum guarantee scheduler claim.

4.4 Discussion

From the theoretical user's calculation and the simulation results for number of users accommodated, the system delay characteristics and the throughput measurements we can recapitulate the following points:

- With a number of service classes defined for LTE, the minimum resource level guarantee and allocation is essential to avoid deprivation of resources from lower classes
- Best Effort classes corresponding to NGBR class can be given minimum guarantee without much compromise in throughput for guaranteed class
- Admission controller is essential to keep the users at a minimum level where different service class requirements like delay budget and packet loss rates can be maintained
- The modified theoretical capacity based users measurement model can be used to implement capacity based admission controller since the results have been verified with close approximations via simulations

- Using delay budget parameters in scheduling decision is useful to limit the overall average system delay to a minimum level. Though different delay budget parameters like 100ms and 300ms have less impact on the user capacity but have significant influence on the Packet Loss Rates.

4.5 Summary

In this chapter we discussed the delay based scheduler design for LTE networks. The performance measuring parameters like system delay, throughput and SNR were discussed. The resource allocation, admission controller and the packet scheduling were discussed and analyzed using theoretical and simulated statistics. Finally the proposed scheme was compared with Proportional Fair, MLWD and EXP-Rule in terms of system delay and throughput achieved.

Chapter 5

Conclusion

Resource Allocation and Scheduling in LTE has been under a lot of research for the past few years, and may scheduling schemes have been proposed to meet different objectives like fairness, throughput maximization and meeting QoS guarantees. These schemes were unable to cater the actual service class requirements for LTE networks including the delay budgets and packet loss ratio. Moreover following a large number of service classes defined in the guaranteed and non-guaranteed classes, no attempt was made to provide a minimum resource level guarantee at service class level. We proposed and implemented a minimum resource level guaranteed scheduler in this research work that incorporated service class attributes including delay budget in the scheduling decision.

5.1 Thesis Summary

To achieve a minimum resource level guarantee to service classes, specifically the best effort traffic while satisfying the delay budget requirements, we proposed a service delay-budget and channel quality aware LTE network scheduler in the downlink with a bound on the number of resources that can be assigned to each class. These bounds were dynamically tested for delay budgets and packet loss rates to determine different number of accommodated and sustained users of a particular service type. For example in a 10MHz spectrum usage, the number of accommodated users in a 7:3 resource ratio for Guaranteed (Video, VoIP and CBR tested individually) and Non-Guaranteed (Best Effort) traffic came out to be ~14, 280, 33 and 480 using theoretical model with delay budget of 100ms. These were validated using simulations with close approximations of ~12, 244, 27, and more than 400 users for each category while running Video at 242kbps, VoIP at 12kbps, CBR at 100kbps and BE at 3kbps. Moreover the data rate of best effort is sustained within specific levels corresponding to the assured resources even when the system is loaded with guaranteed users which in contrast to normal scheduler usage goes down to zero after the resources get mostly occupied by guaranteed service. Using delay budget parameters, the service flow delay is also maintained within margins. Admission Controller for LTE Network is a direct application of this work and its design is also explained. Alternatively the resources needed to accommodate and sustain certain number of users can also be calculated by the theoretical models presented in the dissertation. The main contributions of the thesis are highlighted below:

- Incorporation of Packet Delay Budget parameter from LTE service class standards specification in traffic scheduling
- Controlled Allocation of Physical Resource Block for service classes
- Use of a modified theoretical model to calculate accommodated user capacity keeping in view the data rates or type of service.
- Verification of theoretical model via simulations with close approximations
- We also maintained minimum resource guarantee for Best Effort class while in typical schedulers the Best Effort does not get resources when guaranteed class users are exceeded.
- Finally we presented guidelines using theoretical and simulated users of different traffic types that can be accommodated in LTE Network via Tabular form.

5.2 Future Extensions

Though we tried to incorporate much of the service class attributes in the scheduling of traffic in LTE networks, a lot of other dimensions can still be explored for more resourceful and LTE specifications oriented schemes. For example we have not taken into account in detail the QoS Class Identifiers (QCI) for prioritization of LTE traffic. Attributes like fairness can also be tested for different traffic types to achieve some hybrid method of allocation and scheduling. Moreover, interference from other cell sites and throughput for different sectored cells can also be explored in different frequency setups.

Bibliography

[1] M. Alsati, B. Neekzad, J. Hui and R. Vannithamby, “QoS over LTE and Wimax Networks,” in IEEE Journal of Communications Magazine, vol. 48, no. 5, pp. 104-111, May 2010.

[2] M. Iturralde, T. A. Yahiya, A. Ei and A. Beylot, “Resource Allocation Using Shapley Value in LTE Networks”, in Proc. of IEEE Personal Indoor Mobile Radio Communications, PIMRC. Sep. 2011, Toronto, Canada.

[3] K. Andrasegaran, H. Adibah, M. Ramli and R. Basukala, “Delay-Prioritized Scheduling (DPS) for Real Time Traffic in 3GPP LTE System”, in Proc. of IEEE Wireless Communication and Networking Conference, 2010, Sydney, Australia, pp. 1-6.

[4] M. Gidlund and J.C. Laneri, “Scheduling Algorithms for 3GPP Long-Term Evolution Systems: From a Quality of Service Perspective”, Proceedings of the 10th IEEE International Symposium on Spread Spectrum Techniques and Applications (ISSSTA ’08), pp. 114–117, August 2008.

[5] P. Hung, V. Xuan, N. Hwang, S. Hoon, “Service Class-Aided Scheduling for LTE”, in IEEE 13th International Conference on Advanced Communication Technology, pp. 39-43, Feb 2011

[6] B. Sadiq, R. Madan and A. Sampath. "Downlink Scheduling for Multiclass Traffic in LTE", EURASIP Journal on Wireless Communications and Networking, vol. 2009 pp. 1-18, July. 2009.

[7] R. Basukala, H. M. Ramli, and K. Sandrasegaran, “Performance analysis of

EXP/PF and M-LWDF in downlink 3GPP LTE system", in Proc. of First Asian Himalayas International Conference on Internet, AH-ICI, Kathmandu, Nepal, Nov. 2009.

[8] D. Niyato and E. Hossain. "A Cooperative Game Framework for Bandwidth Allocation in 4G Heterogeneous Wireless Networks", IEEE International Communications Conference (ICC), vol. 9, pp. 4357-4363, June 2006. Istanbul, Turkey.

[9] Elias Z. Tragos, George T. Karetsos and Sofoklis A. Kyriazakos, "Admission Control for QoS Support in Heterogeneous 4G Wireless Networks", IEEE Networks, vol. 22, no. 3, May/June 2008, pp. 30–37.

[10] I. Siomina and Wanstedt, "The Impact of QoS Support on the End User Satisfaction in LTE Networks with Mixed Traffic", IEEE 19th International Conference on Personal, Indoor and Mobile Radio Communications, vol. 19, no. 1, September 2008, pp. 2455-2459

[11] C. J. Huang, Y. T. Chuang, W. K. Lai, Y. H. Sun, C. T. Guan "Adaptive Resource Reservation Schemes for Proportional DiffServ Enabled Fourth-Generation Mobile Communications System", Vol. 30, Issue. 7, pp. 1613-1623, Computer Communications Journal, May 2007

[12] Z. Tang, "Traffic Scheduling for LTE Advanced", PhD Thesis, Linkoping University, Department of Electrical Engineering, 2010

[13] M. Qian, Y. Huang, J. Shi, Y. Yuan, L. Tian, E. Dutkiewicz, "Novel Radio Admission Control Scheme for Multiclass Services in LTE Systems", pages 2230-2235, Proceedings of the IEEE Globecom, 2009

[14] 3GPP Requirements for Support of Radio Resource Management on Evolved

Universal Terrestrial Radio Access (E-UTRA), TS 36.133, RP-51, Version 10.2.0

[15] 3GPP Specifications for Radio Resource Control (RRC) on Evolved Universal Terrestrial Radio Access (E-UTRA) Protocol, TS 36.331, RP-51, Version 10.1.0

[16] M. A. Rawi, R. Jantti, “Opportunistic Best-Effort Scheduling For QoS-Aware Flows”, pp. 1-5, in IEEE PIMRC 2006

[17] G. Monghal, D. Laselva, P.H. Michaelsen, J. Wigard, “Dynamic Packet Scheduling for Traffic Mixes of Best Effort and VoIP Users in E-UTRAN Downlink”, in EEE 71st Vehicular Technology Conference (VTC), pp. 1-5, 2010

[18] O. Iosif, I. Banica, “On the Analysis of Packet Scheduling in Downlink 3GPP LTE System”, The Fourth International Conference on Communication Theory, Reliability, and Quality of Service, CTRQ 2011

[19] K. Pedersen, T. Kolding, F. Frederiksen, I. Kovacs, D. Laselva, and P. Mogensen, “An overview of downlink radio resource management for UTRAN long-term evolution", IEEE Communications Mag., vol. 47, no.7, pp. 86-93, Jul. 2009.

[20] J.G. Choi and S. Bahk, “Cell-throughput analysis of the proportional fair scheduler in the single-cell environment”, IEEE Transactions on Vehicular Technologies, vol. 56, no. 2, pp. 766 –778, Mar. 2007.

[21] R. Basukala, H. M. Ramli, and K. Sandrasegaran, “Performance analysis of EXP/PF and M-LWDF in downlink 3GPP LTE system”, in Proc. of First Asian Himalayas International Conference on Internet, AH-ICI, Kathmandu, Nepal, Nov. 2009

[22] G. Piro, L. A. Grieco, G. Boggia, R. Fortuna, and P. Camarda, "Two-level

downlink scheduling for real-time multimedia services in LTE networks", IEEE Transactions on Multimedia, 2011

[23] G. Piro, L. A. Grieco, G. Boggia, and P. Camarda, "A Two-level Scheduling Algorithm for QoS Support in the Downlink of LTE Cellular Networks", in Proc. of European Wireless, EW'10, Lucca, Italy, Apr, 2010

[24] G. Piro, L. A. Grieco, G. Boggia, F. Capozzi, and P. Camarda “Simulating LTE Cellular Systems: an Open Source Framework”, IEEE Transactions on vehicular technology

[25] E. Cerqueira, L. Velos, M. Curado, E. Monteiro, P. Mendes, “Quality Level Control for Multi-user Sessions in Future Generation Networks”, IEEE Global Telecommunications Conference, Globecom ’08, pages 1-6, Dec 2008

[26] S. Wang, D. Xuan, R. Bettati and W. Zhao, “Toward Statistical QoS Guarantees in a Differentiated Services Network”, SpringerLink Telecommunication Systems, vol. 43, no. 3-4, pp.253-263 Oct 2009

[27] M. Fiedler, T. Hossfeld and P. T. Gia, “A Generic Quantitative Relationship between Quality of Experience and Quality of Service”, IEEE Networks Journal, Vol. 24, pp. 36-41 April 2010

[28] Y. Guo and H. Chaskar, “Class-Based Quality of Service over Air Interfaces in 4G Mobile Networks”, IEEE Communications Magazine, Vol. 40, Issue. 3, pp. 132-137, March 2002

[29] Y. W. Sung, C. Lund, M. Lyn, S. Rao and S. Sen, “Modeling and Understanding End-to-End Class of Service Policies in Operational Networks”, Proceedings of ACM Sigcomm, Volume 39 Issue 4, October 2009

[30] R. Li, L. Ying, A. Eryilmaz and N. B. Shroff, "A Unified Approach to Optimizing Performance in Networks serving Heterogeneous Flows", IEEE Transactions of Networking, Volume 9, Issue 1, pages 223-236, Feb 2011

[31] X. Li, W. Bigos, D. Dulas, Y. Chen, U. Toseef, C. Goerg, A. Timm-Giel, and A. Klug "Dimensioning of the LTE Access Network for the Transport Network Delay QoS", IEEE 2011

[32] H. Wang, D. Jiang and E. Tuomaala, "Uplink Capacity of VoIP on LTE System", IEEE Proceedings of Asia-Pacific Conference on Communications 2007

[33] M. Iturralde, A. Wei, T. A. Yahiya and A. L. Beylot, "Resource Allocation for Real Time Services Using Cooperative Game Theory and a Virtual Token Mechanism in LTE Networks", in IEEE PIMRC 2011

[34] Y. Wang, G. Li, T. Wu and F. Gong, "Adaptive Proportional Fair Scheduling in Multihop OFDMA Systems", IEEE 2010

[35] C. Yang, W. Wang, Y. Qian and X. Zhang, "A Weighted Proportional Fair Scheduling to Maximize Best-Effort Service Utility in Multicell Network", IEEE 2008

[36] W. Ajib, D. Haccoun, "An Overview of Scheduling Algorithms in MIMO-Based Fourth-Generation Wireless Systems", IEEE Networks, Sep-Oct 2005

[37] C. Gueguen and S. Baey, "Compensated Proportional Fair Scheduling in Multiuser OFDM Wireless Networks", IEEE International Conference on Wireless & Mobile Computing, Networking & Communication 2008

[38] S. Abedi, S. Vadgama, "A genetic approach for downlink packet scheduling in HSDPA system", in Springer-Verlag, 19 January 2004

[39] M. Bodin, “Solutions to Fast Multistream Proportional Fair Scheduling in HSDPA Systems”, Licentiate Thesis, Faculty of Computer Science, University of Namur August 2009

[40] C. Q. Luo, H. Ji, and Y. Li, “Utility-based Multi-service Bandwidth Allocation in the 4G Heterogeneous Wireless Access Networks”, in IEEE WCNC 2009