İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

AN ENHANCED RED-BASED WEIGHTED FAIR PRIORITY QUEUING ALGORITHM FOR IEEE 802.16 SUBSCRIBER STATION SCHEDULER

M.Sc. Thesis by
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Department : **Computer Engineering**

Programme : **Computer Engineering**

JANUARY 2010

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Date of submission : **25 December 2009**
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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

IEEE 802.16 KULLANICI İSTASYONLARI İÇİN YENİ RASTGELE ERKEN TESPİT YÖNTEMİ TABANLI KUYRUKLAMA ALGORİTMASI TASARIMI

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FOREWORD

I would like to express my deep appreciation and thanks for my advisor Prof. Dr. Sema OKTUĞ for her contribution and support. I also wish to thank Gökhan YILDIRIM, Berk CANBERK and Zeynep YURDAKUL for their guidance in analyzing the proposed algorithms. In addition to this, I would like to thank my family for their support in my whole life.

This thesis is dedicated to my father, Agop KASACI.

January 2010

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ABBREVIATIONS

BE	: Best Effort
BS	: Base Station
BW	: Bandwidth
BWA	: Broadband Wireless Access
CID	: Connection Identifier
CPS	: Common Part Sublayer
CRC	: Cyclic Redundancy Check
CS	: Convergence Sublayer
DFPQ	: Deficit Fair Priority Queuing
DHCP	: Dynamic Host Configuration Protocol
DIUC	: Downlink Interval Usage Code
DL	: Downlink
DL-MAP	: Downlink MAP
DRR	: Deficit Round Robin
DSA	: Dynamic Service Addition
DSC	: Dynamic Service Change
DSD	: Dynamic Service Deletion
EDF	: Earliest Deadline Fast
FDD	: Frequency Division Duplex
FIFO	: First In First Out
FTP	: File Transfer Protocol
GPC	: Grant Per Connection
GPSS	: Grant Per Subscriber Station
HFDD	: Half-Duplex Frequency Division Duplex
HT	: Header Type
IEEE	: Institute of Electrical and Electronics Engineers
IP	: Internet Protocol
LLC	: Logical Link Control
LOS	: Line-of-Sight
MAC	: Medium Access Control
MPEG	: Moving Pictures Expert Group
MRTR	: Maximum Reserved Traffic Rate
MSDU	: Medium Access Control Service Data Unit
NDSL	: Network and Distributed Systems Laboratory
NLOS	: Non-Line-of-Sight
nrtPS	: non-real-time Polling Service
ns-2	: Network Simulator-2
OFDM	: Orthogonal Frequency Division Multiplex
OFDMA	: Orthogonal Frequency Division Multiple Access
OSI	: Open System Interconnection
PDU	: Protocol Data Unit
PHY	: Physical
PM	: Poll-Me

PMP : Point-to-Multipoint
QoS : Quality of Service
RED : Random Early Detection
RIO : Random Early Detection with In/Out
rtPS : real-time Polling Service
SC : Single Carrier
SDU : Service Data Unit
SF : Service Flow
SFID : Service Flow Identifier
SNMP : Simple Network Management Protocol
SP : Strict Priority
SS : Subscriber Station
TCP : Transmission Control Protocol
TDD : Time Division Duplex
TELNET : Teletype Network
TFTP : Trivial File Transfer Protocol
UCD : Uplink Channel Descriptor
UDP : User Datagram Protocol
UGS : Unsolicited Grant Service
UL : Uplink
UL-MAP : Uplink MAP
VBR : Variable Bit Rate
VoIP : Voice over IP
WAN : Wide Area Network
WFPQ : Weighted Fair Priority Queuing
WiMAX : Worldwide Interoperability for Microwave Access
WLAN : Wireless Local Area Network
WMAN : Wireless Metropolitan Area Network
WPAN : Wireless Personal Area Network
WRR : Weighted Round Robin
WWAN : Wireless Wide Area Network

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AN ENHANCED RED-BASED WEIGHTED FAIR PRIORITY QUEUING ALGORITHM FOR IEEE 802.16 SUBSCRIBER STATION SCHEDULER

SUMMARY

With the increasing use of wireless networks, the IEEE 802.16 standard [1] based on Broadband Wireless Access Systems has been proposed for high-speed wireless access with wide range coverage. IEEE 802.16, which is also called Worldwide Interoperability for Microwave Access (WiMAX), is an air interface for Fixed Broadband Wireless Access Systems. It has been ratified by IEEE as a Wireless Metropolitan Area Network (WMAN) technology [2]. IEEE 802.16d introduces four service classes, which are called Unsolicited Grant Service (UGS), real-time Polling Service (rtPS), non-real-time Polling Service (nrtPS), and Best Effort (BE). The aim of defining these service classes is to provide users options for choosing different services that have different QoS parameters. Each service type is associated with a set of Quality of Service (QoS) parameters, but WiMAX does not specify how to schedule traffic efficiently according to the QoS. Consequently, the bandwidth needs to be scheduled between these service classes in order to meet their QoS. As a result, many researchers have proposed some scheduling algorithms, such as Strict Priority (SP), Weighted Fair Priority Queuing (WFPQ), and RED-based Deficit Fair Priority Queuing (DFPQ). Some of these algorithms attempt to provide all service classes their QoS requirements in a fair and efficient way.

In this thesis, RED-based Weighted Fair Priority Queuing scheduling algorithm is enhanced to increase nrtPS throughput for Point to Multipoint (PMP) networks. RED-based WFPQ has a dynamic structure while granting bandwidth for rtPS as the algorithm is proposed for Grant per Subscriber Schedulers. To schedule bandwidth for rtPS flows, the algorithm considers the queue length of rtPS. If the current queue length of rtPS is lower than the minimum threshold, algorithm schedules minimum weight for them. If the current queue length of rtPS is higher than the maximum threshold, then the algorithm reserves maximum weight. When the current queue length is between minimum and maximum thresholds, the assigned weight changes dynamically. In the RED-based WFPQ algorithm, nrtPS flow is prevented from starving. However, the throughput of nrtPS can be increased via the enhanced scheduling algorithm, we called Enhanced RED-based WFPQ. The second proposed algorithm increases the throughput of nrtPS load. In this algorithm, the RED technique is applied to nrtPS flow as well. In addition the algorithm also prevents from the starvation of BE service flow in a congested network. Simulation results show that in RED-based WFPQ and Enhanced RED-based WFPQ, rtPS throughput is improved without starving lower priority service classes. Furthermore, Enhanced RED-based WFPQ improves nrtPS throughput without starving BE flows.

IEEE 802.16 KULLANICI İSTASYONLARI İÇİN YENİ RASTGELE ERKEN TESPİT YÖNTEMİ TABANLI KUYRUKLAMA ALGORİTMASI TASARIMI

ÖZET

Son zamanlarda kablosuz ağ kullanımına ihtiyacın artması sebebiyle, IEEE 802.16, diğer adıyla WiMAX önerilmiş, bu standart ile beraber yüksek hızlı internet erişimi geniş alanlarda hedeflenmiştir. Bu standart IEEE tarafından Kablosuz Metropol Alan Ağı (WMAN) Teknolojisi olarak onaylanmıştır. WiMAX, UGS, rtPS, nrtPS ve BE olmak üzere dört tip servis sınıfı belirtmiştir. Servis sınıflarının tanımlanmasının asıl amacı, kullanıcılara farklı servislerin verilebilmesini sağlamaktır. Her servis tipinin kendi servis kalitesini karşılayabilmesi için ihtiyacı olduğu bir kalite ihtiyaç kümesi vardır. Bant genişliğinin servisler arasında paylaştırılmasında bu kalite ihtiyaç kümelerinden yararlanılmalıdır. Bu şekilde servisler arası öncelik tanımlanabilir. WiMAX standardı, servis kalitesi ihtiyacının en verimli şekilde sağlanması için kullanılması gereken algoritmaları kesin olarak belirlememiştir. Bunun sonucunda şimdiye kadar bant genişliğinin servisler arasında dengeli, adil ve kalite kümesine bağlı olarak paylaştırılması üzerine sayısız algoritma geliştirilmiştir (Strict Priority, Weighted Fair Priority Queuing, RED-based Deficit Fair Priority Queuing.). Bu algoritmaların bazılarında dikkat edilen husus, verimli bir şekilde, servislerin kalite standartlarını koruyarak bant genişliğinin paylaştırılmasıdır.

Bu tez çalışmasında “Rastgele Erken Tespit tabanlı Dengeli Adil Bant Genişliği Paylaştırma (RED-based WFPQ)” algoritması kullanılarak “Enhanced RED-based WFPQ” önerilmiştir. RED-based WFPQ’te rtPS bant genişliğinin atanması dinamik haldedir ve rtPS için kullanılan kuyruk boyutuna bağlı olarak adaptif bir şekilde değişiklik göstermektedir. Eğer rtPS kuyruk boyutu tanımlanmış olan minimum eşik değerinden küçük ise, rtPS için tanımlanmış olan minimum oranda bant genişliği ayrılacaktır. Eğer rtPS kuyruk boyutu tanımlanmış olan maksimum eşik değerinden büyük ise, rtPS için tanımlanmış olan maksimum oranda bant genişliği ayrılacaktır. Eğer rtPS kuyruk boyutu minimum ve maksimum eşiklerin arasında ise, bu aralıkta kuyruk boyuna bağlı olarak lineer bir şekilde bant genişliği ataması yapılacaktır. RED-based WFPQ algoritmasının geliştirilmesi ile Enhanced RED-based WFPQ algoritması önerilmiştir. Önerilen algoritmada nrtPS servis tipinin verimliliğinin daha fazla arttırılabilmesi için, RED yöntemi nrtPS servis tipi için de uygulanmıştır. Enhanced RED-based WFPQ’da nrtPS’in verimliliği arttırılmış; RED-based WFPQ’den daha iyi sonuç vermiştir. Sonuç olarak, her iki algoritmada da rtPS verimliliği arttırılmış, düşük öncelikli servis tiplerinin, yüksek öncelikli servis tiplerinin yoğun trafiği altında ölmesi engellenmiştir. Önerilen algoritma ile (Enhanced RED-based WFPQ) nrtPS’in verimliliği daha çok arttırılmıştır. İki algoritma da PMP ağ yapısı için GPSS’te kullanılabilir.

1. INTRODUCTION

The Institute of Electrical and Electronics Engineers (IEEE) 802.16 standard, widely known as WiMAX (Worldwide Interoperability for Microwave Access Forum), has been developed to accelerate the introduction of broadband wireless access into the marketplace. The advantages of this standard are easy and low-cost deployment, high data rate, last-mile wireless access, and QoS support for multimedia applications [3]. Consequently, with QoS, this standard can provide different priorities for different traffic classes.

The IEEE 802.16 standard defines two possible network topologies, Point-to-Multipoint (PMP) and Mesh Networks. In the PMP networks, communication between Subscriber Stations (SSs) is possible only through a Base Station (BS). PMP can be categorized as a single-hop network. In a PMP network, every SS has a single hop to communicate with BS as in Figure 1.1. In the mesh mode, SSs can communicate with each other directly as in Figure 1.2. As a result, mesh networks can be categorized as multihop network. In this thesis, we use PMP topology.

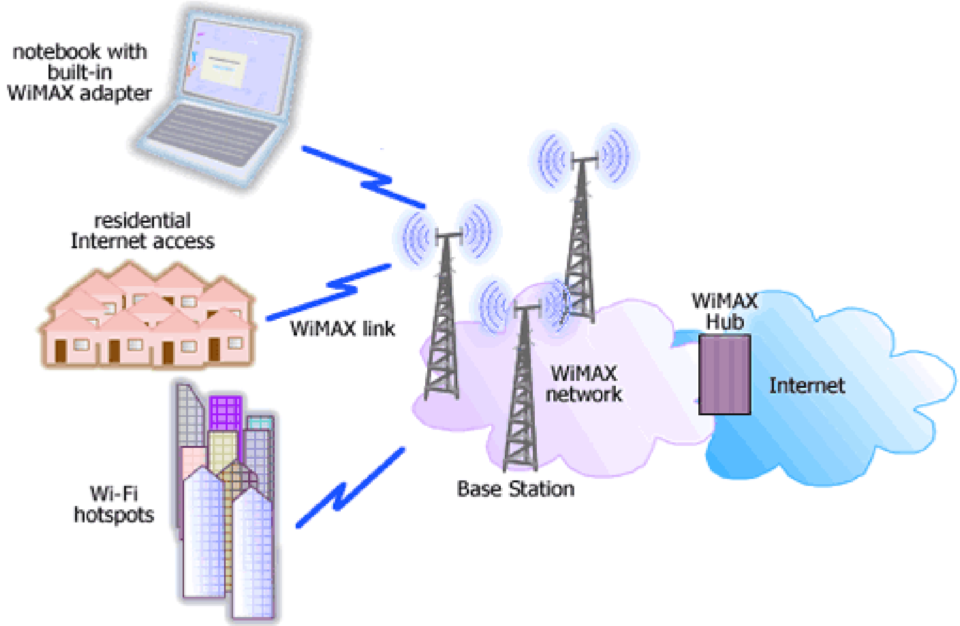

Figure 1.1 : Point-to-Multipoint (PMP) topology.

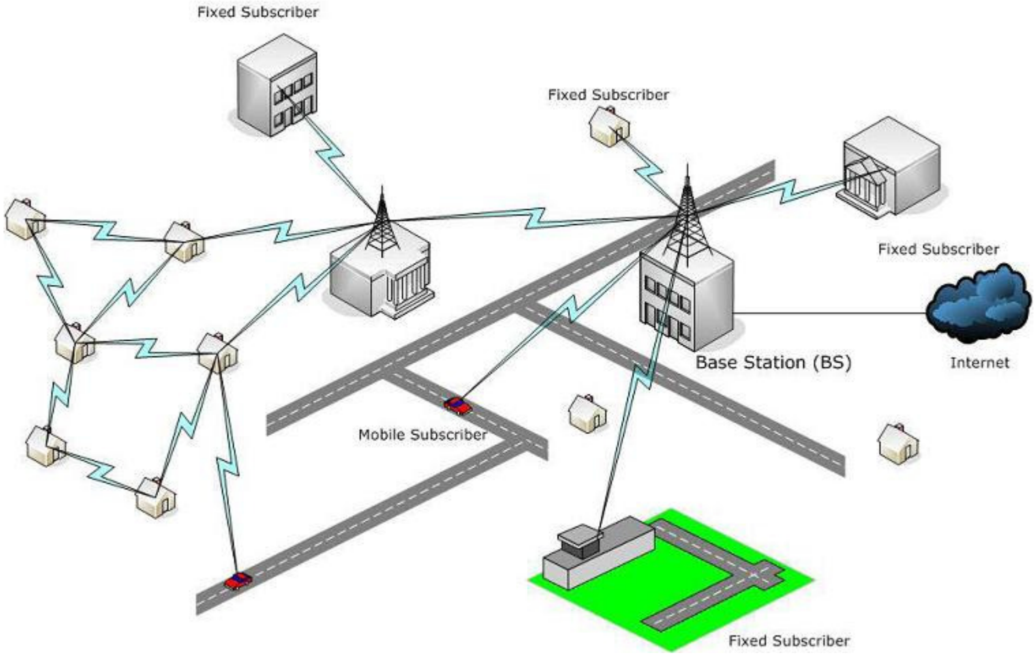

Figure 1.2 : Mesh topology for WiMAX networks.

1.1 Purpose of the Thesis

In this thesis, we focus on designing two new algorithms for an uplink SS Scheduler in PMP mode. We evaluate our new algorithm by comparing them to existing uplink SS Schedulers. As for our main contributions are:

- Update the WiMAX Module of ns-2 by changing the structure from Grant Per Connection (GPC) to Grant Per Subscriber Station (GPSS).
- Investigate and implement the existing algorithms for the SS Scheduler. Identify the strengths and weaknesses of these algorithms.
- RED-based WFPQ algorithm is implemented to increase real-time Polling Service (rtPS) throughput. This algorithm is referred to RED-based DFPQ[15].
- Design an effective, fair, and QoS-based algorithm for SS Scheduler. Enhance the algorithm "RED-based WFPQ algorithm" in order to increase the throughput of non-real-time Polling Service (nrtPS). The proposed algorithm called "Enhanced RED-based WFPQ".

- Evaluate all scheduling algorithms though simulation studies according to performance metrics, such as throughput, delay, fairness, and dropped packet percentage.

1.2 Background

In recent years, research on IEEE 802.16 QoS algorithms has increased significantly. As the WiMAX standard does not specify how to efficiently schedule traffic to fulfill QoS requirements, many articles have been written on this topic. Several works have introduced algorithms for the schedulers in the Base Station and the Subscriber Station.

In [4], an efficient and fair QoS scheduling architecture is proposed for IEEE 802.16. The main purpose of the architecture is to provide tight QoS guarantees to various applications and to maintain fairness among them while still achieving high bandwidth utilization. Their approach is based on enhanced Weighted Fair Priority Queuing (WFPQ).

In [5], Pratik Drohna et al. performed a performance study of the uplink scheduling algorithms, such as Weighted Round Robin (WRR), Earliest Deadline Fast (EDF), Weighted Fair Priority Queuing, and Hybrid Algorithms (EDF+WFQ+FIFO).

In [6], the authors evaluate the performance of scheduling algorithms, such as DropTail, Fair Queuing, Weighted Fair Queuing, Deficit Round Robin (DRR), Random Early Detection (RED), and RED with In/Out (RIO). According to their simulation results, WFQ has worse throughput, delay time, and packet loss than the other algorithms. The RIO scheme has the best throughput.

1.3 Structure of Thesis

The remainder of this thesis is organized as follows. Chapter 2 gives brief information about IEEE 802.16 Broadband Wireless Access. Chapter 3 presents WiMAX MAC Layer and Scheduling Management. Our novel scheduling algorithms are described in Chapter 4. Chapter 5 presents the QoS-included WiMAX patch implementation on ns-2. Simulation results are shown and discussed in Chapter 6. Chapter 7 includes the conclusion and future work. Apendixes includes Confidence Intervals of Throughputs.

2. THE IEEE 802.16 FOR BROADBAND WIRELESS ACCESS

2.1 The IEEE 802.16 Standard

The IEEE 802.16 Standard widely known as WiMAX (Worldwide Interoperability of Microwave Access) has been developed to extend the usage of Broadband Wireless Access (BWA) into the marketplace. It offers a lot of advantages, such as high data rate, easy, low-cost deployment, and QoS support for multimedia streams.

Table 2.1: The IEEE 802.16 standard scheme.

IEEE Standard	Description
802.16-2001	Fixed Broadband Wireless Access (10–66 GHz)
802.16a-2003	Physical layer and MAC definitions for 2–11 GHz
802.16d-2004	Air Interface for Fixed Broadband Wireless Access System
802.16e-2005	Mobile Broadband Wireless Access System

IEEE 802.16-2001 delivered a standard for point-to-multipoint Broadband Wireless transmission in the 10–66 GHz band, with only a line-of-sight (LOS) capability. It uses a single carrier (SC) physical (PHY) standard (Wireless-MAN SC).

IEEE 802.16a-2003 was an enhancement over 802.16-2001 and delivered a point to multipoint capability in the 2–11 GHz band. It also required a non-line-of-sight (NLOS) capability, and the PHY standard was therefore extended to include Orthogonal Frequency Division Multiplex (OFDM) and Orthogonal Frequency Division Multiple Access (OFDMA).

IEEE 802.16-2004 (also known as 802.16d) was approved by the IEEE in June 2004, which provides fixed, point-to-multipoint broadband wireless access service. The IEEE 802.16-2004 standard supports time division duplex (TDD) and frequency division duplex (FDD) services. The standard describes the Pyhsical Layer and Media Access Control (MAC) Layer specifications for fixed wireless access systems which support multiple services [19].

IEEE 802.16-2005 (also known as 802.16e) is an amendment of 802.16-2004, approved in December 2005. It added mobility features to WiMAX in the 2 to 11

GHZ licensed bands. This standard became the Wireless Wide Area Network (WWAN) standart as shown in Figure 2.1. Handover procedures and power save mode are included in IEEE 802.16e due to mobility.

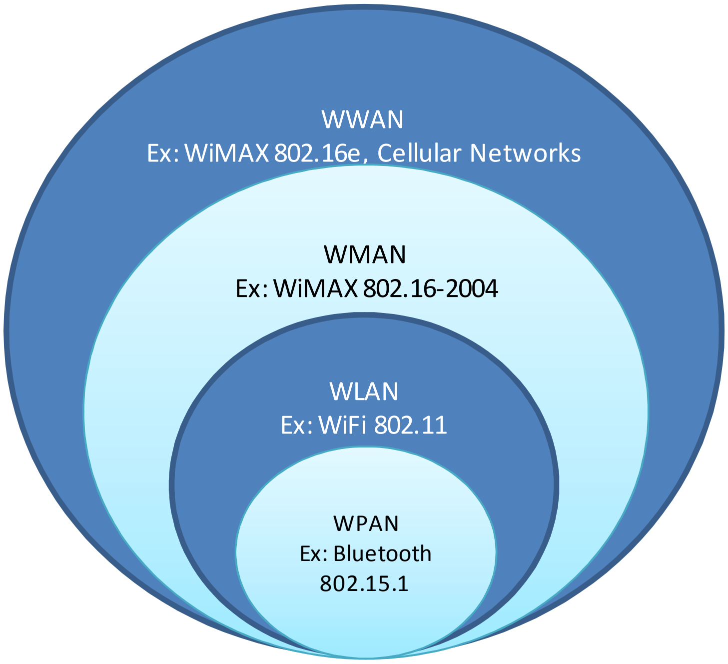

Figure 2.1 : Wireless network types illustration [21].

2.2 IEEE 802.16 Protocol Architecture Overview

The Open System Interconnection (OSI) model separates the function of different protocols into a series of layers. Each layer uses only the functions of the layer below and exporting data to the layer above. IEEE 802 splits the OSI Data Link Layer into two sublayers named Logical Link Control (LLC) and Media Access Control (MAC). MAC layer is responsible for the establishment and maintenance of the connection. LLC provides flow control, acknowledgment, and error notification.

The standard IEEE 802.16 only defines the lowest two layers, the physical layer and the MAC layer.

2.2.1 IEEE 802.16 MAC sublayers

The main purpose of the MAC protocol is the sharing of radio channel resources among multiple accesses of different users. The MAC layer consist of the following three sublayers; Convergence Sublayer (CS), Common Part Sublayer (CPS), and

Security Sublayer. As the MAC protocol is connection-oriented, all data transmission takes place in connections, even for connectionless packets. In other words, connectionless services are mapped to a connection.

2.2.1.1 Convergence sublayer

The service-specific Convergence Sublayer, often simply known as the CS, is just above the MAC CPS sublayer as shown in Figure 2.2. The CS performs the following functions:

- Accepting Protocol Data Units (PDUs) from the higher layer.
- Performing classification of higher layer PDUs.
- Classifying and mapping the MAC SDUs (MSDUs) into appropriate CIDs (Connection Identifier). This is a basic function of the Quality of Service (QoS) management mechanism of 802.16 BWA.
- Delivering CS PDUs to the appropriate MAC SAP.

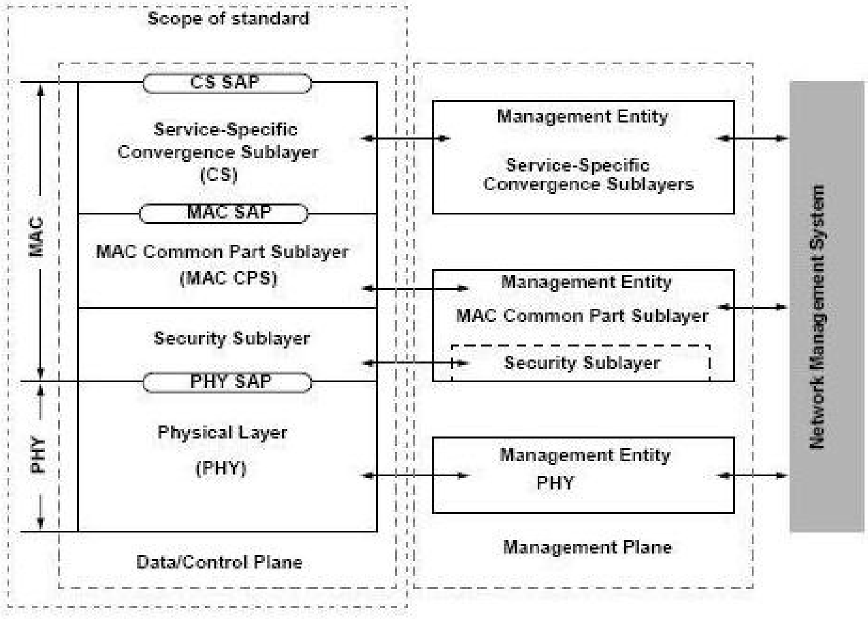

Figure 2.2 : Protocol layers of the 802.16 BWA standard [1].

2.2.1.2 Medium access control common part sublayer (MAC CPS)

The MAC Common Part Sublayer resides in the middle of the MAC Layer and represents the core of the MAC protocol. It is responsible for fragmentation and segmentation of each MAC SDU into MAC protocol data units (PDUs), system access, bandwidth allocation, connection maintenance, QoS control, and transmission scheduling.

2.2.1.3 Security sublayer

The Security Sublayer is responsible for security and performs the following functions:

- Authentication
- Secure key change
- Encryption

2.2.2 Physical layer (PHY)

The PHY Layer establishes the physical connection between uplink and downlink directions. This layer is responsible for transmission of the bit sequences. There are two duplexing techniques for PHY layer of downlink and uplink.

Frequency Division Duplex (FDD): FDD requires two distinct channels for transmitting downlink subframe and uplink subframe at the same time slot. FDD is suitable for bidirectional voice service because it occupies a symmetric downlink and uplink channel pair as in Figure 2.3. FDD is commonly used in cellular networks (2G and 3G). Meanwhile, WiMAX supports both full-duplex FDD and half-duplex FDD (HFDD). The difference is that in full-duplex FDD a user device can transmit and receive simultaneously, while in half-duplex FDD, a user device can only transmit or receive at any given moment [7].

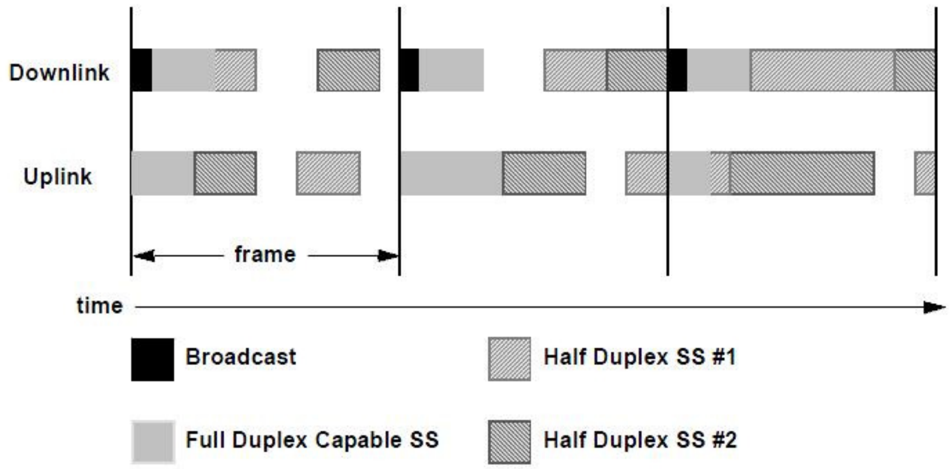

Figure 2.3 : Frequency division duplex [1].

Time Division Duplex (TDD): TDD (Time Division Duplex) is another duplexing scheme that requires only one channel for transmitting downlink and uplink sub-frames at two distinct time slots as shown in Figure 2.4. TDD, therefore, has higher spectral efficiency than FDD. Moreover, using TDD downlink-to-uplink (DL/UL) ratio can be adjusted dynamically. TDD can flexibly handle both symmetric and asymmetric broadband traffic. Most WiMAX implementations either on licensed or license-exempt bands use TDD. The reasons are that TDD uses half of the FDD spectrum hence saving the bandwidth, TDD system is less complex and thus cheaper, and WiMAX traffic will be dominated by asymmetric data [7].

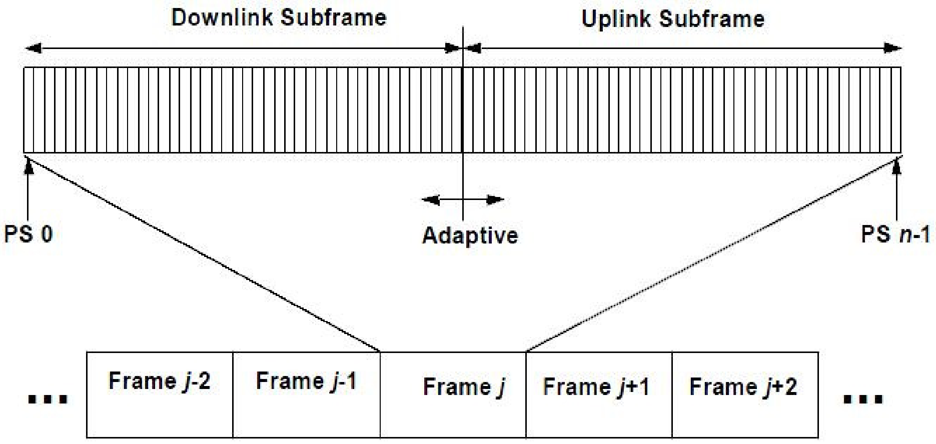

Figure 2.4 : Time division duplex [1].

When we compare FDD and TDD, a fixed duration time is used for downlink and uplink transmissions in FDD while the TDD duration times are adaptive. This means that DL and UL frame times may not be the same. Consequently, TDD is more suitable for networks supporting asymetrical data rates for downlink and uplink, such as the Internet.

A TDD frame consists of two subframes as Downlink Subframe (DL Subframe) and Uplink Subframe (UL Subframe). DL Subframe has DL-MAP, UL-MAP, and DIUCs for SSs. The DL-MAP message defines the usage of the downlink intervals. The UL-MAP defines the uplink usage in terms of the offset of the burst relative to the Allocation Start Time [1]. Figure 2.5 shows an example of the OFDM frame structure with TDD mode.

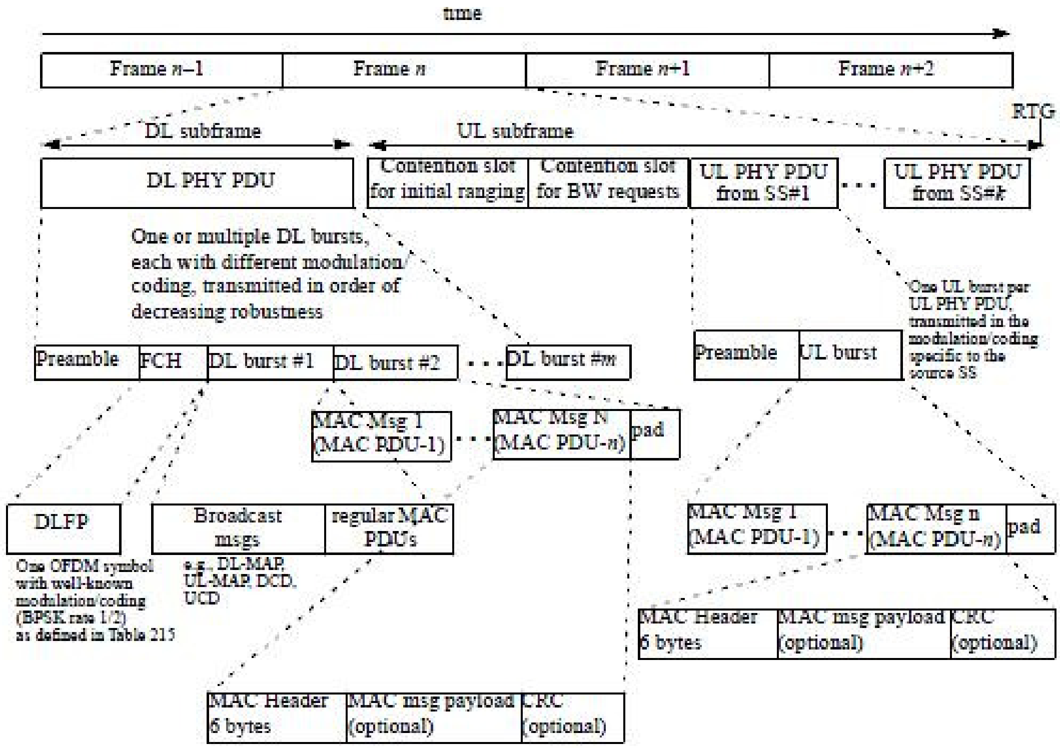

Figure 2.5 : Example of OFDM frame structure with TDD [1].

A UL Subframe contains contention slot for initial ranging, contention slot for bandwidth requests, and UL PHY PDUs from SSs as shown in Figure 2.5. Via Initial Ranging IE, the Base Station provides an interval for new stations to join the network. Ranging Request (RNG-REQ) packets are sent in this interval to join to the network. Via Request IEs, the BS specifies an uplink interval which can be used by the SS to send bandwidth requests. A DL Subframe contains DL physical PDUs.

3. WiMAX MAC LAYER AND SCHEDULING MANAGEMENT

3.1 WiMAX MAC Layer Structure

3.1.1 Connection and service flow

Convergence Sublayer provides mapping of external network data received through the CS Service Access Point (SAP) into MAC SDUs received by the MAC Common Part Sublayer (MAC CPS) through MAC SAP as shown in Figure 2.2. External network Service Data Units (SDUs) are classified and mapped with the proper MAC Service Flow Identifier (SFID) and Connection Identifier (CID).

A Connection IDentifier (CID) is defined using 16 bits and it identifies a unidirectional connection between the BS and SS. In other words, it is a unidirectional mapping between a BS and an SS MAC peers for the purpose of transporting the traffic of a service flow [21].

A Service Flow (SF) is a MAC transport service that provides unidirectional transport of packets on the downlink and uplink. It is identified by a 32-bit SFID. There is only one connection per service flow. The Service Flow has a set of QoS parameters, as described below:

- **Scheduling service type**: In IEEE 802.16-2004, four scheduling types are described, such as UGS, rtPS, nrtPS, and BE. With IEEE 802.16-2005, ertPS is added as a new scheduling service type [20].
- **Minimum Reserved Traffic Rate (MRTR)**: Minimum rate reserved for the related service type.
- **Maximum Sustained Traffic Rate:** Peak rate for the related service type.
- **Traffic Priority:** Priority assigned to the service flow.
- **Maximum Latency**: Maximum latency between the arrival of a packet at the SS or BS and forwarding of this packet to the RF interface.
- **Tolerated Jitter:** Maximum delay variation.
- **Maximum Traffic Burst:** Maximum burst size.

Upon entering the network of an SS, three management connections are assigned in uplink and downlink directions. These three connections reflect three different QoS requirements. The first management connection is “Basic Connection” which is used for time-critical management messages. The second management connection is “Primary Connection”, and it is used for more delay tolerant messages, such as authentication and connection setup. The third management connection is “Secondary Connection”, which is used for transferring of standard-based management messages such as Dynamic Host Configuration Protocol (DHCP), Trivial File Transfer Protocol (TFTP), and Simple Network Management Protocol (SNMP). In addition to these management connections, the SS allocates transport connections for data transmisson.

3.1.2 Classification and mapping

In the Convergence Sublayer, MAC SDUs, that comes from higher layers, are classified and mapped in to a connection. In addition this process creates an association with service flow characteristics of that connection as shown in Figure 3.1. Consequently, MAC SDUs are associated with the appropriate QoS requirements.

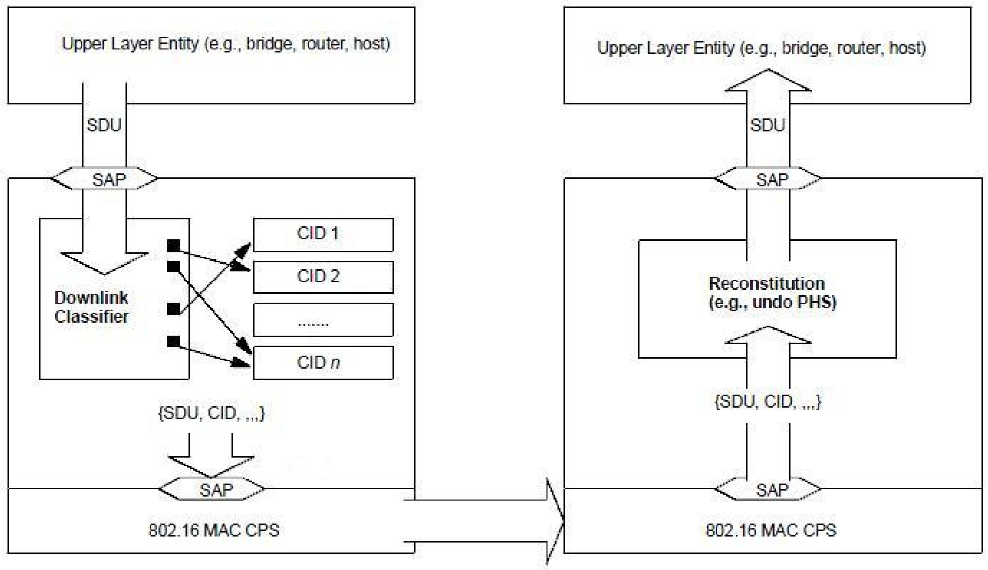

Figure 3.1 : Classification and mapping [1].

For a downlink transmission, the classifier will be present in the BS and for an uplink transmission, the classifier will be present in the SS. Figure 3.1 represents classifier mechanisms in both the BS and the SS. A set of matching criteria is included in a classifier. The set consists of protocol-specific packet matching criteria (destination IP), classifier priority, and a reference to a CID. With the service flow characteristics, the QoS for the packet is provided [21].

3.1.3 IEEE 802.16 MAC frames

Each Subscriber Station has a 48-bit unique MAC address. A MAC PDU is known as a MAC frame which has a 6-byte long “MAC Header”, a 4-byte long CRC (optional), and a “Payload” (optional) section. MAC header has a fixed-length, and a MAC PDU can follow the MAC header. There are two types of MAC headers in the IEEE 802.16 Standard. The first is the generic MAC header that begins each MAC PDU, containing either the MAC management message or CS data. The second is the bandwidth request header used to request additional bandwidth. The single-bit Header Type (HT) field distinguishes the generic MAC header or bandwidth request header formats. The HT field shall be set to zero for the Generic Header and to one for a bandwidth request header[1].

3.2 IEEE 802.16 Scheduling

3.2.1 IEEE 802.16 scheduling services

Scheduling services are used for data handling the mechanism, and as all data transmission takes place in connections, every connection is associated with a data service. The Dynamic Service Addition (DSA) mechanism allows the addition of a new service flow while a connection is being set up. When a connection is created, a new service flow is assigned with DSA, so the connection will have a QoS requirement set. The QoS requirements of a service flow is changed by the Dynamic Service Change (DSC) message. An existing service flow is deleted via Dynamic Service Deletion (DSD) message.

There are four service types of service flows defined in IEEE.802.16-2004: Unsolicited Grant Service (UGS), Real-Time Polling Service (rtPS), Non-real-time Polling Service (nrtPS), and Best Effort (BE). In the 802.16e standard [20], a new service flow, called extended real time Polling Service (ertPS), has been added. However, it is out of the scope of this thesis.

3.2.1.1 Unsolicited grant service (UGS)

The Unsolicited Grant Service (UGS) supports Constant Bit Rate (CBR) flows for real-time applications such as Voice over IP (VoIP) without silence suppression or E1/T1 data streams. Maximum Sustained Traffic Rate, Maximum Latency, Tolerated Jitter, and Request/Transmission Policy are the mandatory parameters of QoS requirements. The Base Station (BS) allocates fixed sized data grants at periodic intervals based on the Maximum Sustained Traffic Rate of the service flow. The SS can not send any bandwidth requests during contention slots, as the Request/Transmission Policy of the UGD service prohibits it. The overhead and latency of SS requests are eliminated for UGS connections because the BS allocates the grants periodically. However, UGS flows are more expensive than other service flows.

3.2.1.2 Real-time polling service (rtPS)

The Real-Time Polling Service supports Variable Bit Rate (VBR) flows, which have variable packet length and periodic packet intervals, such as Moving Pictures Expert Group (MPEG) video. Minumum Reserved Traffic Rate, Maximum Sustained Traffic Rate, Maximum Latency, and Request/Transmission Policy are the mandatory parameters of QoS requirements. The BS provides unicast request opportunities to the SS periodically. This means that the BS allows the SS to send its bandwidth (BW) request. If this BW request is available for the QoS requirements of the service flow and also the BS has sufficient BW to allocate to all the waiting accepted requests, the BS will allocate the BW.

3.2.1.3 Non-real-time polling service (nrtPS)

Non-real-time Polling Service supports variable-sized packets, which delay-tolerant data streams such as File Transfer Protocol (FTP). Therefore, the minimum data rate is required for this service. The BS provides unicast request opportunities periodically as in the rtPS service, so this will guarantee data granting during network congestion. In addition to this, the SS can use contention request mechanism. Minimum Reserved Traffic Rate, Maximum Sustained Traffic Rate, Traffic Priority, and Request/Transmission Policy are the mandatory parameters of QoS requirements.

3.2.1.4 Best effort service

The Best Effort service is designed for best-effort traffic such as HTTP, and this service does not have any minimum service guarantee. Maximum Sustained Traffic Rate, Traffic Priority, and Request/Transmission Policy are the mandatory parameters of QoS requirements. SS can use contention request opportunities. As the BE service does not have a Minimum Reserved Traffic Rate, BE packets may not be transmitted during network congestion.

3.2.2 Uplink bandwidth allocation and BW request handling

The BS performs uplink grant allocation, so the BS scheduler can increase or decrease the throughput and latency of the services. SSs use the requests to indicate to the BS that they need uplink bandwidth allocation.

3.2.2.1 Bandwidth requests

A bandwidth request may be a standalone bandwidth request header or it may come as a PiggyBack Request. PiggyBack request usage is optional. The Bandwidth Request message may be sent during any interval except the initial ranging interval. There are two types of Bandwidth Requests; incremental and aggregate. In an incremental request, the SS demands more bandwidth for a connection. In an aggregate bandwidth request, the SS specifies the total bandwidth needed for a connection. Bandwidth requests are always per connection. The bandwidth requests can be sent in the following ways:

- **Unicast Polling:** When an SS is polled individually in UL-MAP, it responds to the BS with a Bandwidth (BW) Request. Polling is done on a per-SS basis by allocating a Data Grant Information Element directed to its Basic CID.
- **Multicast/Broadcast Polling**: Polling is done on multicast/broadcast group of SS basis by allocating a Data Grant Information Element directed to its multicast/broadcast CID. When a group is polled, the members of the group

which require bandwidth, respond with a request. A contention resolution algorithm is used to resolve conflicts that arise when two or more transmissions occur at the same time.

- **Contention Request Opportunity:** In the Bandwith Request Contention slot, an SS can send its bandwidth request. A contention resolution algorithm is used to resolve conflicts that arise when two or more transmissions occur at the same time.
- **Piggyback Requests:** This request is only used for non-UGS services. The 16-bit field in the Grant Management Subheader is used for piggybacking. This request type is not allowed for UGS.
- **Poll Me (PM) bit:** SSs which have currently active UGS connections, may send request for non-UGS connections using the PM bit. The PM bit, in the Grant Management Subheader, is used to request a unicast poll for bandwidth needs of non-UGS connections.

3.2.2.2 Bandwidth grants

Polling is done on SS basis, bandwidth is requested on a CID basis, but bandwidth grants are allocated on an SS basis. In other words, for an SS, bandwidth requests reference individual connections while each bandwidth grant is addressed to the SS's Basic CID. IEEE 802.16 MAC accommodates two modes of SS, differentiated by their ability to accept bandwidth grants simply for a connection or for the SS as a whole. In the Grant Per Connection (GPC) mode, bandwidth is granted to a connection, so the SS can use this grant for this connection only. In the Grant Per Subscriber (GPSS) mode, the BS grants bandwidth to an SS as an aggregate of grants in response to per connection requests from the SS. Then the SS distributes bandwidth among its connections, with respect to their QoS requirements. Therefore, the GPSS mode is more complex than the GPC mode. In addition, the SS can steal bandwidth, which is granted for the lower priority service flow, to react more quickly for rtPS service flows.

GPC is more suitable for few users per SS and it has higher overhead but allows a simpler SS. GPSS reacts more quickly to QoS requirements but it requires more intelligent SS.

3.2.3 WiMAX scheduling algorithms

A scheduling algorithm has to determine the allocation of the bandwidth among the users and their transmission order. QoS requirements of the users need to be satisfied while utilizing the available bandwidth efficiently [5]. There are two types of schedulers; the SS Scheduler and the BS scheduler. The SS Scheduler is more complicated in the GPSS mode, as the algorithm which works in the SS scheduler distributes the granted bandwidth between its connections [8].

Many scheduling algorithms have been introduced to improve the performance of the system so far. As the WiMAX standard does not specify how to efficiently schedule traffic to fulfill QoS requirements, a lot of research has been done on this topic. Several works have introduced algorithms for the schedulers in the Base Station (BS) and the Subscriber Station (SS). In this thesis, we focus on the GPSS type of SS scheduler and their performance.

3.2.3.1 Strict priority (SP)

Strict Priority is an unfair scheduling algorithm. Bandwidth is allocated for rtPS service flows first, then bandwidth is allocated for nrtPS service flows, and finally the remaining bandwidth is allocated for BE service flows. Consequently, under heavy rtPS traffic load, nrtPS and BE service flows may starve. Strict Priority does not guarantee the QoS requirements of the traffic that comes from lower priority service classes.

3.2.3.2 Weighted fair queuing (WFQ)

WFQ is a generalization of Fair Queuing. WFQ allows different sessions to have different service shares. A link data rate (R), is serviced for the active data flows (N).

The data rate of session j is calculated as follows:

$$R_j = \frac{R \times w_j}{\sum_{i=1}^{N} w_i} \tag{3.1}$$

where w_j represents the weight assigned to session j.

According to equation (3.1), the available bandwidth is shared between the service types in the SS Scheduler. Therefore, we need to define the weights for service types efficiently. For example, as the priority of rtPS is higher than nrtPS, rtPS needs to be given a higher weight than nrtPS.

3.2.3.3 Deficit fair priority queuing (DFPQ)

Chen et al. proposed the Deficit Fair Priority Queuing based scheduler for bandwidth allocation among the service classes of WiMAX networks [22]. DFPQ determines the deficit quantum values based on the priority of each service class. It is fairer than strict priority scheduling. However, the deficit quantum value of the rtPS service class is chosen as a static value, so using this algorithm may result in increased delay.

3.2.3.4 RED-based deficit fair priority queuing

RED-based Deficit Fair Priority Queuing is proposed for SS uplink schedulers to share the bandwidth between service classes [15]. It uses Deficit Counters (DCs) for each rtPS, nrtPS, and BE service class. The deficit counter for the rtPS service class is adaptive based on RED technique as shown in Figure 3.2.

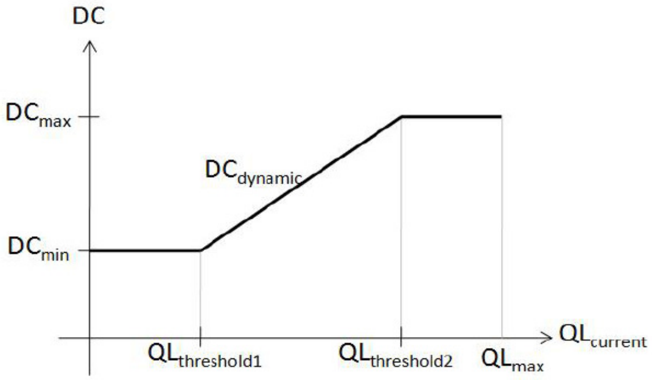

Figure 3.2 : RED-based deficit fair priority queuing [15].

The SS scheduler checks the rtPS queue length, and it sets the deficit counter for rtPS in every corresponding frame. If the current length of the rtPS queue ($QL_{current}$) is less than $QL_{threshold1}$, the DC value will be equal to DC_{min}. If $QL_{current}$ is more than $QL_{threshold1}$ but less than $QL_{threshold2}$, DC will be equal to $DC_{dynamic}$. The $DC_{dynamic}$ is calculated using Equation (3.2).

$$
\begin{aligned}
DC_{\min} &= Q_{rtPS} \\
DC_{dynamic} &= Q_{rtPS} + \frac{QL_{current} - QL_{threshold1}}{QL_{threshold2} - QL_{threshold1}} \times Q_{rtPS} \\
DC_{\max} &= 2 \times Q_{rtPS}
\end{aligned}
\qquad \textbf{(3.2)}
$$

3.2.3.5 Other related scheduling algorithms

In [4], an efficient and fair QoS scheduling architecture for IEEE 802.16 is introduced. The main purpose of the architecture is to provide tight QoS guarantees to various applications and to maintain fairness among them while still achieving high bandwidth utilization. Their approach is based on enchanced Weighted Fair Priority Queuing (WFPQ).

In [5], Pratik Drohna et al. performed a performance study of uplink scheduling algorithms, such as Weighted Round Robin (WRR), Earliest Deadline Fast (EDF), Weighted Fair Queuing (WFQ), and Hybrid Algorithms (EDF+WFQ+FIFO). EDF has the highest avarage throughput for rtPS flows. In addition, EDF has the lowest average delay. So, for rtPS flows, the authors use the EDF algorithm. WFQ has the highest throughput for nrtPS flows. Therefore, they use WFQ for nrtPS flows. According to these results, they recommend using EDF for rtPS, WFQ for nrtPS, and First In First Out (FIFO) for BE flows.

In [6], a performance evaluation of the following scheduling algorithms is conducted: DropTail, Fair Queuing, Weighted Fair Queuing (WFQ), Deficit Round Robin (DRR), Random Early Detection (RED), and RED with In/Out (RIO). The authors find that, WFQ has the worst throughput, delay, and packet loss among these algorithms. The RIO scheme has the best throughput. DRR has the best delay, as the algorithm decreases the delay significantly using the deficit counter mechanism. But DRR does not have good throughput and packet loss rate. The authors claim that WFQ is not appropriate for real-time streams, as WFQ has the worst delay and packet loss.

4. PROPOSED WiMAX UPLINK SCHEDULING ALGORITHM

In this thesis, Enhanced RED-based WFPQ has been proposed and this algorithm depends on RED-based Weighted Fair Priority Queuing (RED-based WFPQ).

4.1 RED-based Weighted Fair Priority Queuing

In RED-based WFPQ, rtPS weight is calculated based on the Random Early Detection (RED) technique. Weights calculation takes place at the beginning of the each frame. This algorithm takes the packet size information of rtPS, and then calculates the weight of rtPS based on the RED technique. In [15], the RED-based Deficit Fair Priority Queuing (DFPQ) algorithm was proposed for the SS Scheduler. This algorithm is more complex than RED-based WFPQ. The RED-based DFPQ algorithm introduces a deficit counter for rtPS service flow. This counter value is calculated at the beginning of each frame. The algorithm assigns different deficit counters for rtPS according to the rtPS queue length, and then service classes start to transmit their data based on the deficit counter. After every service class uses up its counter in one round, the quantum value is added into the deficit counter for each service class, and this process repeats the above action until the frame is over [15].

In RED-based WFPQ, we do not deal with deficit counters; we only determine weights for the service types. The parameters, that define the algorithm, are given in Table 4.1. The weight of rtPS is calculated according to the diagram in Figure 4.1.

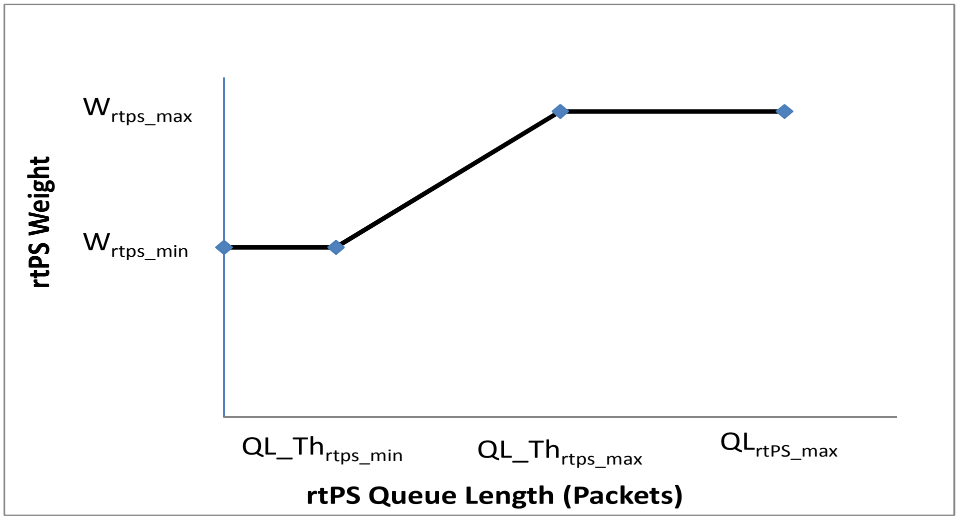

Figure 4.1 : rtPS weights of RED-based WFPQ.

The weight of rtPS changes between W_{rtps_min} and W_{rtps_max} and depends on the rtPS queue length. According to Figure 4.1, when the rtPS queue length is lower than $QL\_Th_{rtps\_min}$, W_{rtps_min} is assigned to the rtPS service flow. When the rtPS queue length is higher than $QL\_Th_{rtps\_max}$, W_{rtps_max} is assigned to rtPS. When the rtPS queue length is between $QL\_Th_{rtps\_min}$ and $QL\_Th_{rtps\_max}$, the rtPS weight changes dynamically according to the rtPS queue length. Equation (4.1) represents the weight assignment of rtPS.

$$W_{rtps} = \begin{cases} if\ (QL_{rtps} \le QL\_Th_{rtps\_\min}) \qquad W_{rtps} = \ W_{rtps\_\min} \\ if\ (QL\_Th_{rtps\_\min} < QL_{rtps} < QL\_Th_{rtps\_\max}) \\ \qquad \mathrm{W_{rtps} = W_{rtps\_min} + m_{rtps} \times (QL_{rtps} - QL\_Th_{rtps\_min})} \\ if\ (QL_{rtps} \ge QL\_Th_{rtps\_\max}) \qquad W_{rtps} = \ W_{rtps\_\max} \end{cases} \tag{4.1}$$

where the slope of W_{rtps} (m_{rtps}) is calculated according to equation (4.2)

$$m_{rtps} = \frac{W_{rtps\_\max} - W_{rtps\_\min}}{QL\_Th_{rtps\_\max} - QL\_Th_{rtps\_\min}} \tag{4.2}$$

The rest of the available weights are distributed between nrtPS and BE flows according to their weights (W_{nrtps} and W_{BE}).

Table 4.1: Variables for RED-based WFPQ.

Variable	Description
W_{rtps_min}	rtPS weight when rtPS queue length is lower than "$QL\_Th_{rtps\_min}$"
W_{rtps_max}	rtPS weight when rtPS queue length is higher than "$QL\_Th_{rtps\_max}$"
$QL\_Th_{rtps\_min}$	Minimum rtPS threshold value
$QL\_Th_{rtps\_max}$	Maximum rtPS threshold value
QL_{rtPS_max}	Maximum rtPS queue length
QL_{rtps}	Current rtPS queue length
W_{rtps}	Current weight of rtPS flow
W_{nrtps}	Current weight of nrtPS flow
W_{BE}	Current weight of BE flow
m_{rtps}	Slope of W_{rtps} variation
W_{total}	Total available weights

4.2 Enhanced RED-based Weighted Fair Priority Queuing

In the RED-based WFPQ algorithm, we use static weights for nrtPS and BE flows. However, we can control the weight of nrtPS flows according to its queue length, just like RED-based WFPQ does for rtPS flows. In other words, we can apply the dynamic weight assignment of RED-based WFPQ algorithm to nrtPS service types. As the dynamic weight assignment is used for both of rtPS and nrtPS, we call this algorithm “Enhanced RED-based WFPQ” algorithm. Determineation of rtPS weights is exactly the same as in RED-based WFPQ algorithm. However, now we do not define any static weight for nrtPS; we control the weight of nrtPS based on the dynamic weight assignment of RED as well. In our algorithm, “Enhanced RED-based WFPQ”, we control the weights of rtPS and nrtPS flows according to their queue lengths. The weight assignment of the rtPS service type is the same as in RED-based WFPQ, as shown in Figure 4.2.

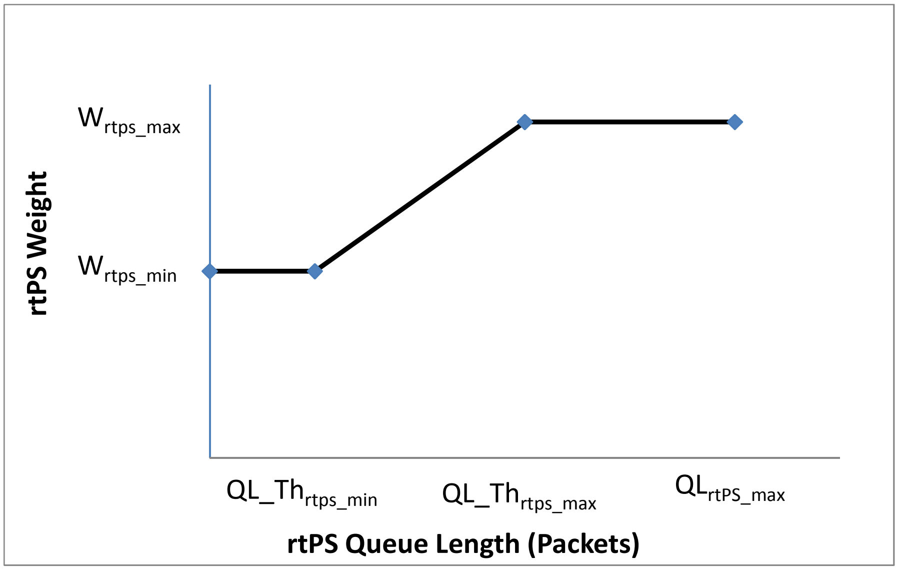

Figure 4.2 : rtPS weights of Enhanced RED-based WFPQ.

The variables of the RED-based WFPQ scheme (Table 4.1) are used in our algorithm, as well. In addition to the variables of Table 4.1, some additional parameters are required to define Enhanced RED-based WFPQ. Table 4.2 lists these additional parameters.

Table 4.2: Variables for Enhanced RED-based WFPQ.

Variables	Description
W_{nrtps_min}	nrtPS weight when nrtPS queue length is lower than "$QL\_Th_{nrtps\_min}$"
W_{nrtps_max}	nrtPS weight when nrtPS queue length is higher than "$QL\_Th_{nrtps\_max}$"
$QL\_Th_{nrtps\_min}$	Minimum nrtPS threshold value
$QL\_Th_{nrtps\_max}$	Maximum nrtPS threshold value
QL_{nrtPS_max}	Maximum nrtPS queue length
QL_{nrtps}	Current nrtPS queue length
m_{nrtps}	Slope of nrtPS variation $(W_{nrtps\_max} - W_{nrtps\_min})/(QL\_Th_{nrtps\_max} - QL\_Th_{nrtps\_min})$
W_{BE_min}	Minimum BE weight

When the nrtPS queue length (QL_{nrtps}) is lower than the minimum threshold of nrtPS ($QL\_Th_{nrtps\_min}$), W_{nrtps_min} is the minimum nrtPS weight. When nrtPS queue length is higher than the maximum threshold of nrtPS ($QL\_Th_{nrtps\_max}$), W_{nrtps_max} is the maximum weight. The RED algorithm uses $QL\_Th_{nrtps\_min}$ and $QL\_Th_{nrtps\_max}$ as the threshold values. While nrtPS queue length is between $QL\_Th_{nrtps\_min}$ and $QL\_Th_{nrtps\_max}$, the slope m_{nrtps} is used.

As the nrtPS weight depends on the variation of the rtPS weight (total weight is distributed between the service types), we need to consider three conditions while determining the nrtPS weight. The conditions are given in Table 4.3.

Table 4.3: rtPS queue length conditions.

Condition-1	[$QL_{rtps} < QL\_Th_{rtps\_min}$]
Condition-2	[$QL\_Th_{rtps\_min} < QL_{rtps} < QL\_Th_{rtps\_max}$]
Condition-3	[$QL_{rtps} > QL\_Th_{rtps\_max}$]

The first condition represents when rtPS queue length is lower than the minimum threshold of rtPS. The second condition represents when rtPS queue length is higher than the minimum threshold and lower than the maximum threshold. The third condition represents when rtPS queue length is higher than the maximum threshold. In each condition, rtPS weights will be set differently; therefore nrtPS weight characteristics are impacted dynamic. In other words, nrtPS weights always depend on rtPS weights.

rtPS Queue Length Condition-1

When the rtPS queue length (QL_{rtps}) is lower than $QL\_Th_{rtps\_min}$, the rtPS weight is set to the predefined W_{rtps_min} value. Details of the assignment is given in Table 4.4.

Table 4.4: rtPS weight assignment in Condition-1.

Condition-1	**Weight Value for rtPS Service Type**
$QL_{rtps} \leq QL\_Th_{rtps\_min}$	$W_{rtps} = W_{rtps\_\min}$

Consequently, the available weight that remains for nrtPS and BE service type, is $W_{total} - W_{rtps\_min}$. In Figure 4.3, the weight assignment for the nrtPS flow is shown. The variation of the nrtPS weight is RED-based.

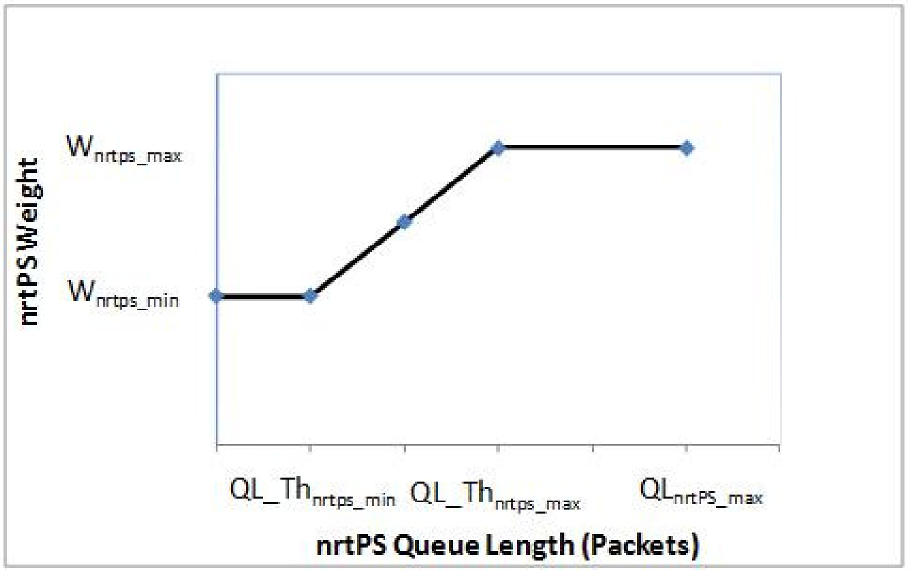

Figure 4.3 : nrtPS weights of Enhanced RED-based WFPQ.

The weight assignment of the nrtPS service type is given in Table 4.5. When nrtPS queue length is lower than the minimum threshold of nrtPS, $W_{\text{nrtps\_min}}$ is assigned as the weight of nrtPS. When nrtPS queue length is between minimum and maximum threshold values, the nrtPS weight varies dynamically. When nrtPS queue length is higher than the maximum threshold of nrtPS, $W_{\text{nrtps\_max}}$ is assigned as the nrtPS weight.

Table 4.5: nrtPS weight assignment in Condition-1.

rtPS Queue Length Condition-1	Weight Value for nrtPS Service Types
$QL_{\text{nrtps}} < QL\_Th_{\text{nrtps\_min}}$	$W_{nrtps} = W_{nrtps\_\min}$
$QL\_Th_{\text{nrtps\_min}} \leq QL_{\text{nrtps}} \leq QL\_Th_{\text{nrtps\_max}}$	$W_{nrtps} = W_{nrtps\_\min} + (QL_{nrtps} - \text{QL\_Th}_{\text{nrtps\_min}}) \times m_{nrtps}$
$QL_{\text{nrtps}} > QL\_Th_{\text{nrtps\_max}}$	$W_{nrtps} = W_{nrtps\_\max}$

In each condition, weights for BE service types are calculated according to equation 4.3:

$$W_{BE} = W_{total} - W_{rtps} - W_{nrtps} \tag{4.3}$$

rtPS Queue Length Condition-2

When the rtPS queue length (QL_{rtps}) is lower than $QL\_Th_{rtps\_max}$ and higher than $QL\_Th_{rtps\_min}$, the rtPS weight is set dynamically according to queue length. Details of the assignment is given in Table 4.6.

Table 4.6: rtPS weight assignment in Condition-2.

Condition-2	Weight Values for rtPS Service Type
$QL\_Th_{rtps\_min} < QL_{rtps} \leq QL\_Th_{rtps\_max}$	$W_{rtps} = W_{rtps\_\min} + (QL_{rtps} - QL\_Th_{rtps\_min}) \times m_{rtps}$

Consequently, the available weight that remains for nrtPS and BE service type is $W_{total} - W_{rtps}$. In Figure 4.3, the weight assignment of nrtPS flow is shown. The variation of the nrtPS weight is RED-based, and is given in Table 4.7.

Table 4.7: nrtPS weight assignment in Condition-2.

Condition-2	Weight Value for nrtPS Service Type
$QL_{nrtps} < QL\_Th_{nrtps\_min}$	$W_{nrtps} = \begin{pmatrix} W_{Total} - W_{BE\_\min} - \\ (QL\_Th_{nrtps\_max} - QL\_Th_{nrtps\_min}) * m_{nrtps} - W_{rtps} \end{pmatrix}$ $= W_{nrtps\_\min}$
$QL\_Th_{nrtps\_min} \leq QL_{nrtps}$ $QL_{nrtps} \leq QL\_Th_{nrtps\_max}$	$W_{nrtps} = W_{nrtps\_\min} + (QL_{nrtps} - QL\_Th\_{nrtps\_min}) \times m_{nrtps}$
$QL_{nrtps} > QL\_Th_{nrtps\_max}$	$W_{nrtps} = W_{Total} - W_{rtps} - W_{BE\_\min} = W_{nrtps\_\max}$

In each condition, weights for BE service types are calculated according to equation (4.3). The rest of the available weights are assigned for BE flows. We reserve a little bandwidth for BE flows (W_{BE_min}) to prevent their starving in a congested network.

rtPS Queue Length Condition-3

When rtPS queue length (QL_{rtps}) is higher than $QL\_Th_{rtps\_max}$, the rtPS weight is set to W_{rtps_max}. In Condition-3, nrtPS and BE weights are statically assigned. Details of the assignments are given in Table 4.8. The maximum value for Condition-3 is W_{nrtps_max}. In Condition-1 and Condition-2, maximum values of nrtPS are not the same, as the weight intervals depend on the weight rtPS.

Table 4.8: Weights assignment in Condition-3.

Condition-3	Values for Service Types
$QL_{rtps} \geq QL\_Th_{rtps\_max}$	$W_{rtps} = W_{rtps\_\max}$ $W_{nrtps} = W_{nrtps\_\max}$ $W_{BE} = W_{Total} - W_{rtps\_\max} - W_{nrtps\_\max}$

5. WiMAX MODULE FRAMEWORK in NS-2

5.1 The IEEE 802.16 WiMAX Module in NS-2

The Network Simulator (NS-2) [9] is a widely used wireless network simulator. There exist WiMAX ns-2 modules implemented by the National Institute of Standards and Technology (NIST) [10], and the Network and Distributed Systems Laboratory (NDSL) [11]. These modules implement the Physical and MAC layers of a WiMAX system. The NIST module supports the Orthogonal Frequency Division Multiplexing (OFDM) PHY layer, while the NDSL module supports the Orthogonal Frequency Division Multiple Access (OFDMA) PHY layer. Both modules use TDD. The MAC layer of these WiMAX modules contains the management messages [12].

In this thesis, IEEE 802.16 WiMAX NIST module has been used on NS-2 version 2.29 [10]. The simulator supports a class hierarchy in C++ and a similar hierarchy within the OTcl interpreter. Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) are implemented in NS-2. The existing module implements the OFDM PHY and TDD MAC layers. However, NIST's WiMAX module does not support a QoS mechanism. In [12], the authors implement a QoS-included WiMAX Module for NS-2.29 [12]. They have added QoS classes, their requirements, mechanisms specified by the IEEE 802.16 standard, and some scheduling algorithms for QoS.

The MAC layer in NIST's contains some MAC management messages, such as Downlink Channel Descriptor (DCD), Uplink Channel Descriptor (UCD), Downlink MAP (DL-MAP), Uplink MAP (UL-MAP), ranging request, ranging response, registration request, and registration response. One downlink and one uplink data connection can be added per SS. The BS uses Round Robin scheduler to allocate radio resources for uplink connections.

[12] adds some QoS parameters to the service flow, the link adaptation, and some scheduling algorithms for three QoS classes: UGS, rtPS, and BE. The authors also implement the unicast and contention request opportunities mechanisms as specified

in the IEEE 802.16 standard. The IEEE 802.16 MAC class diagram is shown in Figure 5.1.

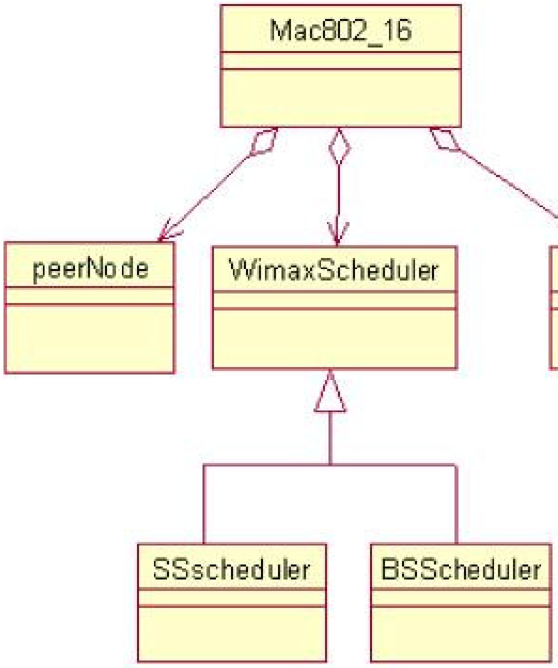

Figure 5.1 : MAC 802.16 class diagram [13].

The Mac802_16 class represents the MAC layer. It represents the base class. ServiceFlowHandler, peerNode, and WimaxScheduler are the other related classes.. ServiceFlowHandler is responsible for the management of the downlink and uplink connections. Each connection has an association with a service flow that contains the QoS parameters. The QoS parameters of a service flow are set according to the connection requirements. peerNode contains information about the SS or the BS. WimaxScheduler is responsible for ranging and registration, and it also runs scheduling algorithms. It includes two schedulers: one for the BS (BSScheduler) and one for the SS (SSscheduler)[12].

5.2 Enhancement of Existing QoS-included WiMAX Patch

Since we wanted to investigate GPSS based algorithm, we had to modify QoS-included WiMAX Patch. The existing QoS-included WiMAX Patch includes UGS, rtPS and BE service types. nrtPS is commonly used in the WiMAX world; therefore, this service type is added to our patch. In addition to this, existing QoS-included WiMAX Patch supports only one connection per subscriber. One data connection for downlink, one data connection for uplink. For the GPSS system, the patch needs to support four connections one for each of the following service types: UGS, rtPS, nrtPS and BE. ServiceFlowHandler handles the management of the uplink and downlink connections. This connection is associated with a service flow which has the QoS parameter set. Therefore, we add the "nrtPS" service flow type into the ServiceFlow class. In the existing QoS-included WiMAX Patch, the service classifier is designed simply and does not make any complex classifying because there was only 1 connection supported (one service flow) and there is not any complex classification required. So, we modify the "DestClassifier" class to support four service types. When a CBR packet is received, the module classifies this packet as UGS, and puts it into the outdata connection of UGS. When a VBR packet is received, this packet is classified as a rtPS service type and the classifier puts it into the outdata connection of rtPS. When a FTP packet is received, this packet is classified as nrtPS service type and the lassifier places it into the outdata connection of nrtPS. When a TELNET packet is received, this packet is classified as a BE service type and classifier puts it into the outdata connection of BE. As a result, the enchanced patch supports four outdata and four indata connections (for UGS, rtPS, nrtPS, and BE). These connections will keep the packets regarding their service types. The BS scheduler is modified to support four connections from an SS.

In Figure 5.2, SSs send their bandwidth requests on per connection-basis. However BS grants bandwidth to each individual SS, so that the resources are allocated to the aggregation of active flows at each SS. Each SS is then in charge of allocating the granted bandwidth to active flows; this allocation can be done efficiently since each SS has complete knowledge of the status of its queues [14].

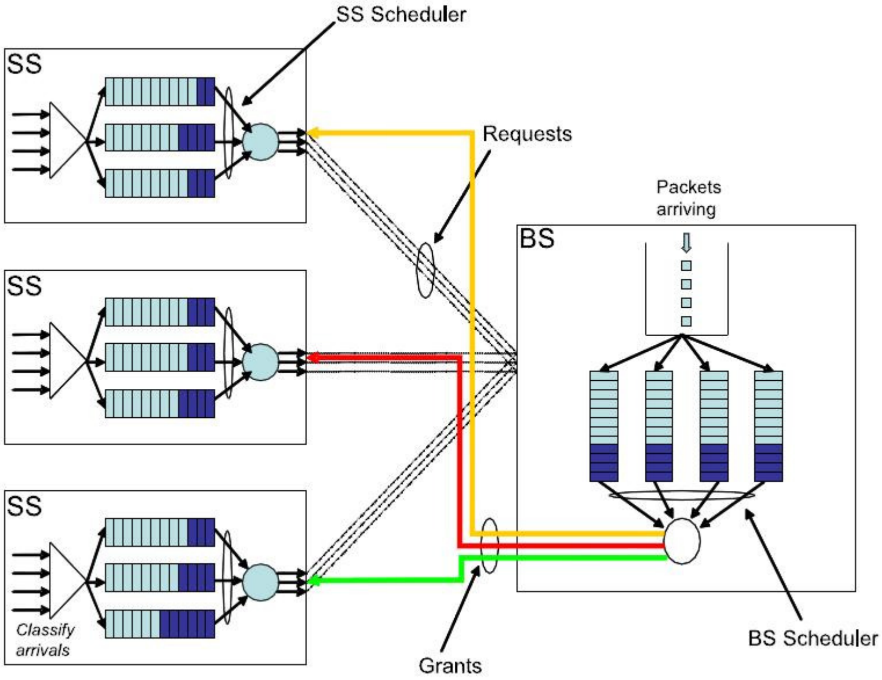

Figure 5.2 : Grant per SS scheduling architecture [14].

After the GPSS implementation is completed, some existing GPSS SS scheduler algorithms, such as Strict Priority, and Weighted Fair Priority Queuing are implemented. As these algorithms are not efficient for the QoS-based WiMAX system, the throughput of the system needs to be increased.

Strict Priority (SP) is not a fair algorithm. Bandwidth allocation order is strict and such rtPS, nrtPS, BE. For UGS flows, the SS will not send any bandwidth request as BS allocates the bandwidth in an unsolicited manner. Therefore, we disregard UGS flow while in our analysis. In Strict Priority, the SS will send rtPS packets first, and then if there is bandwidth left, nrtPS packets will be sent. If there are no rtPS or nrtPS packets left, BE packets will be sent. As a result, if the network is congested with a high rtPS load, nrtPS and BE packets will not be sent, so nrtPS QoS requirements will not be guaranteed.

In the Weighted Fair Priority Queuing algorithm, we define weights for rtPS, nrtPS and BE statically. In our WFPQ implementation, we assign a weight of 5 to rtPS, a weight of 3 to nrtPS, and a weight of 2 to BE. The algorithm behaves fairly. If any service type is assigned some weights but there is some unused bandwidth left, the unused bandwidth is distributed between the lower priority service flows according to their weights.

In this thesis, we do not deal with the BS Scheduler algorithms. We choose the Round Robin Scheduling algorithm for the BS Scheduler. As our focus is on GPSS systems, for SS schedulers, we implemented Enhanced RED-based WFPQ algoritm referring to RED-based WFPQ. We made analysis of the simulation results for these algorithms. The details of our algorithm were given in Section 4.

6. SIMULATIONS AND RESULTS

6.1 Simulation Environment

The simulations are perfomed on the NS-2 Simulator [9]. The QoS-included patch in [12] is used and modified to perform simulations. The simulation topology consists of one SS and one BS. The SS has one UGS, one rtPS, one nrtPS and one BE flows. The SS can use QPSK 1/2, QPSK 3/4, 16-QAM 1/2, 16-QAM 3/4, 64-QAM 2/3 and 64-QAM 3/4 modulation and coding schemes. The simulation parameters are given in Table 6.1. To achive 95% confidence intervals, the simulations are executed five times.

Table 6.1 : Simulation parameters.

PHY specification	WirelessMAN-OFDM
Frequency Band	5MHz
Antenna Model	Omni Antenna
Antenna Height	1.5 m
Propogation Model	TwoRayGround
Transmit Antenna Gain	1
Transmit Power	0.25 W
Frame Duration	20 ms
Cyclic Prefix	0.025 s
Simulation Duration	100 s
Packet Length	1000 bytes
Frame Structure	TDD

Scheduler parameters of RED-based WFPQ are given in Table 6.2. The weights W_{nrtPS} and W_{BE} have a 3:2 ratio. Maximum queue length of rtPS is 50 packets.

Table 6.2 : RED-based WFPQ scheduler parameters.

Variables	**Selected Values**
W_{rtps_min}	0.5
W_{rtps_max}	0.7
$QL\_Th_{rtps\_min}$	(20% of max Queue Length) 10 packets
$QL\_Th_{rtps\_max}$	(60% of max Queue Length) 30 packets
QL_{rtps_max}	50 packets
W_{nrtPS}	W_{nrtps}
W_{BE}	$\frac{2}{3}W_{nrtps}$
m_{rtps}	0.01
W_{Total}	1

Figure 6.1 shows the behaviour of the algorithm when we use the values in Table 6.2.

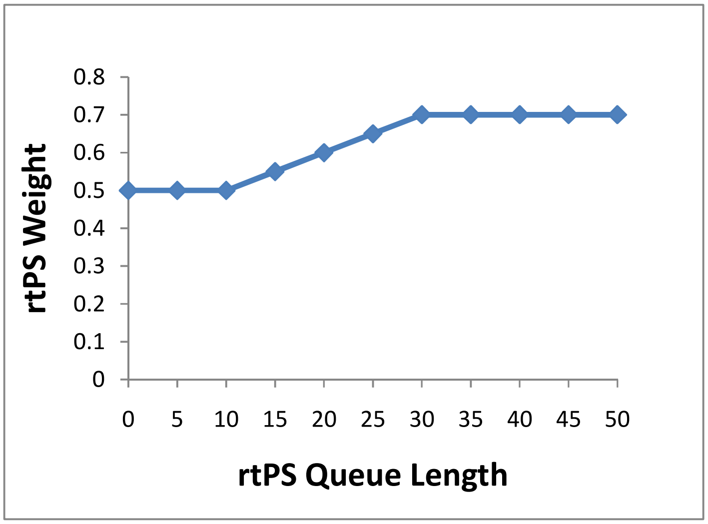

Figure 6.1 : rtPS weights of RED-based WFPQ.

Scheduler parameters of Enhanced RED-based WFPQ are shown in Table 6.3.

Table 6.3 : Enhanced RED-based WFPQ scheduler parameters.

Variables	Selected Values
W_{rtps_min}	*0.5*
W_{rtps_max}	*0.7*
W_{Total}	*1*
$QL\_Th_{rtps\_min}$	*(20% of max Queue Length) 10 packets*
$QL\_Th_{rtps\_max}$	*(60% of max Queue Length) 30 packets*
QL_{rtps_max}	*50 packets*
m_{rtps}	*0.01*

Figure 6.2 shows the behaviour of the algorithm when we use the parameter values as in Table 6.3. As we use the same values for rtPS parameters, RED-based WFPQ and Enhanced RED-based WFPQ's rtPS weight graphs are the same.

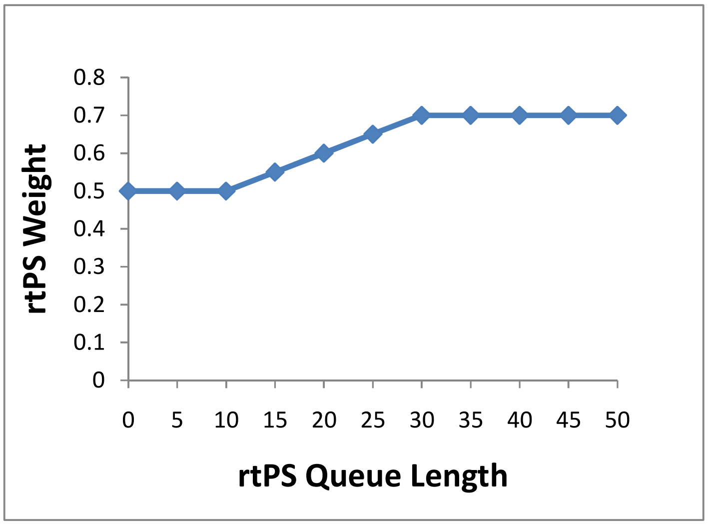

Figure 6.2 : rtPS weights of Enhanced RED-based WFPQ.

Parameters that are chosen in Condition 1 are given in Table 6.4.

Table 6.4 : Parameters of Enhanced RED-based WFPQ in Condition-1.

Condition-1	**[$QL_{rtps} < QL\_Th_{rtps\_min}$]**
Variables	***Selected Values***
W_{nrtps_min}	*0.35*
W_{nrtps_max}	*0.45*
$QL\_Th_{nrtps\_min}$	*(20% of max Queue Length) 10 packets*
$QL\_Th_{nrtps\_max}$	*(60% of max Queue Length) 30 packets*
QL_{nrtps}	*50 packets*
m_{nrtPS}	*0.05*
W_{rtps_min}	*0.5*

Figure 6.3 shows the behaviour of the algorithm when we use the parameter values in Table 6.4. As we use static weights for the nrtPS weight in RED-based WFPQ, Enhanced RED-based WFPQ's nrtPS weight graph is different and RED-based.

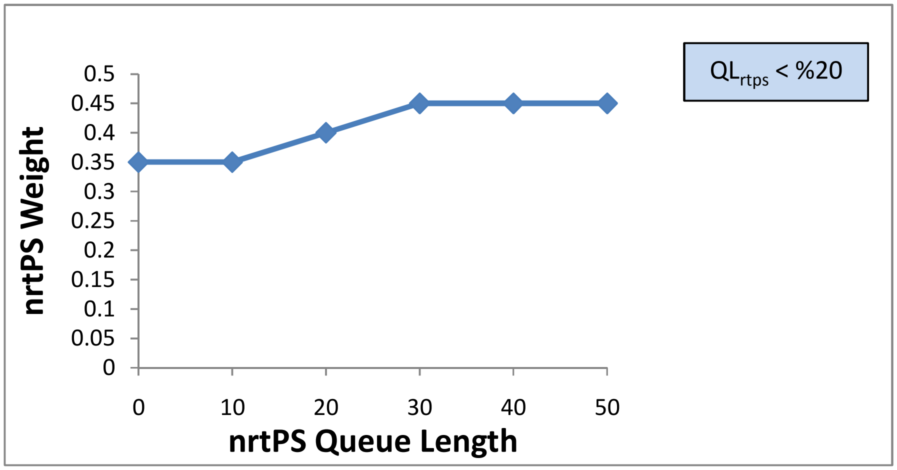

Figure 6.3 : nrtPS weights of Enhanced RED-based WFPQ in Condition-1.

W_{BE} is calculated according to equation (4.3). We need to subtract W_{rtps} and W_{nrtps} from W_{Total}.

Parameters of nrtPS and rtPS, which are used in Condition-2, are given in Table 6.5.

Table 6.5 : Parameters of Enhanced RED-based WFPQ in Condition-2.

Condition-2 [$QL\_Th_{rtps\_min} < QL_{rtps} < QL\_Th_{rtps\_max}$]	
Variables	***Selected Values***
W_{nrtps_min}	*0.2*
W_{nrtps_max}	*0.35*
$QL\_Th_{nrtps\_min}$	*(20% of max Queue Length) 10 packets*
$QL\_Th_{nrtps\_max}$	*(80% of max Queue Length) 40 packets*
QL_{nrtps}	*50 packets*
m_{nrtPS}	*0.05*
rtPS weight ex.	*0.6*
rtPS QL percentage	*40%*
W_{BE_min}	*0,05*

Figure 6.4 shows the behaviour of the algorithm when we use the parameter values nrtPS as in Table 6.5. In this condition, the diagram depends on rtPS weights. Therefore, to draw a diagram for nrtPS weights, we need to define a rtPS weight value. In our example, we take rtPS weight to be 0.6.

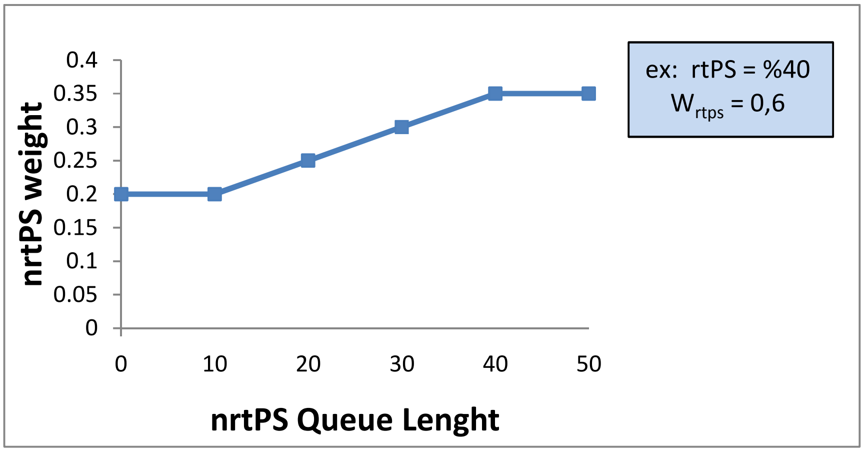

Figure 6.4 : nrtPS weights of Enhanced RED-based WFPQ in Condition-2.

W_{BE} is calculated according to the equation (4.5). We need to substract W_{rtps} and W_{nrtps} from W_{Total}.

Parameters of service types (rtPS, nrtPS, and BE), which are used in Condition-3, are given in Table 6.6.

Table 6.6 : Parameters of Enhanced RED-based WFPQ in Condition-3.

Condition-3 [$QL_{rtps} > QL\_Th_{rtps\_max}$]	
$W_{rtps} = W_{rtps\_max}$	0.7
$W_{nrtps} = W_{nrtps\_max}$	0.25
$W_{BE} = W_{Total} - W_{rtps\_max} - W_{nrtps\_max}$	0.05

Figure 6.5 shows the behaviour of the algorithm when we use the parameter values in Table 6.6. In this condition, the chosen weights are chosen static values, as most of the weights are being used by rtPS. To increase the throughput of nrtPS in that condition is difficult.

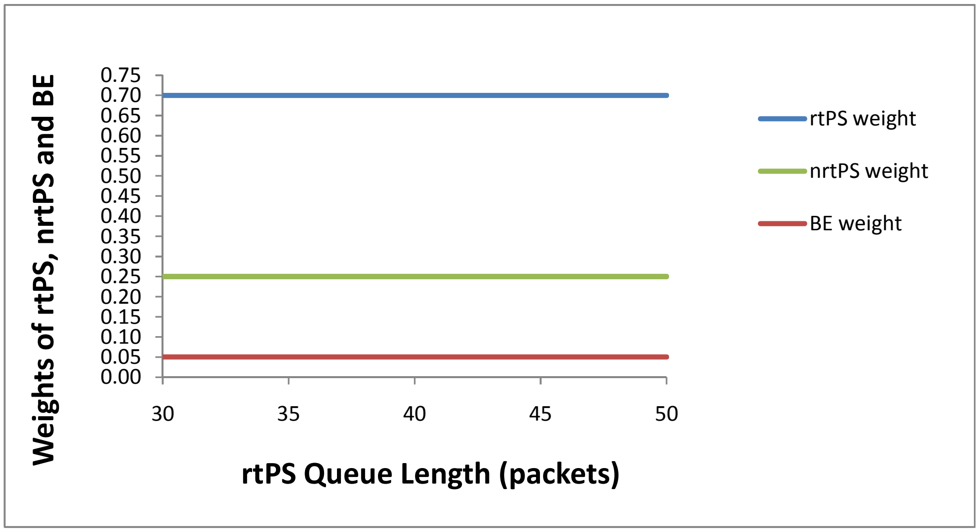

Figure 6.5 : Weights for rtPS, nrtPS, and BE in Condition-3.

6.2 Performance Metrics

For our performance metrics, we choose throughput, delay, fairness index, and dropped packet percentage. Throughput of the service types are given as kbps and they provide the transmitted bit number of per second. Throughput for rtPS, nrtPS and BE are calculated 5 times to achieve 95% confidence intervals.

Delay represents the time interval between a packet arrives to MAC layer and the transmission of the packet from the SS. This provides us queue waiting delay significantly.

Fairness Index (FI), which is known as "Jain's Fairness Index Method" [17] is used while calculating the fairness index. While calculating fairness index, the formula (6.1) is used:

$$FI = f(x_1, x_2, ..., x_n) = \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n \sum_{i=1}^{n} x_i^2} \qquad \textbf{(6.1)}$$

Fairness index is commonly used between the users who wait the same service. For example, between the service flows which have the same QoS requirements. In [5], fairness index is measured between the users of the same traffic class (Intra-class Fairness) and among all users (Inter-class). They calculated Inter-Class Fairness based on "Jain's Fairness Index". Due to the fact that all connections from the same class should receive the same QoS, they used "Min-Max Fairness Index" (6.2).

$$Min - Max \quad FI = \frac{x_{\min}}{x_{\max}} \qquad \textbf{(6.2)}$$

To calculate Jain's Fairness Index (inter-class), we need to use normalized average throughputs of the service types. The average throughput of an SS is normalized by the Minumum Reserved Traffic Rate (MRTR) as shown in the equation (6.3).

$$x_i = \frac{X_{Throughput}}{MRTR} \quad \textbf{(6.3)}$$

MRTR values are chosen as 64 for rtPS, 45 for nrtPS, and 1 for BE [17]. As we transmit voice data via rtPS flows, 64 kbps is chosen for rtPS MRTR. FTP traffic is generated to support 45 kbps for MRTR. As BE flows do not have any MRTR QoS requirements, we give 1 kbps for BE flows as in [17]. As we measure throughputs of different service types (for one SS), we calculated Inter-Class Fairness Index only.

The number of dropped packets are calculated by substracting the number of transmitted packets from the number of incoming packets. In equation (6.4), this metric is given as the percentage of dropped packets.

$$DroppedPac\ ketPercent\ age\% = \frac{DroppedPac\ ketNumber}{NumberOfPa\ ckets} * 100 \quad \textbf{(6.4)}$$

6.3 Simulation Results

6.3.1 Throughput analysis

We calculate the throughputs of rtPS, nrtPS, and BE under the submission of rtPS Load for 50, 100, 500, 1000, 1500, 2000, 2500, and 3000 kbps. While increasing the rtPS load, the throughput of the each service flow is calculated. Strict Priority has the maximum throughput level as the algorithm always grants bandwidth for rtPS first, if there is no packet in the rtPS queue and there is available bandwidth left for the SS, then the bandwidth is allocated for the nrtPS service flow. If there are no packets in rtPS and nrtPS queues and there is available bandwidth left for the SS, then the bandwidth is allocated to the BE service flow. Consequently, rtPS flows have more granted bandwidth. As expected, the throughput of SP is the highest in the Figure 6.6. RED2-based WFPQ represents for Enhanced RED-based WFPQ algorithm.

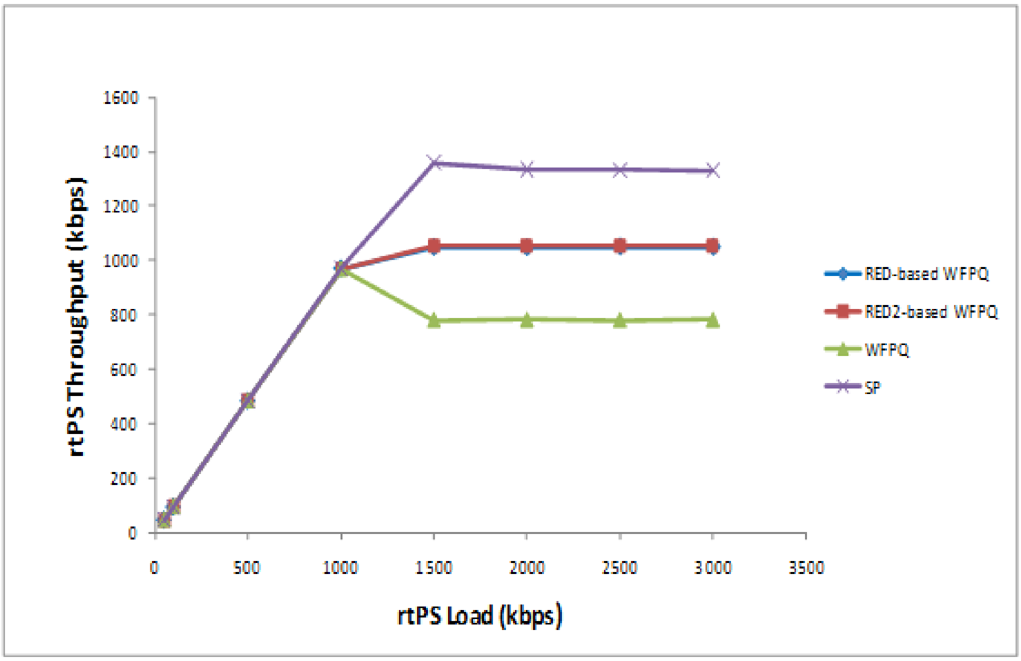

Figure 6.6 : rtPS throughput analysis.

In the WFPQ algorithm, as the weights are chosen statically, we cannot increase the throughput of rtPS significantly while increasing rtPS load. RED-based WFPQ and Enhanced RED-based WFPQ have higher rtPS throughput as they can dynamically change the weights of rtPS according to the queue length of the rtPS flow. Initial weights are the same in WFPQ and RED algorithms. However, as rtPS load submission increases, due to higher rtPS traffic, the queue length will also increase. Consequently, RED-based WFPQ and Enhanced RED-based WFPQ yield better perfomance than WFPQ. WFPQ turns out to be the worst in terms of rtPS throughput. RED-based WFPQ and Enhanced RED-based WFPQ use the same approach for rtPS flows, so their performance is identical.

For Strict Priority, when rtPS traffic increases significantly, there will be no resource left for nrtPS and BE flows. Therefore, their throughputs will drop to zero. As a result, nrtPS and BE flows may starve under high rtPS traffic. In Figure 6.7, the nrtPS throughput of Strict Priority drops to zero, once the rtPS load exceeds 1500 kbps.

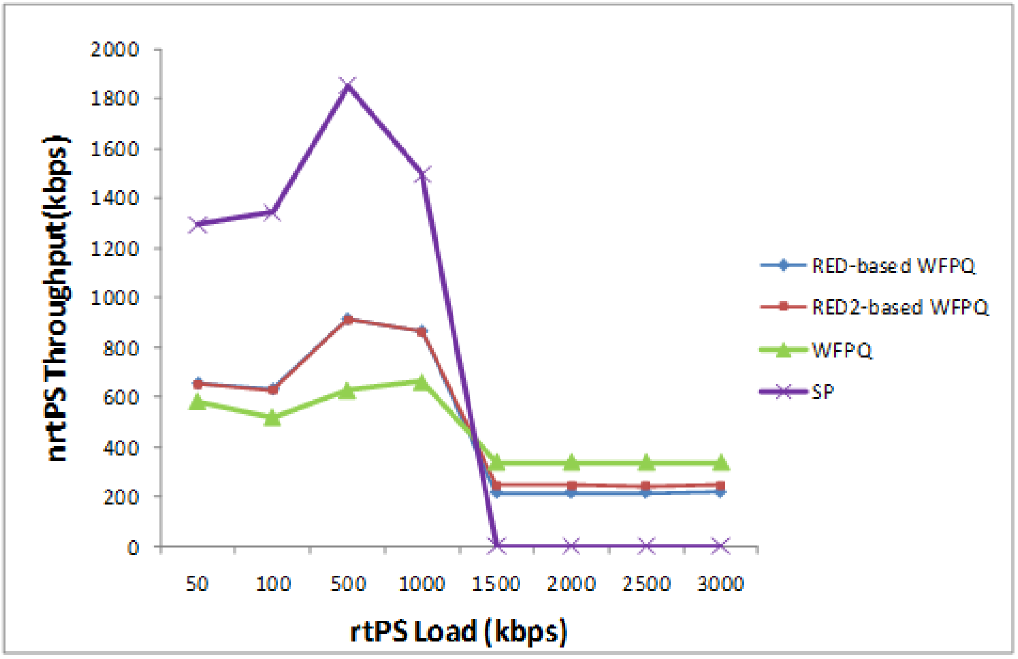

Figure 6.7 : nrtPS throughput analysis.

Under high rtPS traffic, WFPQ has the highest nrtPS throughput as it has the maximum nrtPS weights than the others. The main reason is that, WFPQ has lower rtPS load than the others, so it can grant more weight for the nrtPS flow.

Enhanced RED-based WFPQ has higher nrtPS throughput than RED-based WFPQ. When the rtPS load is 3000kbps, Enhanced RED-based WFPQ yields 244 kbps and RED-based WFPQ yields 214 kbps throughput. This means that Enhanced RED-based WFPQ increases the nrtPS throughput as much as 14% over RED-based WFPQ.

When we evaluate the BE throughput, we observe in Figure 6.8 that the WFPQ algorithm yields the best throughput. This is because among all the algorithms, WFPQ assigns the highest weight to BE. However, we do not need to grant bandwidth for BE flows, as they do not have significant QoS requirements. As long as we prevent the starvation of the BE flows in a congested network, we have an acceptable QoS-based system. Therefore, in RED-based WFPQ and Enhanced RED-based WFPQ, we allocate very little weight to BE, so that we can continue serving them. In Strict Priority, the BE users have no chance of being served if the network is congested. Consequently, as rtPS load increases, BE flows cannot transmit their packets, and their throughputs drops to zero beyond 1500 kbps rtPS load in Figure 6.8.

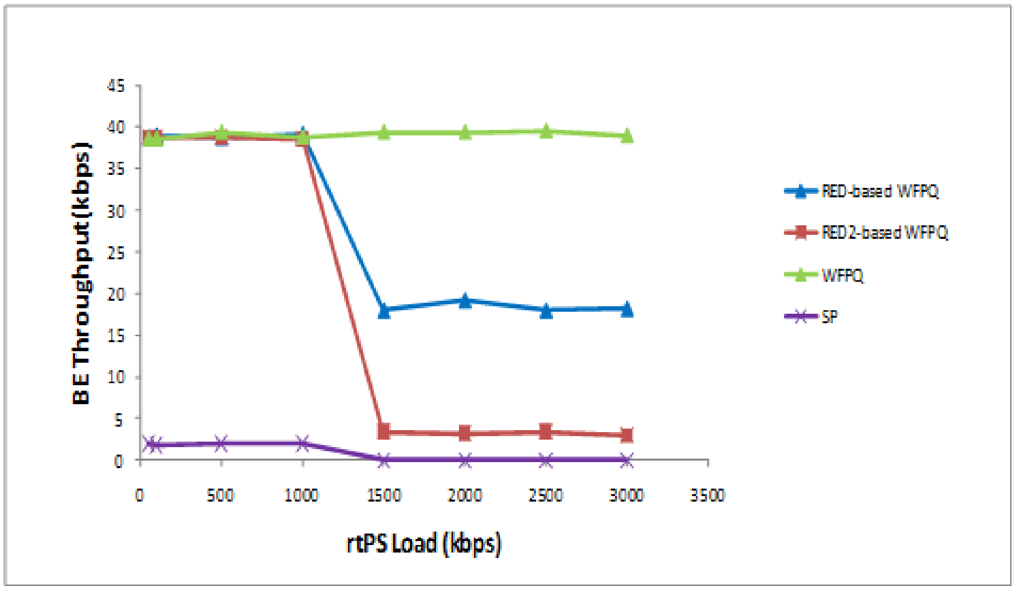

Figure 6.8 : BE throughput analysis.

The total throughput analysis is given in Figure 6.9. Strict Priority has the maximum total throughput; however, it is not fair, so it not acceptable for a QoS-based system. RED-based WFPQ and Enhanced RED-based WFPQ algorithms yield better throughput than WFPQ. In addition RED-based WFPQ and Enhanced RED-based WFPQ algorithms yield approximately the same total throughput. The reason is that in our algorithm, Enhanced RED-based WFPQ, we decrease the BE throughput and so increase the nrtPS throughput. The total throughput, thus, remains unaffected.

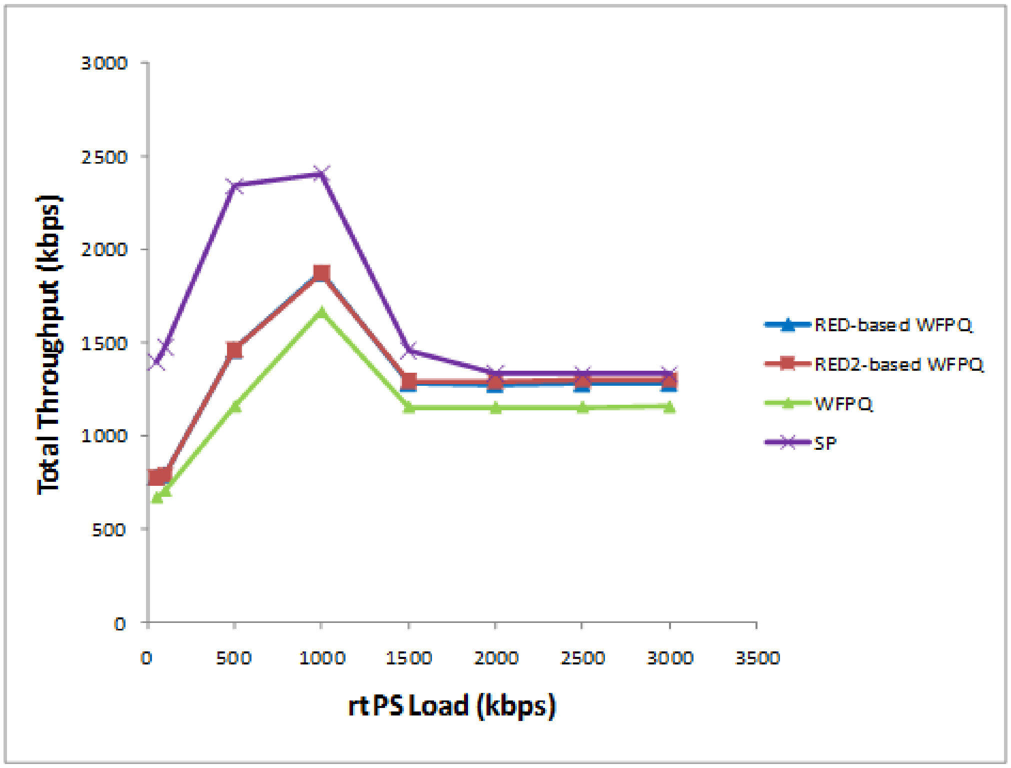

Figure 6.9 : Total throughput analysis.

6.3.2 Delay Analysis

As we increase the rtPS load, we observe that Strict Priority yields the lowest delay. This is because Strict Priority allocates higher bandwidth for rtPS flows than the others. This increases the throughput of rtPS and, consequently, decreases the delay of rtPS. Figure 6.10 shows the rtPS delay results. WFPQ has the highest rtPS delay as its throughput is lower than the others. RED-based WFPQ and Enhanced RED-based WFPQ decrease the delay of rtPS, as they control the weight of rtPS according to the queue length of rtPS.

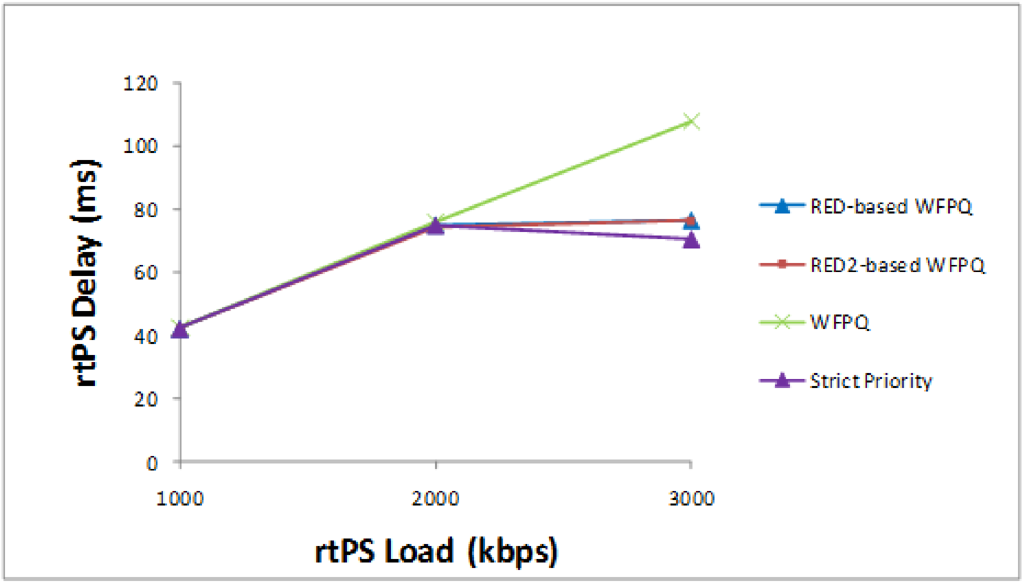

Figure 6.10 : rtPS delay.

The variation of nrtPS delay with increasing rtPS load is shown in Figure 6.11. In this graph, we do not show the results of Strict Priority. The reason is that beyond 1500 kbps the nrtPS flow cannot transmit any packets, and the delay increases extremely. Consequently, the result for SP is not comparable with the other algorithms. The Enhanced RED-based WFPQ algorithm succeeds in decreasing the delay of nrtPS flows over RED-based WFPQ and WFPQ increasing the throughput. Among all three algorithms, WFPQ allocates the highest weight for nrtPS, thus, it has the lowest nrtPS delay.

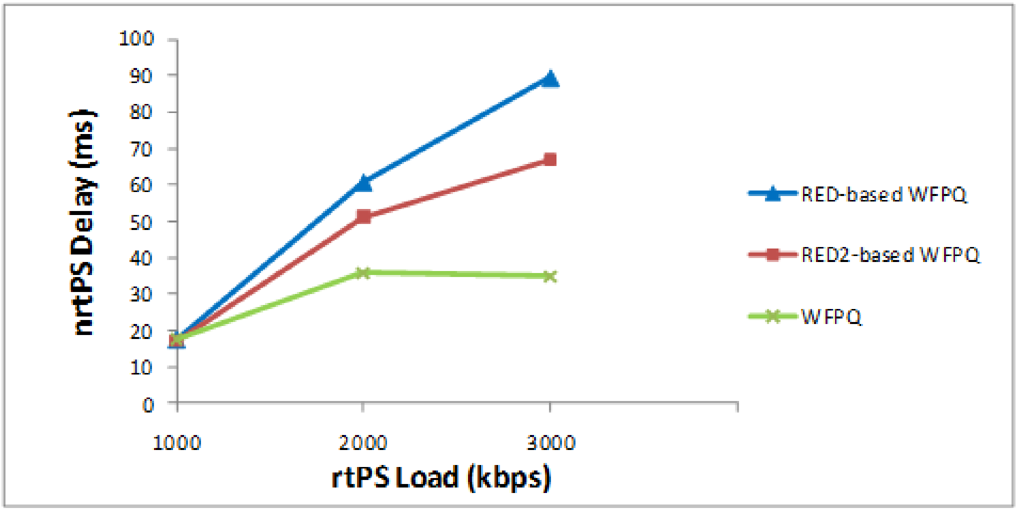

Figure 6.11 : nrtPS delay.

The delay of BE flows are given in Figure 6.12. In this graph we do not show the results for SP. The reason is that beyond 1500 kbps, the BE flow cannot transmit any packets, and the delay increases extremely. Consequently, the results are not comparable with the other algorithms. Enhanced RED-based WFPQ algorithm increases the delay of BE flows, as the algorithm increases the throughput of nrtPS. Therefore, RED-based WFPQ has lower BE delay than Enhanced RED-based WFPQ. In that point, we provide to transmit BE flows but as BE flow do not have QoS requirement, we increase nrtPS throughput in order to BE's. Among the three algorithms, WFPQ allocates the highest weight to BE, so it yields the lowest delay.

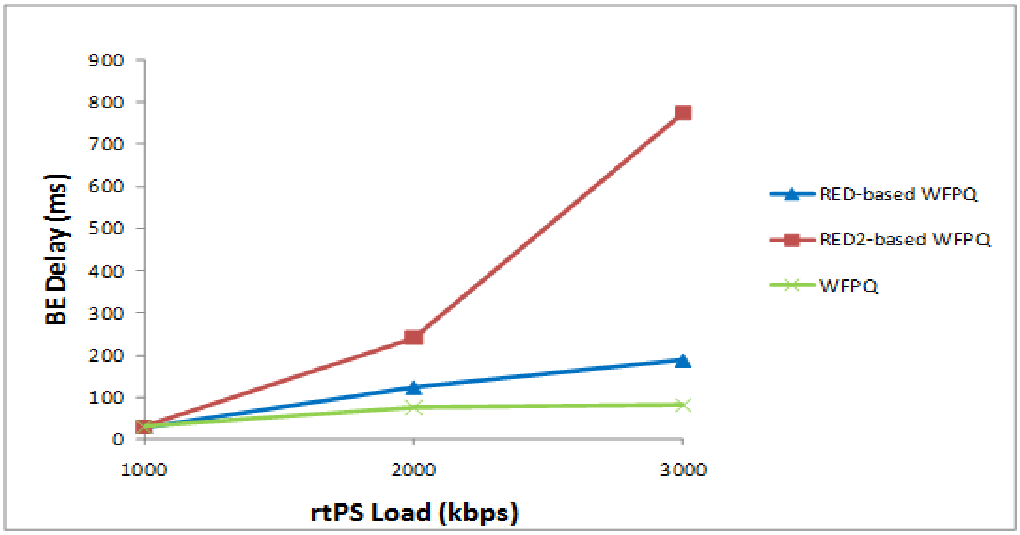

Figure 6.12 : BE delay.

6.3.3 Dropped packet analysis

In Figure 6.13, when we analyze the percentage of dropped rtPS packets in each algorithm, we observe that SP yields the lowest dropped packet percentage. WFPQ yields the highest dropped packet percentage, as RED-based WFPQ and Enhanced RED-based WFPQ algorithms increase the throughput of rtPS over that of WFPQ.

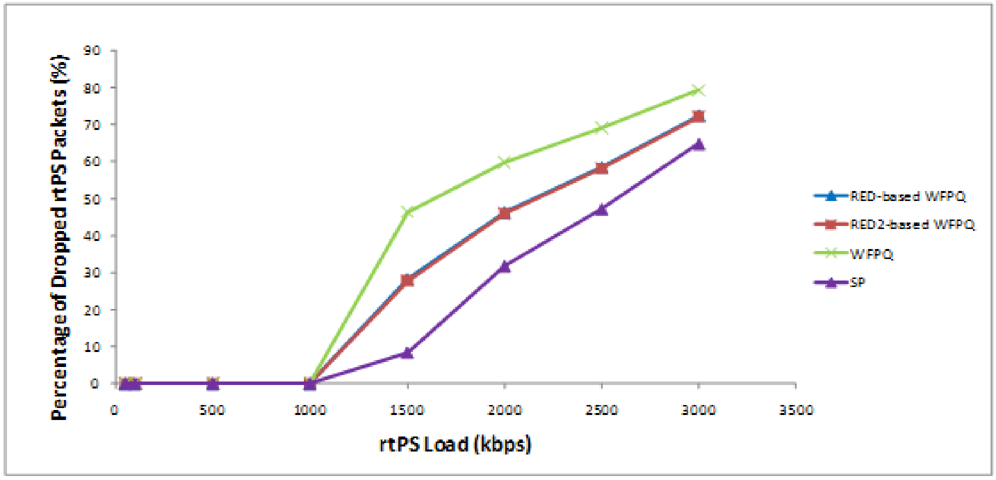

Figure 6.13 : Percentage of dropped rtPS packets (%).

In Figure 6.13, when rtPS load is lower than 1500 kbps, system is acceptable for rtPS traffic. When the submitted rtPS load increases, the percentage of rtPS packets increase as well, so 30% dropped rtPS packets percentage is high enough for our system. Therefore, we analyze the dropped packets percentage between 1000 and 1500 kbps seperately. The simulation results are shown in Figure 6.14.

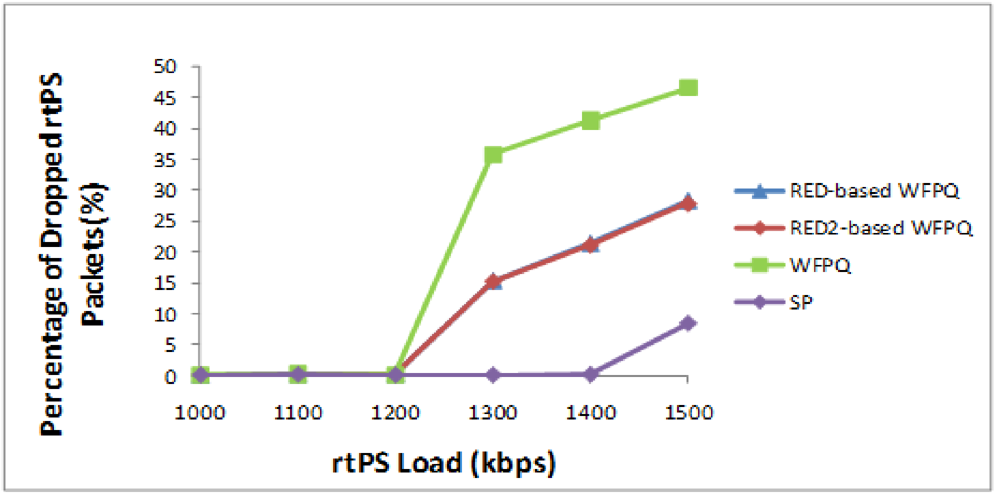

Figure 6.14 : Percentage of dropped rtPS packets between 1000-1500 kbps (%).

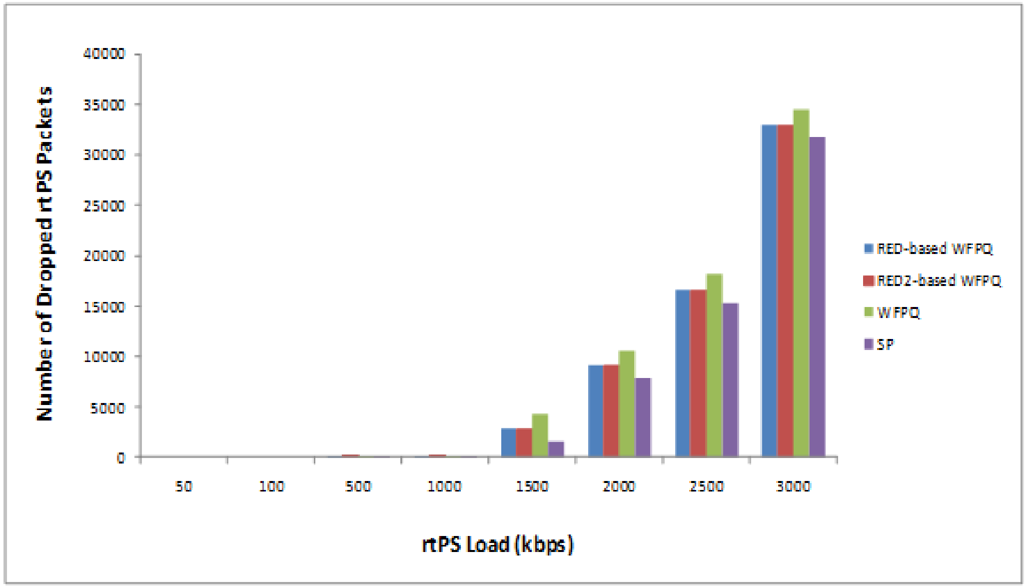

Figure 6.15 : Number of dropped rtPS packets.

Figure 6.15 gives the number of dropped rtPS packets. WFPQ has the highest number of packets dropped. As Strict Priority yields the highest throughput for rtPS, its number of dropped packets is the lowest. RED-based WFPQ and Enhanced RED-based WFPQ have the same number of dropped packets. The reason is that their granting mechanism for rtPS flows are the same.

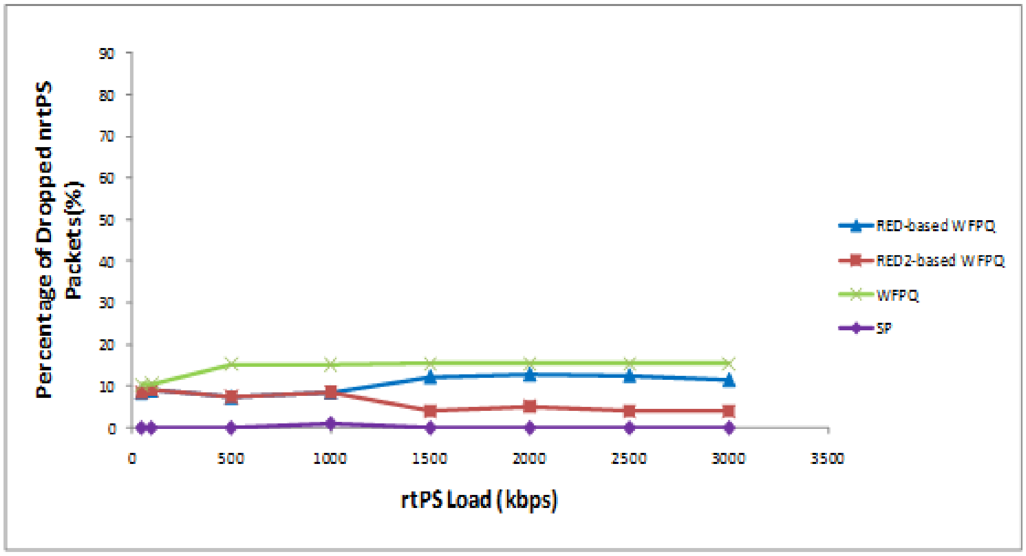

Figure 6.16 : Percentage of dropped nrtPS packets (%).

Figure 6.16 shows the percentage of dropped nrtPS packets. Strict Priority sends nrtPS packets until 1500 kbps rtPS load is reached. Beyond that, due to TCP congestion, nrtPS flows cannot be allocated any bandwidth. Since there are no nrtPS packets submitted, the percentage of dropped nrtPS packets equals zero.

WFPQ has the highest percentage of dropped nrtPS packets, as RED-based WFPQ and Enhanced RED-based WFPQ increase the nrtPS throughput over that of WFPQ. Also, beyond 1000 kbps rtPS load, Enhanced RED-based WFPQ has a lower percentage of dropped nrtPS packets than RED-based WFPQ. This is to be expected, as Enhanced RED-based WFPQ increases the nrtPS throughput.

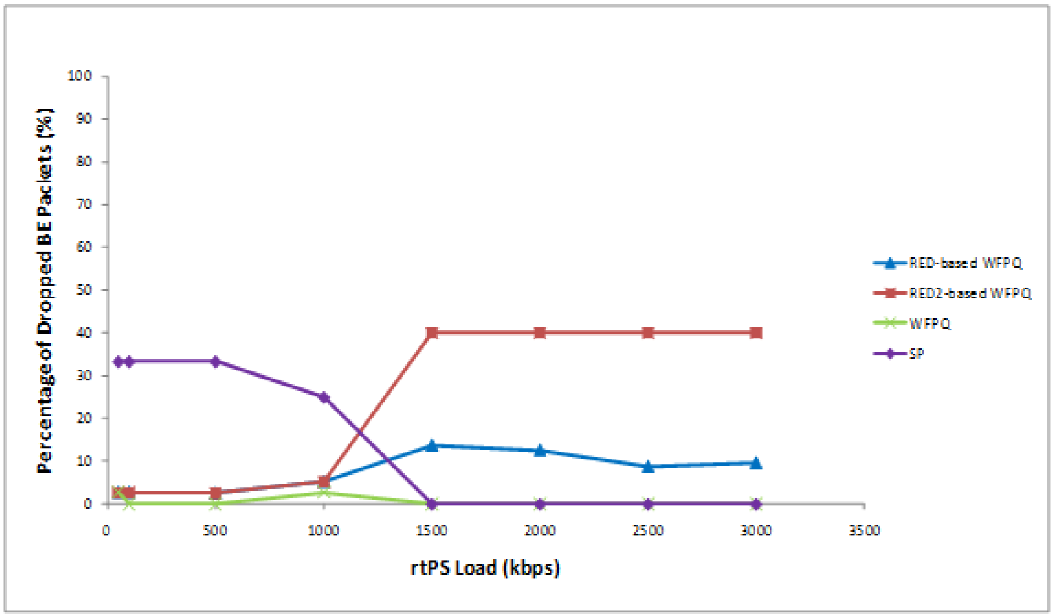

Figure 6.17 : Percentage of dropped BE packets (%).

Figure 6.17 shows the percentage of dropped BE Packets. Strict Priority sends BE packets until 1500 kbps rtPS load is reached. Beyond that, due to TCP congestion, BE flows can not be allocated any bandwidth. Since there are no BE packets submitted, the percentage of dropped packets equals zero.

WFPQ has the lowest percentage of dropped BE packets, as RED-based WFPQ and Enhanced RED-based WFPQ decrease the BE throughput. Also, beyond 1000 kbps rtPS load, Enhanced RED-based WFPQ has a higher percentage of dropped BE packets than RED-based WFPQ. This is to be expected, as Enhanced RED-based WFPQ decreases the BE throughput.

6.3.4 Fairness index analysis

Fairness Index is calculated according to [18] using equations (6.1) and (6.3). Therefore, we normalized rtPS flow with 64 kbps, nrtPS flow with 45 kbps, and BE flow with 1 kbps as equation (6.3). Inter-class fairness is calcutated according to Equation (6.1). Figure 6.18 gives the Fairness Index of all algorithms. Enhanced RED-based WFPQ has a lower Fairness Index than RED-based WFPQ, but its value is acceptable. In a QoS-based system, we do not need to provide strong fairness if we increase the QoS of the system. But, we still evaluate if fairness is provided at an acceptable level.

Strict Priority has the lowest Fairness Index, as it is an unfair algorithm. Enhanced RED-based WFPQ is slightly fairer than WFPQ. As Enhanced RED-based WFPQ allocates sufficient bandwidth for rtPS flows, it achieves higher fairness over WFPQ. RED-based WFPQ has the highest Fairness Index because the algorithm provides more allocation for BE flows. Consequently, normalized values of rtPS, nrtPS, and BE are closer to each other, resulting in a higher Fairness Index.

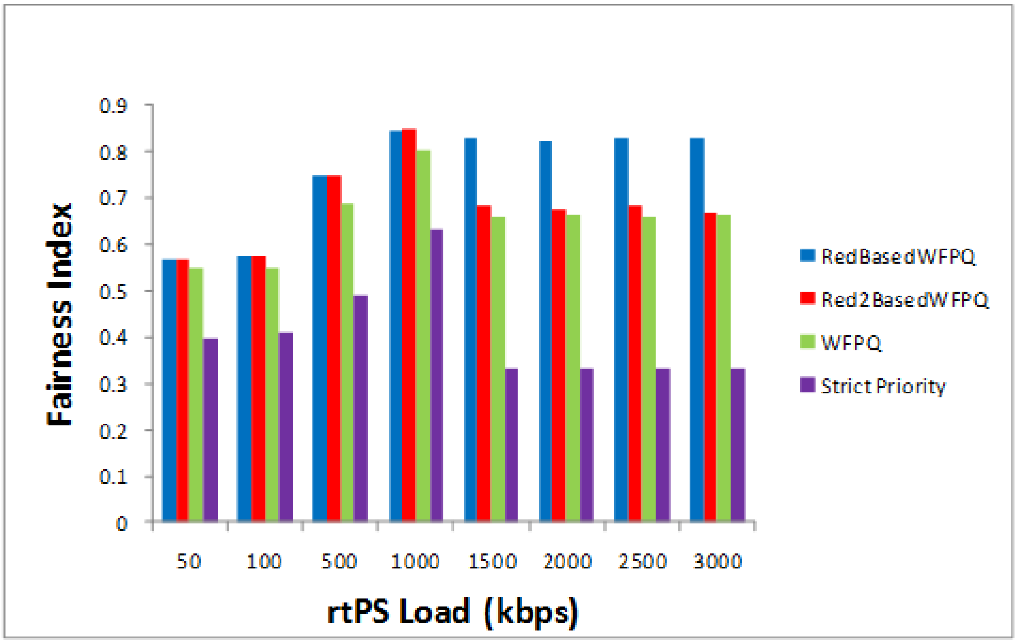

Figure 6.18 : Fairness index.

7. CONCLUSION

In this thesis, QoS based WiMAX patch is enhanced to provide Grant Per Subscriber Station mode. After implementing GPSS supported WiMAX patch, existing scheduler algorithms of SS are implemented such as Strict Priority, Weighted Fair Priority Queuing. RED-based WFPQ is implemented referring to RED-based DFPQ. To improve the throughput of nrtPS flow, RED-based WFPQ is enhanced. Our algorithm is named Enhanced RED-based WFPQ. RED-based WFPQ and Enhanced RED-based WFPQ try to increase the throughput of rtPS. In addition, the Enhanced RED-based WFPQ algorithm also tries to increase the throughput of nrtPS.

Simulation results showed that RED-based WFPQ and Enhanced RED-based WFPQ increase the rtPS throughput, as they follow the same approach while allocating rtPS bandwidth. The rtPS throughput of Strict Priority is the highest and the throughput of WFPQ is the lowest. The nrtPS throughput of Enhanced RED-based WFPQ is higher than that of RED-based WFPQ. As rtPS traffic increases, WFPQ has the highest throughput as it allocates less rtPS weight than the others and Strict Priority cannot transmit nrtPS and BE packets due to high rtPS load. The BE throughput of Enhanced RED-based WFPQ is lower than that of RED-based WFPQ. Enhanced RED-based WFPQ increases nrtPS throughput, but it decreases the throughput of BE flows. However, the starvation of BE flows in congested network is prevented.

RED-based WFPQ and Enhanced RED-based WFPQ significantly decrease the delay of rtPS. Strict Priority has the lowest delay, and WFPQ has the highest delay. The delays experienced depend on the throughput of the flows. The nrtPS delay of Enhanced RED-based WFPQ algorithm is lower than that of RED-based WFPQ. The BE delay of RED-based WFPQ algorithm is lower than that of Enhanced RED-based WFPQ.

The number of dropped rtPS packets is directly proportional to the delay; therefore, Strict Priority exhibits the lowest number of dropped rtPS packets, while WFPQ exhibits the highest number of dropped rtPS packets. The number of dropped rtPS packets for RED-based WFPQ and Enhanced RED-based WFPQ are the same.

As Strict Priority is unfair, its Fairness Index is the lowest. RED-based WFPQ and Enhanced RED-based WFPQ have higher Fairness Index than WFPQ. The reason is the allocation of the bandwidth depend on the queue length and shows dynamic characteristic. RED-based WFPQ has a higher Fairness Index than Enhanced RED-based WFPQ. Actually, in a QoS-based system, we do not have to provide fairness for BE flows. Increasing the QoS of the system (as indicated by the fairness index) is good enough.

In our implementation, the weight thresholds were chosen as static. Future work could investigate dynamically changing weight thresholds. The thresholds could adapt to the state of the service flow queues. The resulting throughput for different service types could be compared to our current results.

REFERENCES

[1] **IEEE Standard 802.16-2004**, 2004. IEEE standard for Local Metropolitan Area Networks, Part16: Air interface For Fixed Broadband Wireless Access Systems, June 2004.

[2] **C.Eklund et al.,** 2002. IEEE standard 802.16: A technical overview of the WirelessMAN^{TM} air interface for broadband wireless access, *IEEE Commun. Mag.*, pp. 98-107

[3] **Borin, J. F., Fonseca, N. L. S. da,** 2008. Simulator for WiMAX networks, *Elsevier Simulation Modelling Practice and Theory 16*, **1**, pp. 817-833

[4] **Maheshwari, S.** 2005. An Efficient QoS Scheduling Architecture for IEEE 802.16 Wireless MANs: Master Thesis, Indian Institute of Technology, Bombay, India.

[5] **Pratik, D. et al.,** 2009. A Performance Study of Uplink Scheduling Algorithms in Point-to-Multipoint WiMAX Networks, *Elsevier Computer Communications 32* 511-521.

[6] **Lin, J.C. et al.,** 2008. Performance Evaluation For Scheduling Algorithms In WiMAX Network, *22nd Conference on Advanced Information Networking and Applications – Workshops.*

[7] <*http://www.conniq.com/WiMAX/tdd-fdd.htm*>, last accessed in December 2009.

[8] **Masri et al.,** 2009. An Uplink Bandwidth Management Framework for IEEE 802.16 with QoS Guarantees, *IFIP Networking, Aachen, Germany.*

[9] <*http://www.isi.edu/nsnam/ns/*>, last accessed in November 2009.

[10] <http://w3.antd.nist.gov/seamlessandsecure/files/80216/doc/>, last accessed in October 2009.

[11] **J. Chen, et al.,** 2006. The design and implementation of wimax module for ns-2 simulator, *Workshop on ns-2, 202.*

[12] **Belghith, A. et al.,** 2008. Design and Implementation of QoS Included WiMAX Module for NS-2 Simulator, *SIMUtools, Marseille, France.*

[13] **T. Tsai, C. Jiang, and C. Wang,** 2006. Cac and packet scheduling using token bucket for ieee 802.16 networks *Journal of communications, 1(2):30-37.*

[14] **Pellegrini, F. et al.,** 2006. QoS Support in WiMAX Networks: Issues and Experimental Measurements : a survey, *Create-Net, Trento, Italy.*

[15] **Po-Chun Ting, Chia-Yu Yu, Naveen Chilamkurti.,** 2009. A Proposed RED-Based Scheduling Scheme for QoS in WiMAX Networks, *IEEE International Symposium on Wireless Pervasive Computing (ISWPC).*

[16] < http://www.cs.berkeley.edu/~kfall/EE122/lec21/sld005.htm>, last accessed in December 2009.

[17] <http://en.wikipedia.org/wiki/Fairness_measure >, last accessed in December 2009.

[18] **Pratik, D**., 2007. A Performance Study of Uplink Scheduling Algorithms in Point to Multipoint WiMAX Networks: MSc Thesis, *Queen's University, Canada.*

[19] **Şekercioğlu, A**., 2009. A survey of MAC based QoS implementations for WiMAX networks: a survey, *Computer Networks*, **53**, 2517-2536.

[20] **IEEE Standard 802.16e-2005**, 2005. IEEE standard for Local Metropolitan Area Networks, Part16: Air Interface for Fixed Broadband Wireless Access Systems - Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands, December 2005.

[21] **Nuaymi, L.,** 2007. WiMAX Technology for Broadband Wireless Access: a book, *John Wiley & Sons, Ltd.*

[22] **Chen, J., Jiao, W. , Wang, H.**, 2005. A Service Flow Management Strategy for IEEE 802.16 Broadband Wireless Access Systems in TDD Mode, *IEEE International Communications Conference (ICC).*

APPENDICES

APPENDIX A.1 : Confidence Intervals of Throughputs

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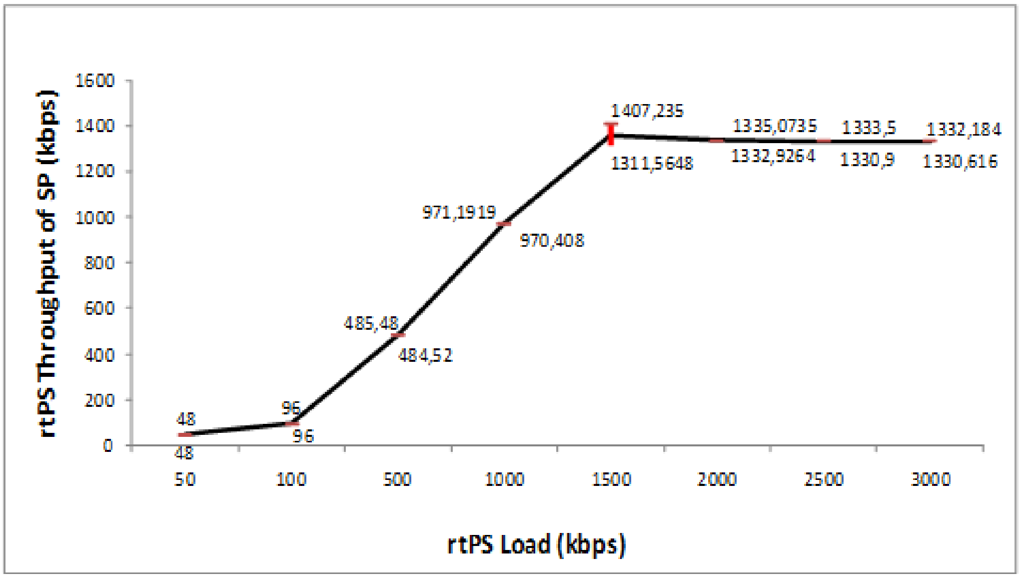

Figure A.1 : Confidence interval of SP rtPS throughput.

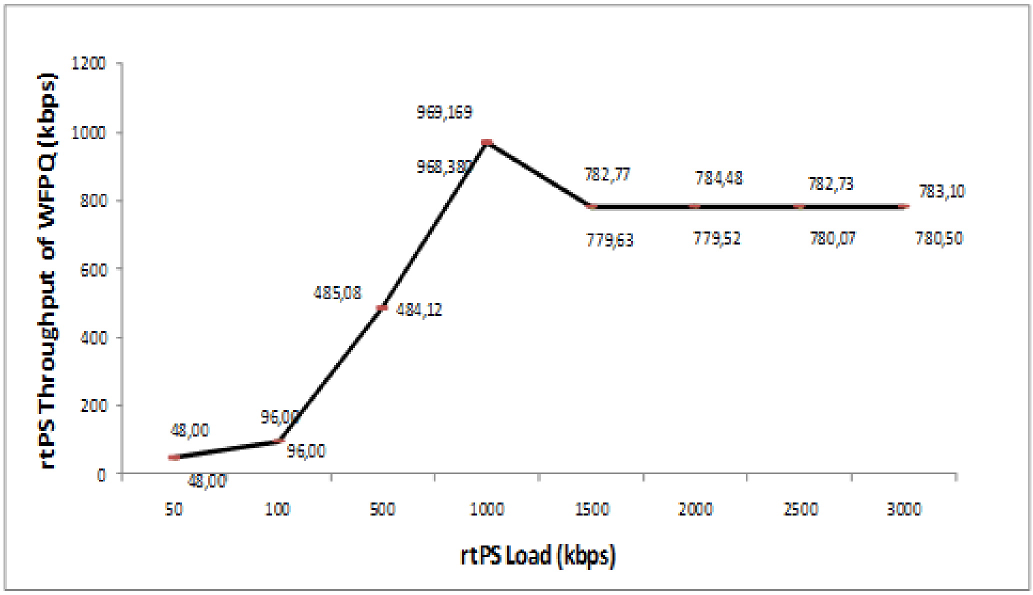

Figure A.2 : Confidence interval of WFPQ rtPS throughput.

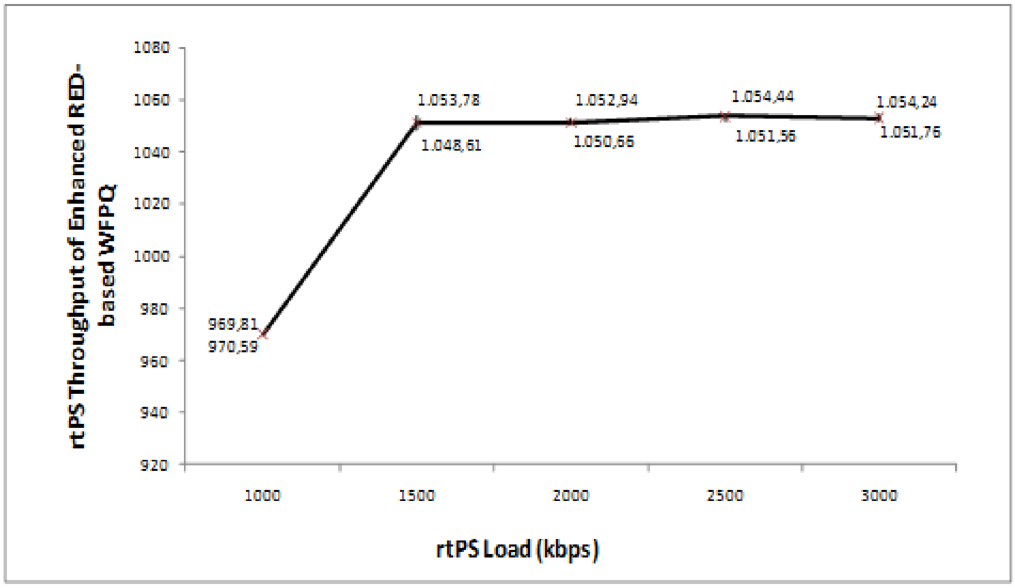

Figure A.3 : Confidence interval of RED-based WFPQ rtPS throughput.

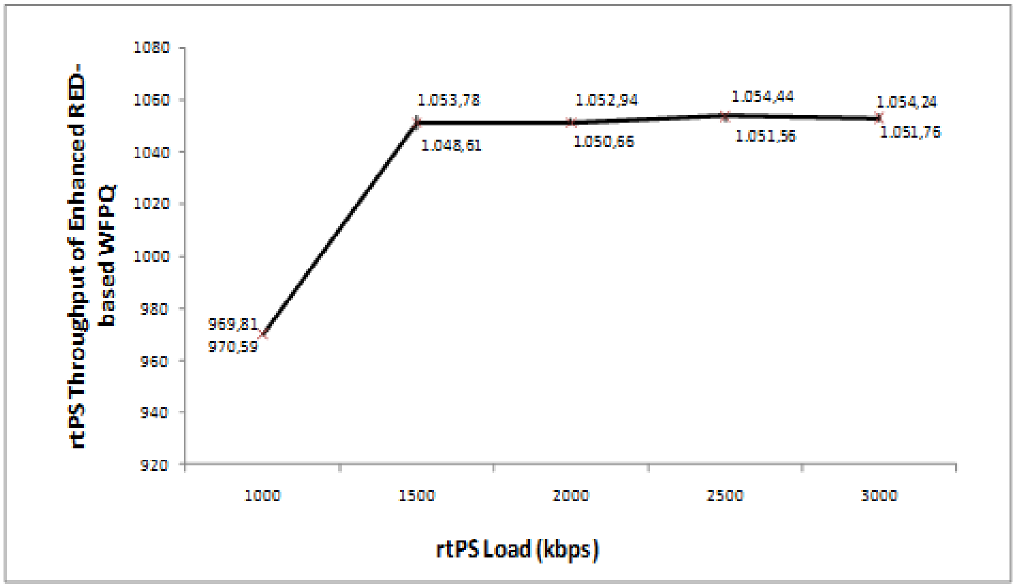

Figure A.4 : Confidence interval of Enh. RED-based WFPQ rtPS throughput.

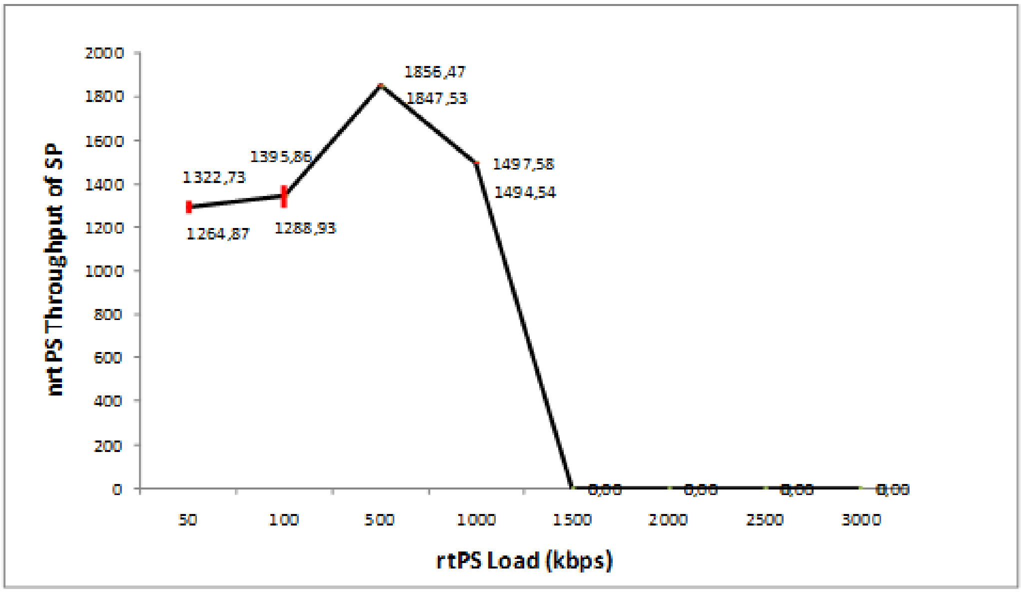

Figure A.5 : Confidence interval of SP nrtPS throughput.

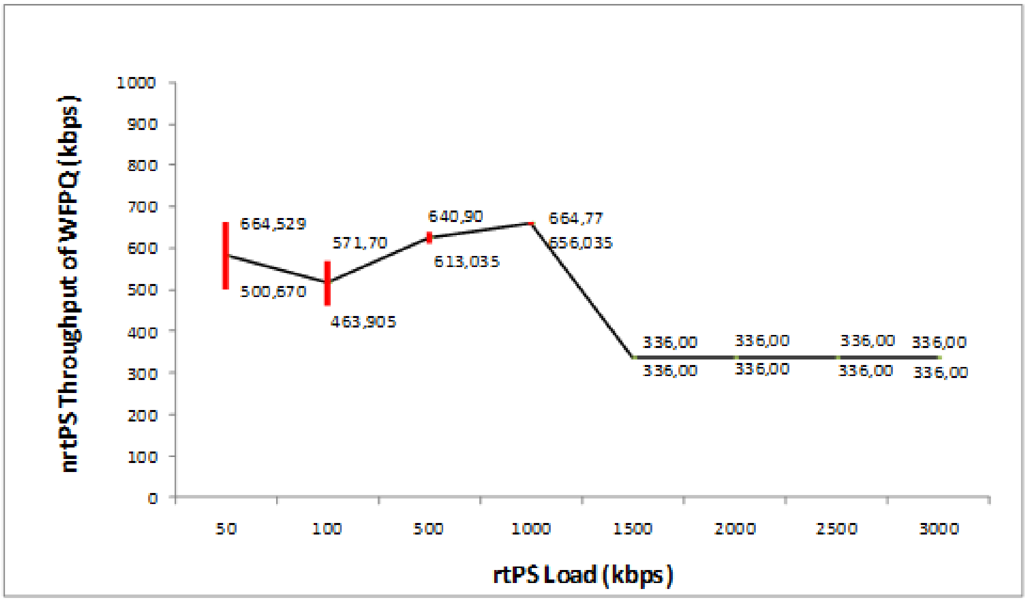

Figure A.6 : Confidence interval of WFPQ nrtPS throughput.

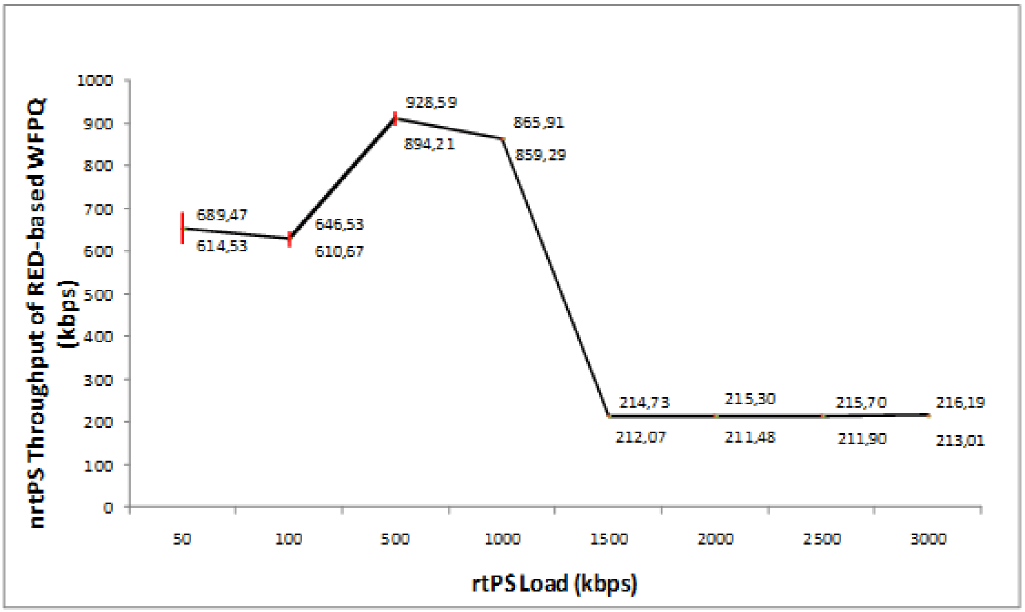

Figure A.7 : Confidence interval of RED-based WFPQ nrtPS throughput.

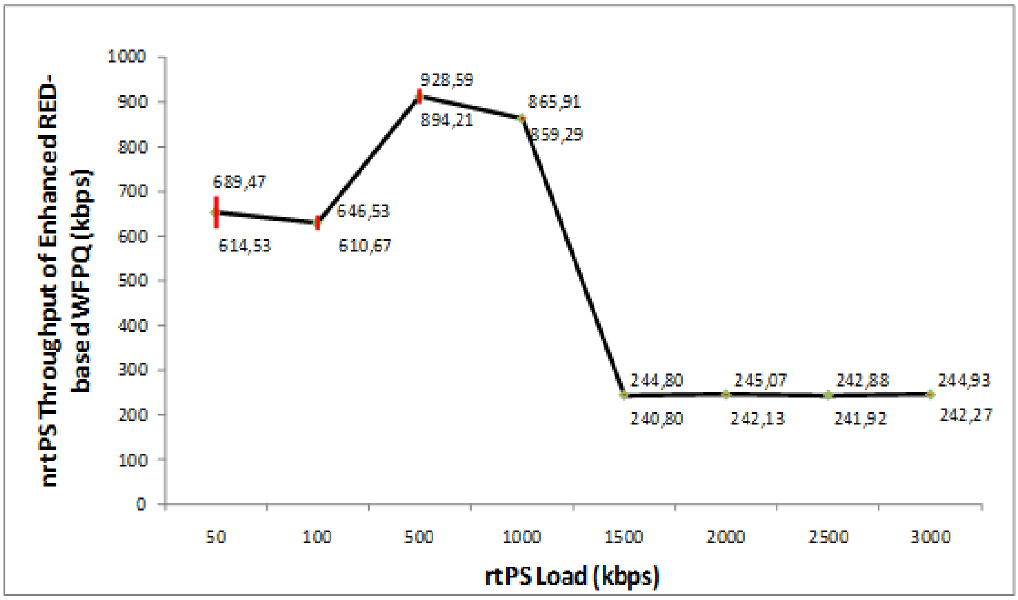

Figure A.8 : Confidence interval of Enh. RED-based WFPQ nrtPS throughput.

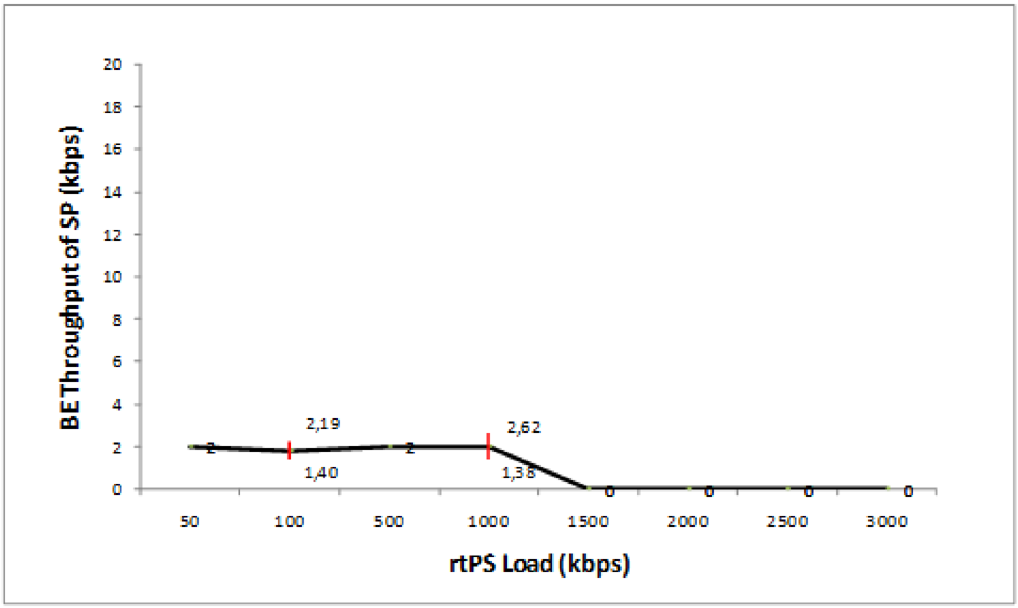

Figure A.9 : Confidence interval of SP BE throughput.

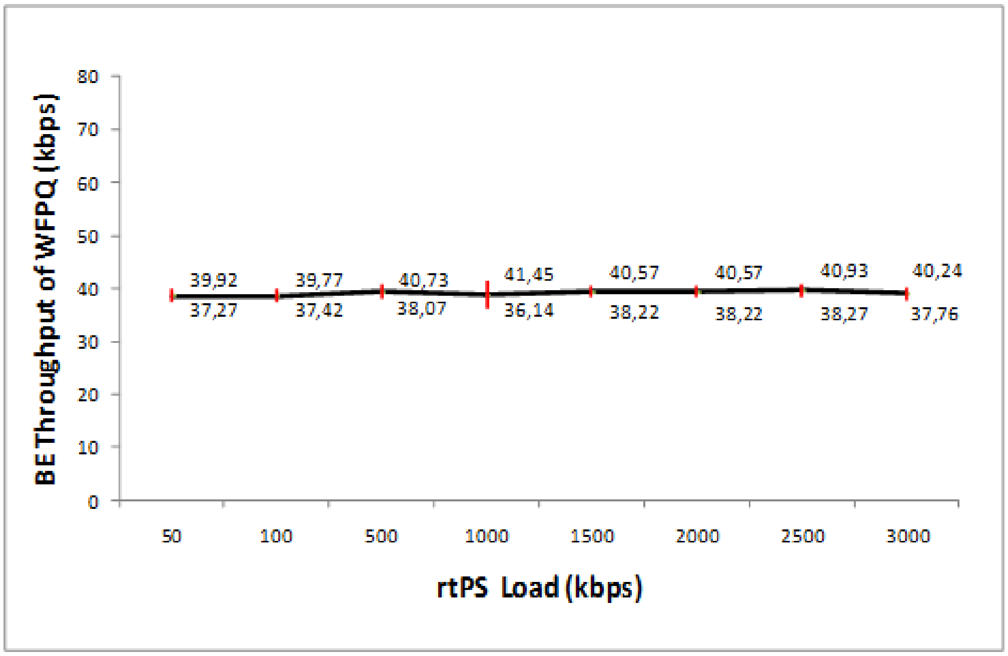

Figure A.10 : Confidence interval of WFPQ BE throughput.

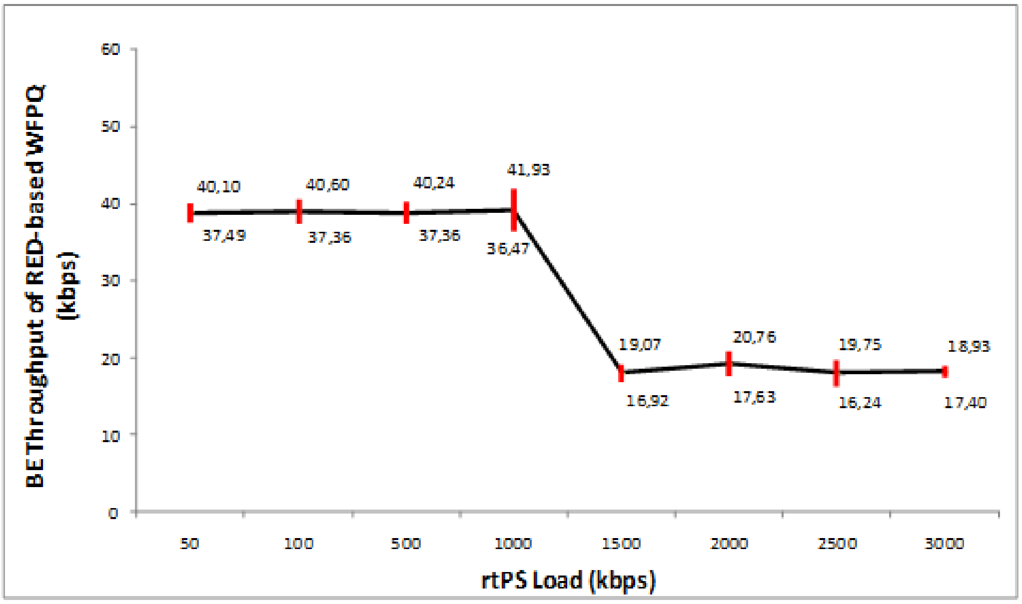

Figure A.11 : Confidence interval of RED-based WFPQ BE throughput.

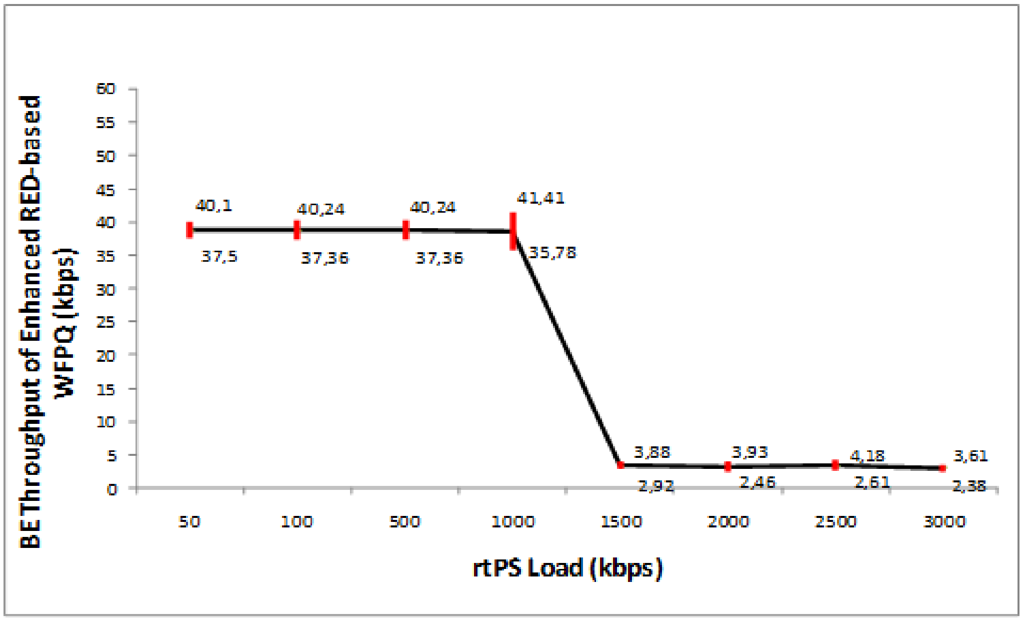

Figure A.12 : Confidence interval of Enh. RED-based WFPQ BE throughput.

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