İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF INFORMATICS

A HIERARCHICAL CHANNEL AWARE UPLINK SCHEDULER FOR WIMAX BASE STATIONS

M.Sc. Thesis by
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Programme : Computer Science

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IEEE 802.16 ERİŞİM TERMİNALLERİ İÇİN SIRADÜZENSEL KANAL DUYARLI ÇİZELGELEYİCİ

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FOREWORD

I would like to express my deep appreciation and thanks to my supervisor Prof. Dr. Sema OKTUĞ for her contribution and support.

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ABBREVIATIONS

BE	: Best Effort
BPSK	: Binary Phase Shift Keying
BS	: Base Station
BWA	: Broadband Wireless Access
dB	: Decibel
DFPQ	: Deficit Fair Priority Queuing
DL	: Downlink
FTP	: File Transfer Protocol
Kbps	: Kilobits per second
m	: Meter
MAC	: Medium Access Layer
Mb/s	: Megabits per second
ms	: Millisecond
mSIR	: Maximum Signal-to-Interference Ratio
MHz	: MegaHertz
nrtPS	: Non-real-time Polling Service
OFDM	: Orthogonal Frequency Division Multiplexing
OFDMA	: Orthogonal Frequency Division Multiple Access
PHY	: Physical Layer
PMP	: Point-to-Multiple Point
QAM	: Quadrature Amplitude Modulation
QoS	: Quality of Service
QPSK	: Quadrature Phase Shift Keying
RED	: Random Early Detection
RED_WF-PFmSIR	: RED based Weighted Fair Priority Queuing – Proportional Fair Maximum Signal-to-Interference Ratio
RR	: Round Robin
rtPS	: Real-time Polling Service
s	: Second
SNR	: Signal-to-Noise Ratio
SP-mSIR	: Strict Priority - Maximum Signal-to-Interference Ratio
SP-RR	: Strict Priority – Round Robin
SS	: Subscriber Station
UGS	: Unsolicited Grant Service
UL	: Uplink
VoIP	: Voice over IP
WFPQ	: Weighted Fair Priority Queuing
WiMAX	: Worldwide Interoperability for Microwave Access

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LIST OF SYMBOLS

$\mathbf{BW_i}$: Bandwidth of ith SS
$\mathbf{DC_{dynamic}}$: Dynamic deficit counter
$\mathbf{DC_{min}}$: Minimum deficit counter
$\mathbf{DC_{max}}$: Maximum deficit counter
$\mathbf{QL_{current}}$: Current rtPS queue length
$\mathbf{QL_{thr1}}$: First threshold of rtPS queue length
$\mathbf{QL_{thr2}}$: Second threshold of rtPS queue length
$\mathbf{QL_{rtPS}}$: Queue length of rtPS service class
$\mathbf{SNR_i}$: SNR of ith SS
$\mathbf{W_i}$: Weight of ith SS
$\mathbf{W_{min}}$: Minimum weight
$\mathbf{W_{max}}$: Maximum weight
$\mathbf{W_{rtPS}}$: Weight of rtPS service class

A HIERARCHICAL CHANNEL AWARE UPLINK SCHEDULER FOR WIMAX BASE STATIONS

SUMMARY

There are many kinds of applications with a wide range of Quality of Service (QoS) requirements such as bandwidth and delay: Video and audio streaming, online gaming, video conferencing, Voice over IP (VoIP) and File Transfer Protocol (FTP). Deploying wireless technologies to meet the diverse traffic requirements is expensive in non-urban areas. A feasible alternative for wireless broadband access, supporting a wide range of applications, is Worldwide Interoperability for Microwave Access (WiMAX). The IEEE 802.16 standard defines Medium Access Control (MAC) and physical layer (PHY) protocols for broadband wireless access; however it does not specify any scheduling algorithm. Scheduling is a critical part of the MAC layer specification, which resolves contentions for bandwidth and determines the transmission order of the subscribers. Therefore, an effective scheduling is critical for the WiMAX system. Many traffic-scheduling algorithms are proposed for WiMAX networks, such as Round Robin (RR) and maximum Signal to Interference Ratio (mSIR). Some of these schedulers cannot utilize the bandwidth, some of them cannot differentiate services.

This thesis proposes a hierarchical channel aware uplink scheduler for WiMAX base stations, which not only utilizes the available bandwidth by considering Signal to Noise (SNR) variations, but also provides differentiated services among the various traffic classes based on the QoS requirements. A Random Early Detection (RED) based Weighted Fair Priority Queuing (WFPQ) algorithm for inter-class scheduling and a channel aware algorithm for intra-class scheduling are proposed. Weights of the service classes are adaptive according to the QoS requirements of each service class. Weights of the subscriber stations are assigned based on their channel quality and bandwidth requests. The proposed scheduler is implemented on ns-2. Simulation results show that overall system throughput is improved without starving lower priority service classes.

IEEE 802.16 ERİŞİM TERMİNALLERİ İÇİN SIRADÜZENSEL KANAL DUYARLI ÇİZELGELEYİCİ

ÖZET

Bantgenişliği ve gecikme gibi farklı Hizmet Nitelikleri (QoS) gerektiren birçok uygulama vardır: Video ve ses akışı, çevrimiçi oyunlar, video konferans, IP tabanlı ses (VoIP), dosya gönderim protokolü (FTP), bu uygulamalardan bazılarıdır. Çeşitli trafik gereksinimlerini karşılayacak telsiz teknolojileri kırsal alanlarda konuşlandırmanın maliyeti yüksektir. Birçok uygulamayı destekleyen WiMAX (Worldwide Interoperability for Microwave Access), genişbant telsiz erişim için uygulanabilir bir alternatif oluşturmaktadır. IEEE 802.16 standardı, genişbant telsiz erişim için, ortam erişim (MAC) ve fiziksel (PHY) katmanlar için kullanılacak protokolleri belirlemiş olmakla birlikte, çizelgeleme için standart bir algoritma belirtmemektedir. Çizelgeleme, bantgenişliği çekişmelerini çözme ve abonelerin iletim sıralarını belirleme gibi görevlerle ortam erişim katmanının önemli bir bölümünü oluşturmaktadır. Bu nedenle, etkili bir çizelgeleme algoritması WiMAX sistemi açısından kritik önem taşımaktadır. WiMAX için, RR (Round Robin) ve mSIR(maximum Signal to Interference Ratio) gibi birçok trafik çizelgeleme algoritması önerilmiştir. Bu çizelgeleyicilerin bazıları bantgenişliğini etkin olarak kullanamazken bazıları da hizmetleri farklılaştıramamaktadır.

Bu tez, IEEE 802.16 erişim terminalleri için, hem SNR (Signal to Noise) değişikliklerini dikkate alarak bantgenişliğini etkin kullanımını sağlayan, hem de hizmet niteliği (QoS) gereksinimlerine dayalı olarak farklı trafik sınıfları için farklılaştırırılmış hizmet sağlayan, sıradüzensel kanal duyarlı bir çizelgeleyici önermektedir. Hizmet sınıfları arası çizelgeleme için RED (Random Early Detection) tabanlı bir Ağırlıklı Adil Öncelikli Kuyruklama (WFPQ) algoritması önerilirken, sınıf içi çizelgeleme için kanal duyarlı bir çizelgeleyici önerilmiştir. Hizmet sınıflarının ağırlıkları her hizmet sınıfının Hizmet Niteliği (QoS) gereksinimlerine dayalı olarak değişmektedir. Abonelerin ağırlıkları ise kanal niteliği ve bantgenişliği isteklerine göre belirlenmektedir. Önerilen çizelgeleyici ns-2 ile gerçeklenmiştir. Simülasyon sonuçları, sistemde iletilen toplam veri miktarının, daha düşük öncelikli hizmet sınıflarının bantgenişliği yokedilmeden, arttığını göstermektedir.

1. INTRODUCTION

In the last few years, Worldwide Interoperability for Microwave Access (WiMAX) has been proposed as alternative to traditional wireline technologies such as coaxial cable networks and digital subscriber line (DSL) based on PSTN access networks. WiMAX is a promising wireless communication technology due to the fact that it can provide high speed data communications over long distances and can support different qualities of services in Metropolitan Area Networks (MANs).

WiMAX is an IEEE standard for wireless broadband access networks [1]. Two basic operational modes are defined for MAC layer: mesh mode and Point to Multiple point (PMP) mode. In mesh mode, Subscriber Stations (SSs) communicate directly each other. In PMP mode, SSs communicate only over a Base Station (BS).

Transmission from SS to BS is performed on UpLink (UL) channel and transmission from BS to SS is performed on DownLink (DL) channel. Both UL and DL channels are divided into sequences of frames. The frame structures for OFDM (Orthogonal Frequency Division Multiplexing) and OFDMA (Orthogonal Frequency Division Multiple Access) are described in the standard. In OFDM frame structure, each frame is also divided into an integer number of time slots.

In IEEE 802.16 [1], four service classes are supported according to QoS requirements. These are Unsolicited Grant Service (UGS), real time Polling Service (rtPS), non-real time Polling Service (nrtPS), and Best Effort (BE). They will be covered in detail, in the following chapters.

Modulation and Coding Schemes (MCS) are adaptive based on Signal to Noise Ratio (SNR). SNR of the receiver is transferred to the BS via MAC management messages.

1.1 Purpose of the Thesis

Scheduling mechanisms for both uplink and downlink channels in IEEE 802.16 standard are open for research [1, 2]. There are some scheduling algorithms proposed for uplink scheduling like Round-Robin (RR) [3], Maximum Signal-to-Interference

Ratio (mSIR) [4] for intra-class scheduling and Strict Priority (SP) [5] and Random Early Detection based Deficit Fair Priority Queuing (RED-based DFPQ) [6] for inter-class scheduling.

In this thesis, a new uplink scheduling algorithm, which handles both inter-class and intra-class scheduling has been proposed. The algorithm uses a RED-based Weighted Fair Priority Queuing technique considering SNR variation. The goal of this work is to improve overall system throughput without starving lower priority service classes.

1.2 Background

Various scheduling algorithms were proposed to improve performance of WiMAX networks. WiMAX schedulers are studied under two classes: Inter-class scheduler, intra-class scheduler.

A strict priority scheme was proposed for allocating bandwidth between service classes [5]. Bandwidth is allocated for rtPS service flows first, the remaining bandwidth is allocated for nrtPS service flows, and finally the remaining bandwidth is allocated for BE service flows. Under heavy rtPS traffic load, it starves the nrtPS and BE service flows. Thus, it does not guarantee the QoS requirements of the traffic from the lower priority service classes.

Chen et al. proposed the deficit fair priority queuing scheduler for bandwidth allocation among the service classes of WiMAX networks [7]. It determines the deficit quantum values based on the priority of each service class. It is fairer than the strict priority scheduling. However, it uses fixed deficit counter for rtPS service class, which may result in increasing delay.

RED-based Deficit Fair Priority Queuing is proposed for SS uplink scheduler in [6]. The deficit counter for rtPS service class is calculated in the beginning of every frame based on RED [8]. It uses packet size information of each packet in the rtPS queue of the SS. Therefore, this algorithm is not suitable to be applied to a BS uplink scheduler. Hence, we propose RED-based Weighted Fair Priority Queuing for inter-class scheduling in the BS uplink scheduler.

In [3], Round Robin is applied as an intra-class scheduler into WIMAX networks. The RR is a channel unaware algorithm and it does not take SNR values of the SS into account. SSs can have different SNR values in each frame. So, SSs can use different modulation and coding scheme, i.e. in every frame different SSs may use the bandwidth more effective.

Maximum Signal to Interference (mSIR) Ratio algorithm, which was proposed in [4], sorts the SSs in descending order according to the SNR values and then allocates the bandwidth for each SS in this order. Therefore, it achieves higher throughput, with the cost of starving some SSs and it does not guarantee fairness.

1.3 Structure of the Thesis

The remainder of this thesis is organized as follows. Chapter 2 gives brief information about wireless broadband microwave access networks as described in IEEE 802.16 standard. Chapter 3 presents previously introduced scheduling algorithms for WIMAX. The proposed scheduling algorithm is described in Chapter 4. Simulation results are shown and discussed in Section 5. Section 6 concludes the paper by giving future directions.

2. WORLDWIDE INTEROPERABILITY MICROWAVE ACCESS

2.1 Overview of IEEE 802.16 Standard

WIMAX is an IEEE standard for broadband wireless access networks [1]. Range of the BWA networks are much greater than WLAN WiFi's. There are two variants of IEEE 802.16 BWA: IEEE 802.16-2004, which defines a fixed wireless access WMAN technology, and IEEE 802.16e [2], which is an improvement on 802.16-2004 approved in December 2005. It included mobility and then fast handover, then becoming a Wireless WAN. 802.16e is not a standalone document. Only some changes and additions to the 802.16-2004, are proposed. It was reported that the IEEE intention was to have a unique document resulting from 16-2004 and 16e fusion, called 802.16-2005. Figure 2.1 shows the standard history for 802.16 [9].

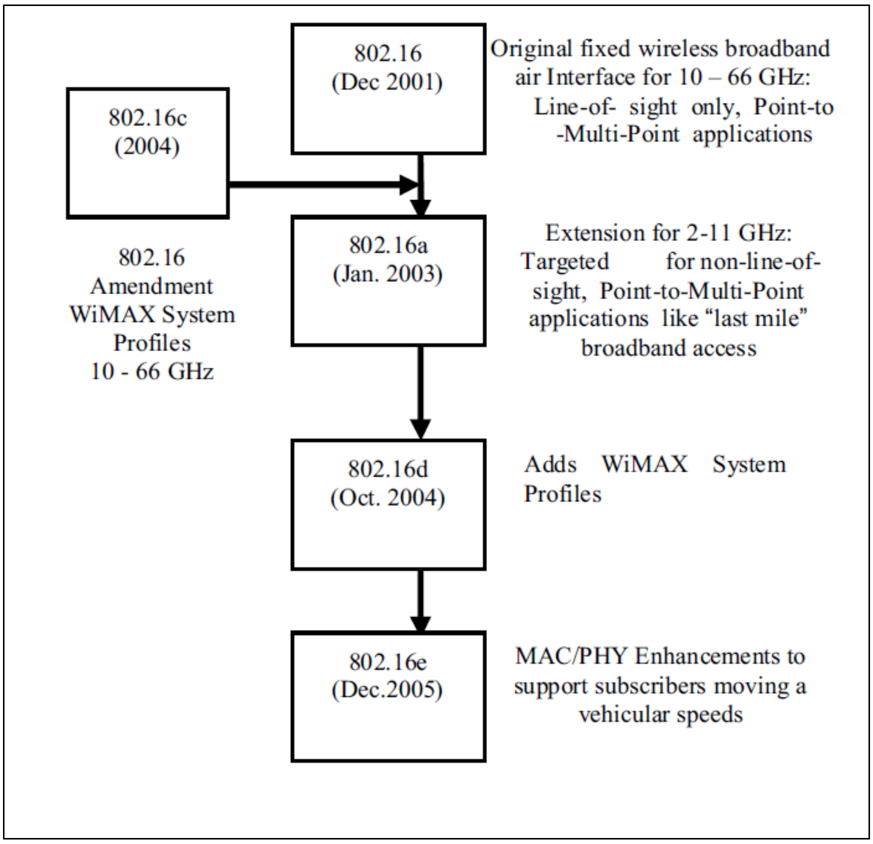

Figure 2.1 : IEEE 802.16 Standard Evolution

The first application of BWA is fixed-position high data rate access. This access can then evidently be used for Internet, TV and other expected high data rate applications such as Video-on-Demand (VoD). It will also surely be used for other applications that are not really apparent yet. In one word, the first target of BWA is to be a wireless DSL (Digital Subscriber Line, originally called the Digital Subscriber Loop) or also a wireless alternative for the cable. Some business analysts consider that this type of BWA application is interesting only in countries and regions having relatively underdeveloped telecommunications infrastructure. Indeed, using WiMAX for the fixed-position wireless Internet in Paris or New York does not seem economically viable.

Another possible use of high data rate access with BWA is WiFi Backhauling. As shown in Figure 2.2[10], the Internet so-called backbone is linked to a BS which may be in Line-of-Sight (LOS) of another BS. This has a Non-Line-of-Sight (NLOS) coverage of Subscriber Stations (SSs).

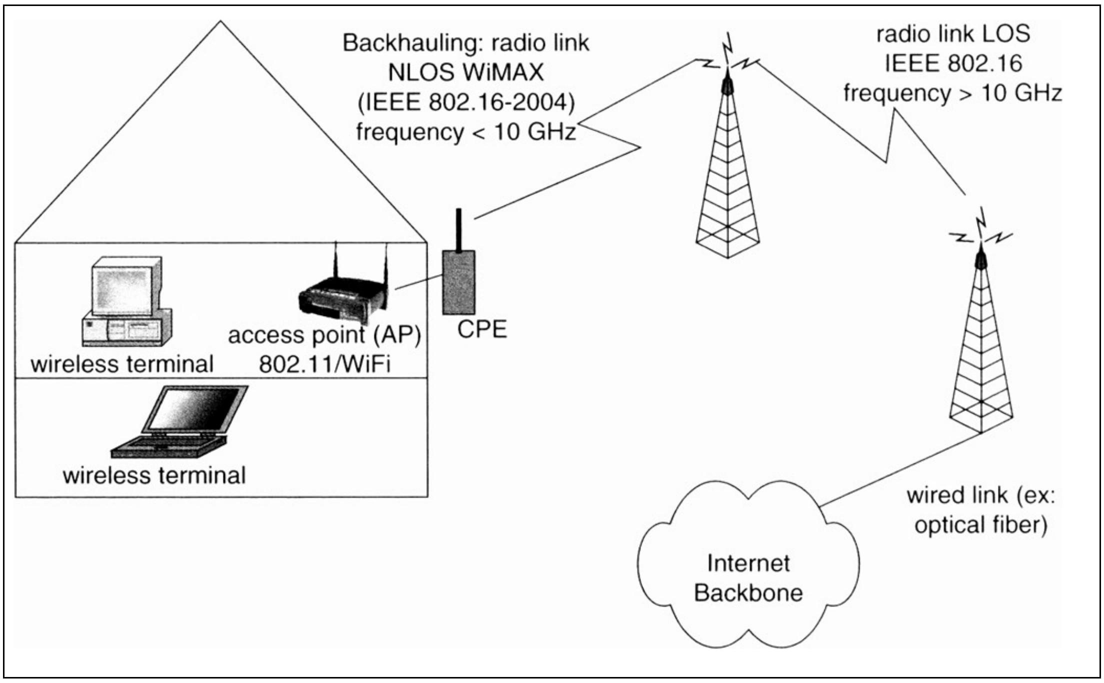

Figure 2.2 : Boadband Wireless Access (BWA) applications with a fixed access

Two basic operational modes are defined for MAC layer: mesh mode and Point to Multiple point (PMP) mode. In mesh mode, Subscriber Stations (SSs) communicate directly each other as illustrated in Figure 2.3 [11]. In PMP mode, SSs communicate only over a Base Station (BS) as illustrated in Figure 2.4 [12].

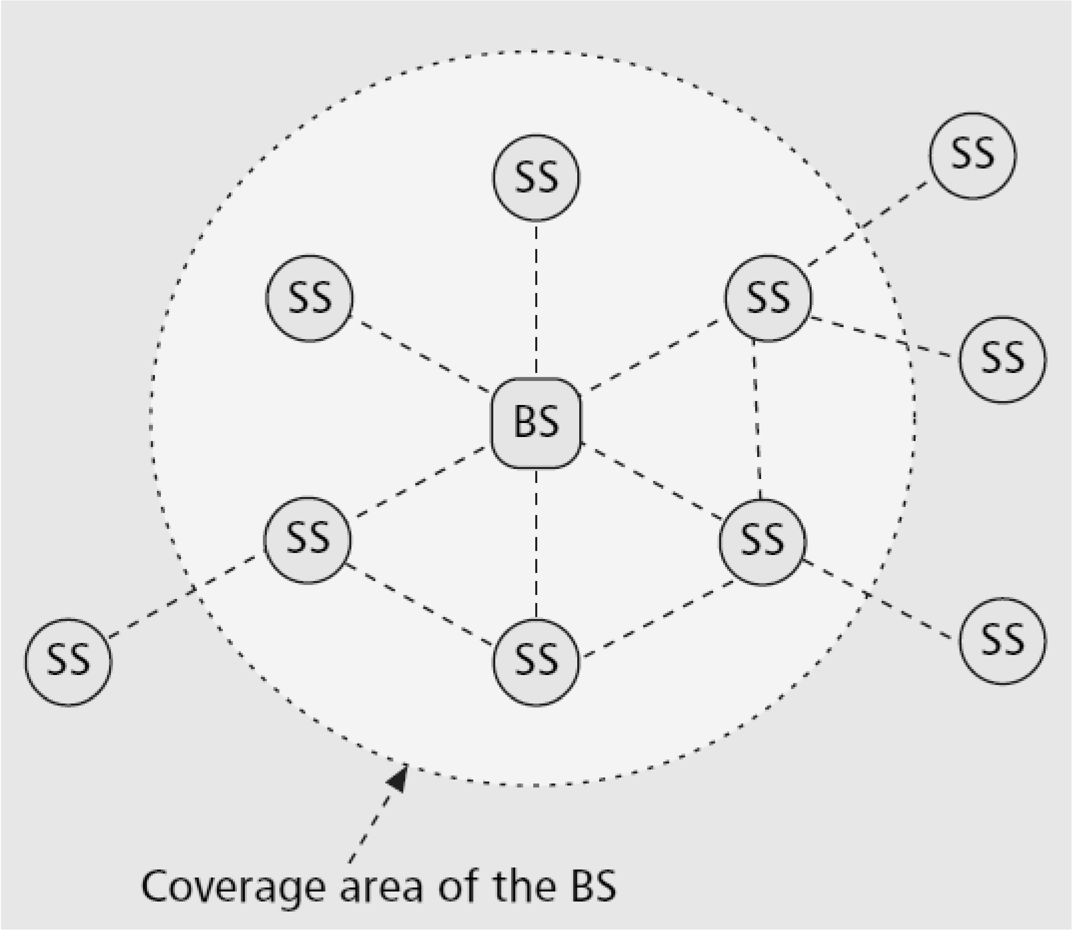

Figure 2.3 : WiMAX Mesh Topology (Mesh Mode)

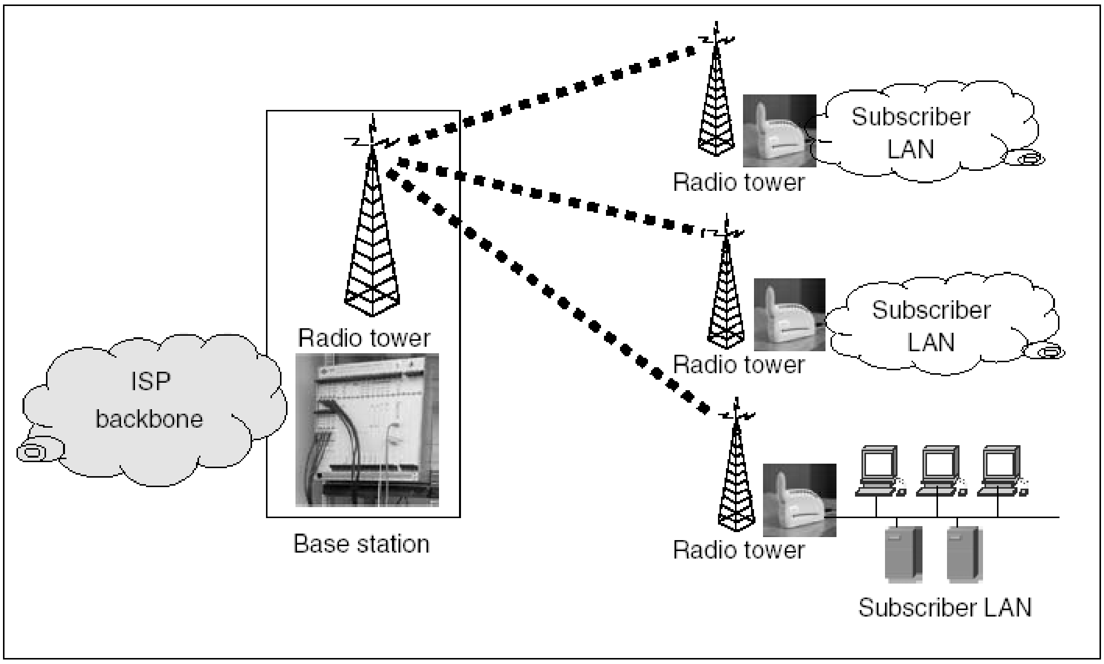

Figure 2.4 : WiMAX PMP Topology (PMP Mode)

Transmission from SS to BS is performed on UpLink (UL) channel and transmission from BS to SS is performed on DownLink (DL) channel. Both UL and DL channels are divided into sequences of frames. The frame structures for OFDM (Orthogonal Frequency Division Multiplexing) and OFDMA (Orthogonal Frequency Division Multiple Access) are described in the standard.

2.2 PHY Layer in IEEE 802.16

2.2.1 Broadband Wireless Access Background

There are several frequency bands for the 802.16 products. In IEEE 802.16a-2001, all of the available frequency over the world, is addressed from 10 to 66 GHz. As the frequency is high, Line-of-Sight (LOS) propagation is a necessity. Roof tops may be too low for a clear sight line to a BS in a local application. Multipath propagation affection must be considered, also. The need for non-LOS (NLOS) operations has led to the design of the 2-11 GHz PHY. There are three different air interfaces, which can be used to provide a reliable end-to-end link:

- SCa : A single-carrier modulated air interface.
- OFDM : A 256-carrier orthogonal-frequency division multiplexing (OFDM). Multiple access of different SSs is time-division multiple access (TDMA)-based.
- OFDMA : A 2048-carrier OFDM scheme. However, a subset of the carriers can be assigned to an individual user. It is referred to be OFD multiple accesses.

Among these three air interfaces, the two OFDM-based systems are more suitable for NLOS due to the simplicity of the equalization process for multicarrier signals [13].

In this thesis, OFDM with TDD is considered as the access interface in the following chapters. An example of the OFDM frame structure with TDD mode is illustrated in Figure 2.5 [14].

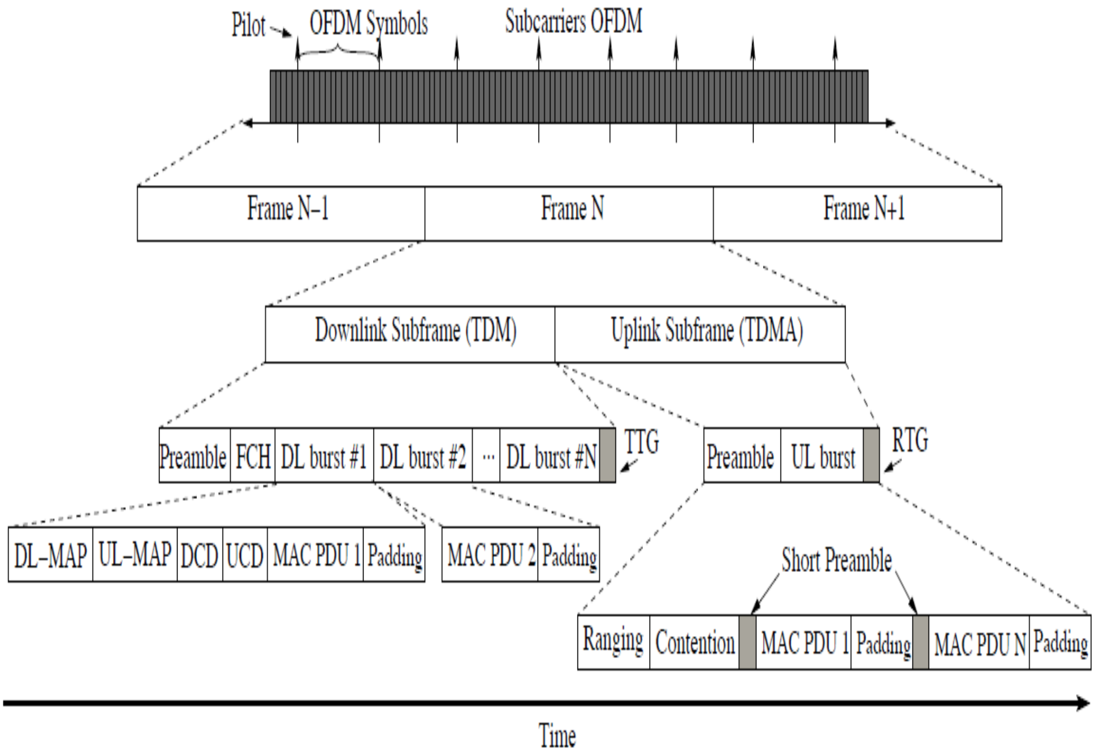

Figure 2.5 : Example of OFDM Frame structure with TDD

2.2.2 Adaptive Modulation and Coding (AMC)

The following seven modulation and coding schemes (MCS) can be used in the 802.16 networks: Binary Phase Shift Keying (BPSK) ½, Quadrature Phase Shift Keying (QPSK) ½, QPSK ¾, 16-Quadrature Amplitude Modulation (QAM) ½, 16-Quadrature Amplitude Modulation (QAM) ¾, 64-QAM ½, 64-QAM ¾ .

Modulation and coding schemes are used adaptively based on Signal to Noise Ratio (SNR). If the radio link is good, a high-level modulation is used, and if the radio link is bad, a low-level but robust modulation is used. SNR of the receiver is transferred to the BS via MAC management messages. The modulation and schemes defined in IEEE 802.16e standards are shown in Table 2.1 [2].

Table 2.1: Modulation and coding schemes in IEEE 802.16e

Modulation	Coding Rate	SNR (dB)
BPSK	1/2	3.0
QPSK	1/2	6.0
QPSK	3/4	8.5
16-QAM	1/2	11.5
16-QAM	3/4	15.0
64-QAM	2/3	19.0
64-QAM	3/4	21.0

Data rates that can be achieved based on the modulation and coding schemes are shown in Table 2.2 [1].

Table 2.2: OFDM Physical data rates in Mb/s

G ratio	BPSK 1/2	QPSK 1/2	QPSK 3/4	16-QAM 1/2	16-QAM 3/4	64-QAM 2/3	64-QAM 3/4
1/32	2.92	5.82	8.73	11.64	17.45	23.27	26.18
1/16	2.82	5.65	8.47	11.29	16.94	22.59	25.41
1/8	2.67	5.33	8.00	10.67	16.00	21.33	24.00
1/4	2.40	4.80	7.20	9.60	14.40	19.20	21.60

2.3 MAC Layer in IEEE 802.16

The IEEE 802.16 standard specifies the air interface of a fixed BWA system supporting multimedia services. The Medium Access Control (MAC) Layer supports a primarily point to-multipoint (PMP) architecture, with an optional mesh topology.

The MAC Layer is structured to support many physical layers (PHY) specified in the same standard. In fact, only two of them are used in WiMAX.

The protocol layers architecture defined in WiMAX/802.16 is shown in Figure 2.6 [1]. It can be seen that the 802.16 standard defines only the two lowest layers, the PHYsical Layer and the MAC Layer, which is the main part of the Data Link Layer, with the Logical Link Control (LLC) layer very often applying the IEEE 802.2 standard. The MAC layer is itself made of three sublayers, the CS (Convergence Sublayer), the CPS (Common Part Sublayer) and the Security Sublayer.

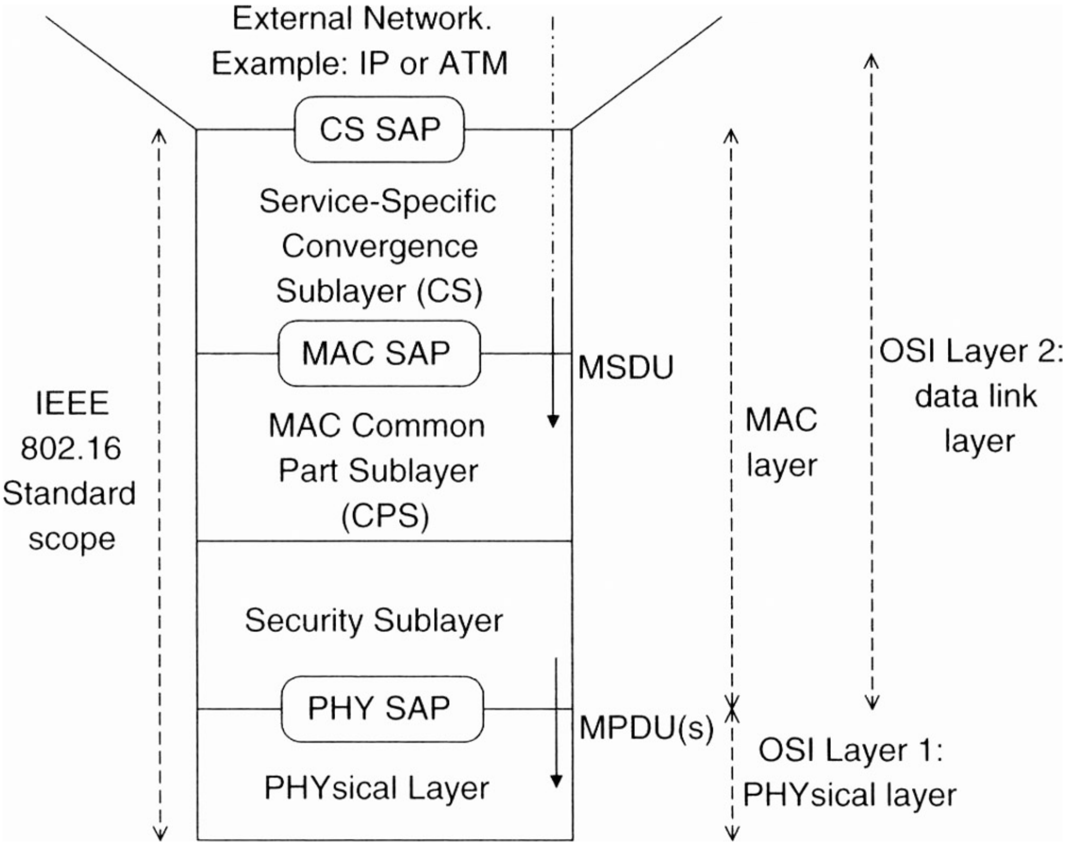

Figure 2.6 : Protocol layers of the 802.16 BWA standard

2.3.1 Convergence Sublayer

The service-specific Convergence Sublayer (CS), often simply known as the CS, is just above the MAC CPS sublayer. The CS uses the services provided by the MAC CPS, via the MAC Service Access Point (SAP). The CS performs the following functions:

- Accepting higher-layer PDUs from the higher layers.
- Classifying and mapping the MSDUs into appropriate CIDs (Connection IDentifier). This is a basic function of the Quality of Service (QoS) management mechanism of 802.16 BWA.
- Processing (if required) the higher-layer PDUs based on the classification.
- An optional function of the CS is PHS (Payload Header Suppression), the process of suppressing repetitive parts of payload headers at the sender and restoring these headers at the receiver.

- Delivering CS PDUs to the appropriate MAC SAP and receiving CS PDUs from the peer entity.

The CS provides any transformation or mapping of external network data received through the CS Service Access Point (SAP) into MAC SDUs received by the MAC Common Part Sublayer (CPS) through the MAC SAP. This includes classifying external network Service Data Units (SDUs) and associating them with the proper MAC Service Flow Identifier (SFID) and Connection Identifier (CID). Classification and mapping are then based on two 802.16 MAC layer fundamental concepts: Connection and Service Flow, as shown in Figure 2.7 [10].

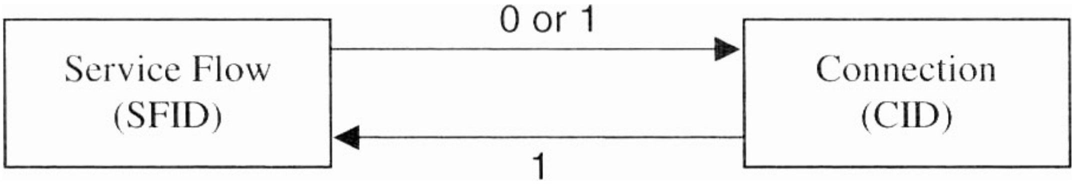

Figure 2.7 : Correspondence between the CID and SFID

The definitions of connection and service flow in the 802.16 standard allow different classes of QoS to be found easily for a given element (SS or BS), with different levels of activation. Figure 2.8 illustrates the connection and service flow concept [10].

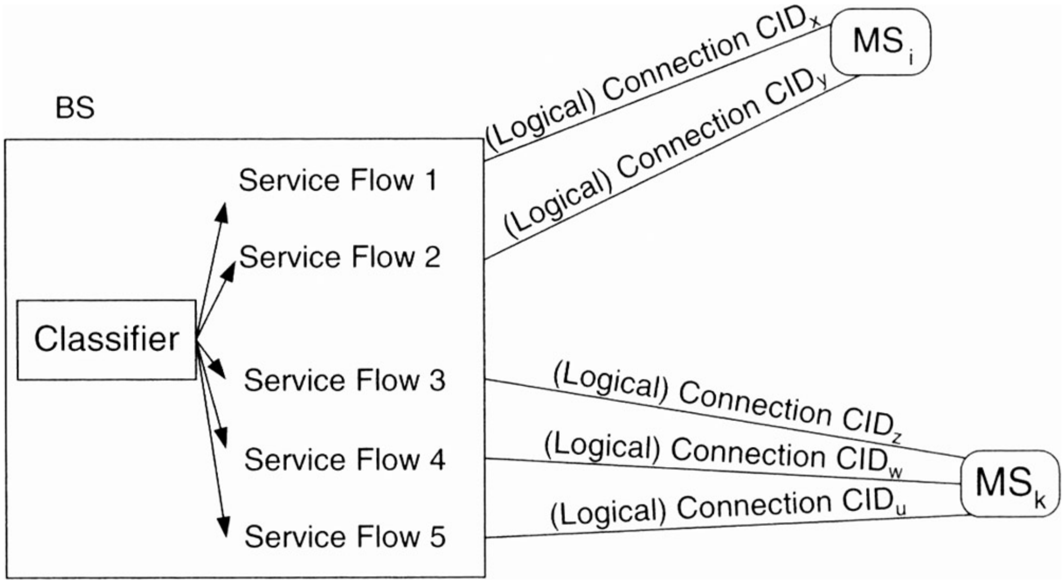

Figure 2.8 : Service flows and connections

2.3.1.1 Connection

A connection is a MAC Level connection between a BS and an SS (or MS) or inversely. It is a unidirectional mapping between a BS and an SS MAC peers for the purpose of transporting a service flow's traffic. A connection is only for one type of service (e.g. voice and email cannot be on the same MAC connection). A connection is identified by a CID (Connection IDentifier), an information coded on 16 bits.

2.3.1.2 Service flow

A Service Flow (SF) is a MAC transport service that provides unidirectional transport of packets on the uplink or on the downlink. A service flow is identified by a 32-bit SFID (Service Flow IDentifier). The service flow defines the QoS parameters for the packets (PDUs) that are exchanged on the connection.

The standard has defined three types of service flow:

- Provisioned service flows. This type of service flow is known via provisioning by, for example, the network management system. Its AdmittedQoSParamSet and ActiveQoSParamSet are both null.
- Admitted service flow. The standard supports a two-phase activation model that is often used in telephony applications. In the two-phase activation model, the resources for a call are first ‘admitted’ and then, once the end-to-end negotiation is completed, the resources are ‘activated’.
- Active service flow. This type of service flow has resources committed by the BS for its ActiveQoSParamSet. Its ActiveQoSParamSet is non-null.

Service flows are sketched in Figure 2.9 [1].

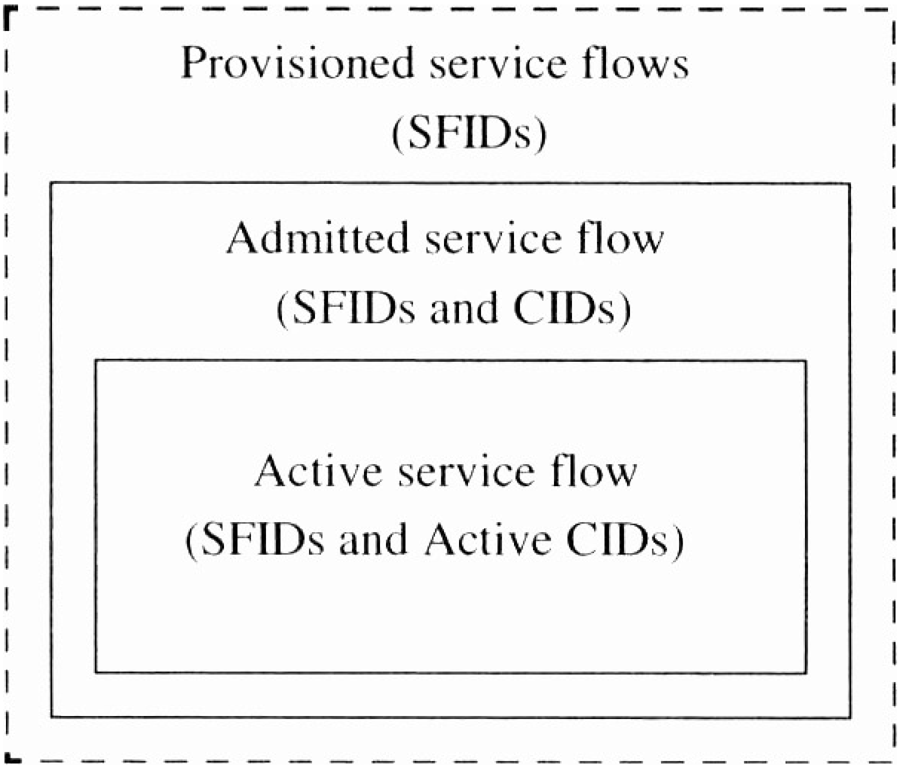

Figure 2.9 : Model structure of the service flow types

2.3.2 Control Common Part Sublayer

The Common Part Sublayer (CPS) resides in the middle of the MAC layer. The CPS represents the core of the MAC protocol and is responsible for: bandwidth allocation; connection establishment; maintenance of the connection between the two sides.

The 802.16-2004 standard defines a set of management and transfer messages. The management messages are exchanged between the SS and the BS before and during the establishment of the connection. When the connection is realised, the transfer messages can be exchanged to allow the data transmission.

The CPS receives data from the various CSs, through the MAC SAP, classified to particular MAC connections. The QoS is taken into account for the transmission and scheduling of data over the PHY Layer. The CPS includes many procedures of different types: frame construction, multiple access, bandwidth demands and allocation, scheduling, radio resource management, QoS management, etc.

2.3.3 Security Sublayer

The MAC Sublayer also contains a separate Security Sublayer providing authentication, secure key exchange, encryption and integrity control across the BWA system. The two main topics of a data network security are data encryption and authentication. Algorithms realising these objectives should prevent all known security attacks whose objectives may be denial of service, theft of service, etc.

In the 802.16 standard, encrypting connections between the SS and the BS is made with a data encryption protocol applied for both ways. This protocol defines a set of supported cryptographic suites, i.e. pairings of data encryption and authentication algorithms. An encapsulation protocol is used for encrypting data packets across the BWA. This protocol defines a set of supported cryptographic suites, i.e. pairings of data encryption and authentication algorithms. The rules for applying those algorithms to an MAC PDU payload are also given.

2.4 Scheduling Services in IEEE 802.16

In IEEE 802.16, four service classes are supported according to QoS requirements. These are Unsolicited Grant Service (UGS), real time Polling Service (rtPS), non-real time Polling Service (nrtPS), and Best Effort (BE). Table 2.3 gives an overview of QoS parameters for these services [10].

In the 802.16e standard [2], a new service flow called extended real time Polling Service (ertPS) has been added. However, it is out of the scope of this thesis.

Table 2.3: Mandatory QoS parameters of the scheduling services defined in IEEE 802.16-2004

Scheduling Service	Maximum Sustained Traffic Rate	Minimum Reserved Traffic Rate	Request/ Transmission Policy	Tolerated Jitter	Maximum Latency	Traffic Priority
UGS	•	(Can be present)	•	•	•	
rtPS	•	•	•		•	
nrtPS	•	•	•			•
BE	•		•			•

UGS is designed to support real time applications with fixed-sized periodic packets such as T1/E1 and VoIP. BS provides grants for this type in unsolicited manner. Figure 2.10 shows UGS uplink scheduling mechanism [10].

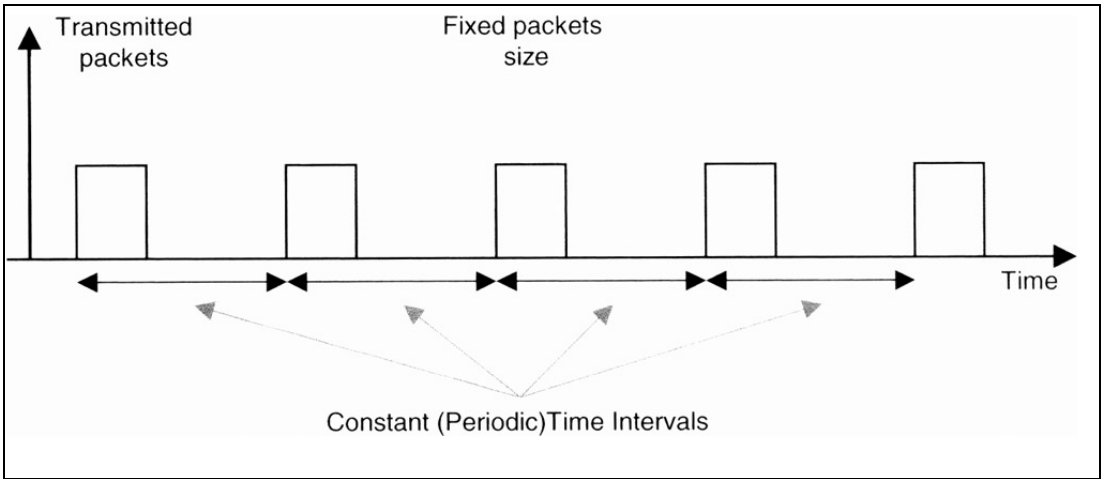

Figure 2.10 : UGS scheduling service uplink grants allocation mechanism

rtPS is designed to support real time variable-sized packets, such as Moving Pictures Expert Group (MPEG) video. Bandwidth request for this type data is received via unicast request opportunities. rtPS packets and intervals are graphed in Figure 2.11 [10].

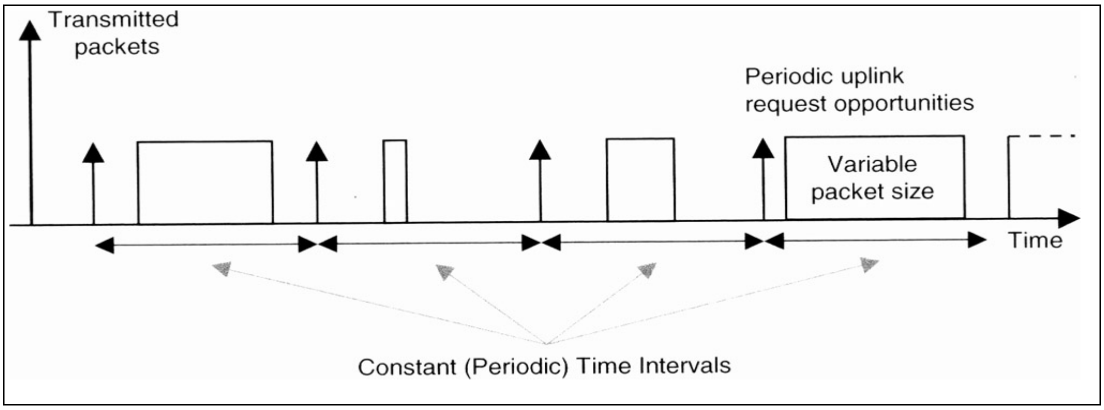

Figure 2.11 : rtPS scheduling service uplink grants allocation and request mechanism

nrtPS is designed to support applications without any specific delay requirement, but requiring a minimum amount of bandwidth, such as File Transfer Protocol (FTP). SS can use contention request opportunities to send bandwidth request for nrtPS data. nrtPS packets and intervals are graphed in Figure 2.12 [10].

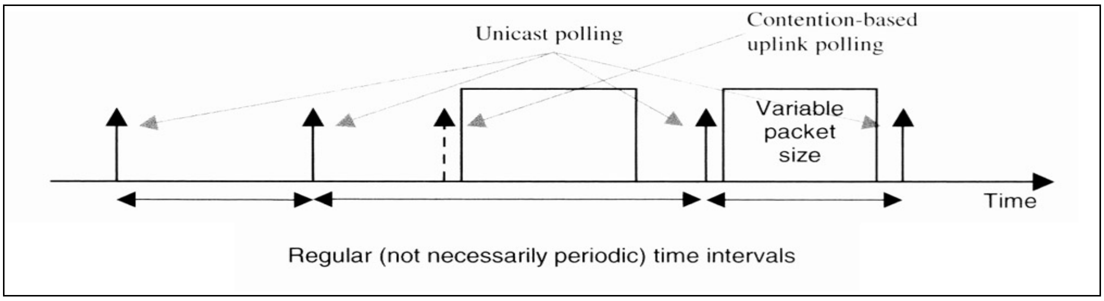

Figure 2.12 : nrtPS scheduling service uplink grants allocation and request mechanism

BE is designed for best-effort traffic such as HTTP. SS uses contention request opportunities to send bandwidth request for BE data. Figure 2.13 shows BE uplink scheduling mechanism [10].

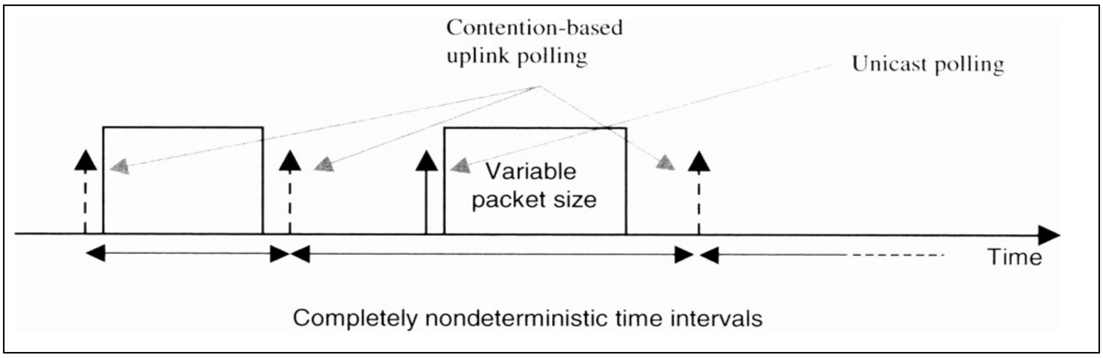

Figure 2.13 : BE scheduling service uplink grants allocation and request mechanism

WiMAX/802.16 uses the PMP centralised MAC architecture where the BS scheduler controls all the radio interface related system parameters. It is the role of the BS scheduler to determine the burst profile and the transmission periods for each connection; the choice of the coding and modulation parameters are decisions that are taken by the BS scheduler according to the quality of the link and the network load and demand. Therefore, the BS scheduler must permanently monitor the received CINR values (of the different links) and then determine the bandwidth requirements of each station taking into consideration the service class for this connection and the quantity of traffic required.

By specifying a scheduling service and its associated QoS parameters, the BS scheduler can anticipate the throughput and latency needs of the uplink traffic. This is a mandatory operation in determining the appropriate burst profile for each connection. The BS may transmit without having to coordinate with other BSs, except possibly for the Time Division Duplexing (TDD) mode, which may divide time into uplink and downlink transmission periods common for different BSs.

Based on the uplink requests and taking into account QoS parameters and scheduling services priorities, the BS scheduler decides for uplink allocations. These decisions are transmitted to the SSs through the UL-MAP MAC management message. Figure 2.14 shows the BS scheduler operation for the uplink and Figure 2.15 shows the BS scheduler operation for the downlink [15].

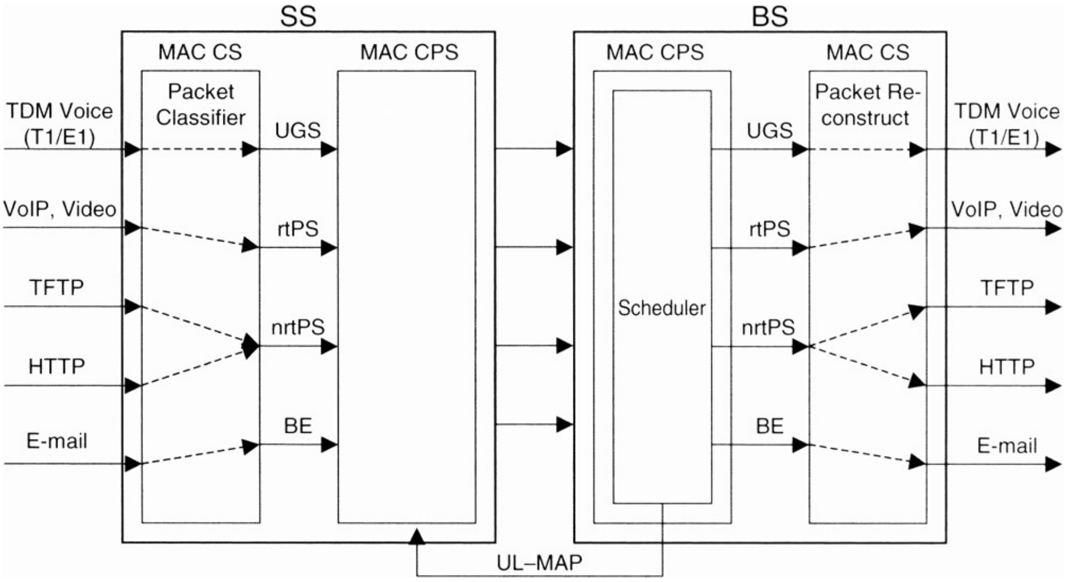

Figure 2.14 : BS scheduler operation for the uplink

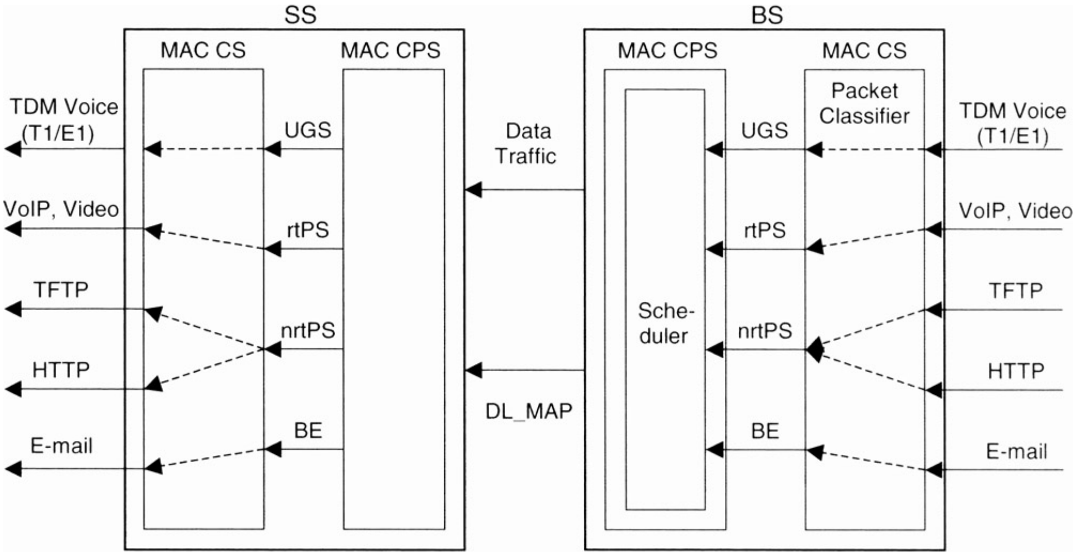

Figure 2.15 : BS scheduler operation for the downlink

3. SCHEDULING ALGORITHMS IN WIMAX

Various scheduling algorithms were proposed to improve performance of WIMAX networks. WIMAX schedulers are studied under two classes: Inter-class scheduler, intra-class scheduler.

3.1 Strict Priority (SP)

A strict priority scheme was proposed for allocating bandwidth between service classes [5]. Bandwidth is allocated for rtPS service flows first, the remaining bandwidth is allocated for nrtPS service flows, and finally the remaining bandwidth is allocated for BE service flows. Under heavy rtPS traffic load, it starves the nrtPS and BE service flows. Thus, it does not guarantee the QoS requirements of the traffic from the lower priority service classes.

3.2 Deficit Fair Priority Queuing (DFPQ)

Chen et al. proposed the deficit fair priority queuing scheduler for bandwidth allocation among the service classes of WIMAX networks [7]. It determines the deficit quantum values based on the priority of each service class. It is fairer than the strict priority scheduling. However, it uses fixed deficit counter for rtPS service class, which may result in increasing delay.

3.3 RED-Based Deficit Fair Priority Queuing

RED-based deficit fair priority queuing is proposed for SS uplink schedulers [6]. It uses Deficit Counters (DCs) for each rtPS, nrtPS, and BE service class. The deficit counter for rtPS service class is adaptive based on RED queuing technique [8] as illustrated in Figure 3.1 [6].

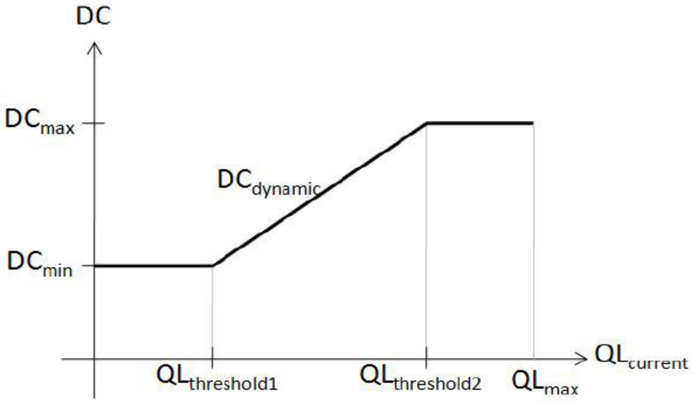

Figure 3.1 : RED-based DC for rtPS service class

The scheduler checks the rtPS queue length in the beginning of every round (corresponding a frame), and it sets the deficit counter for rtPS in every round. 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 the $QL_{current}$ is more than $QL_{threshold1}$ but less than $QL_{threshold2}$, DC will be equal to DCdynamic. The $DC_{dynamic}$ is calculated using Equation (3.1). If the $QL_{current}$ is more than $QL_{threshold2}$, than DC for rtPS is set to DC_{max} which is two times DC_{min}:

$$\begin{aligned} DC_{min} &= Q_{rtPS} \\ DC_{dynamic} &= Q_{rtPS} + \frac{QL_{current} - QL_{thr1}}{QL_{thr2} - QL_{thr1}} Q_{rtPS} \\ DC_{max} &= 2.Q_{rtPS} \end{aligned} \quad \textbf{(3.1)}$$

where Q_{rtPS} is the original fixed quantum of the rtPS service class.

The RED-based DFPQ uses DCs to decide about the number of packets to be transmitted. After transmitting rtPS packets, the scheduler transmits nrtPS packets, and then BE packets.

It uses packet size information in the rtPS queue of an SS. Therefore, this algorithm is not suitable to be used in a BS uplink scheduler in its original form.

3.4 Round Robin (RR)

Round Robin approach is applied as an intra-class scheduler to WIMAX networks [3]. This is a channel unaware algorithm and it does not take SNR values of the SSs into account. SSs can have different SNR values in each frame. So, they can use different modulation and coding schemes, i.e. in every frame some SSs which having higher SNR values can use the bandwidth more effectively.

3.5 Maximum Signal to Interference Ratio (mSIR)

Maximum Signal to Interference Ratio (mSIR) algorithm sorts the SSs in descending order according to the SNR values and then allocates the bandwidth for each SS in this order [4]. Therefore, it achieves higher throughput, with the cost of starving some SSs and it does not guarantee fairness.

4. THE PROPOSED SCHEDULER

In this work, we consider BS-based uplink scheduling. Here, the scheduling problem is examined as two separate sub-problems: inter-class scheduling and intra-class scheduling. We propose a RED-Based Weighted Fair Priority Queuing scheduler which does not require packet size information, instead it uses aggregate bandwidth requests of SSs for the inter-class scheduling. We also propose a long-term proportional fair algorithm based on mSIR for intra-class scheduling.

4.1 Inter-Class Scheduling

In our work, the weights of service classes are determined according to their QoS requirements. Moreover, these values are adaptive based on the rtPS queue length. Weights versus queue lengths are illustrated in Figure 4.1.

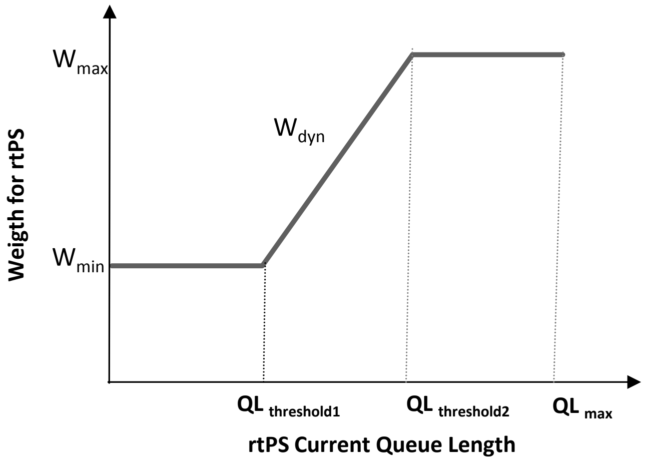

Figure 4.1 : RED-based weights for rtPS service class

If rtPS queue length is less than or equal to QLthreshold1, then the weight of rtPS service class (W_{rtPS}) is set as W_{min}. If rtPS queue length is greater than QLthreshold1 and less than or equal to QLtreshold2, the weight increases linearly between W_{min} and W_{max}. If rtPS queue length is greater than or equal to $QL_{threshold2}$, then it is set as W_{max}. The weight for rtPS service class is calculated as:

$$W_{rtPS} = \begin{cases} W_{\min} & if\ QL_{curr} \leq QL_{thr1} \\ W_{dyn} = W_{\min} + \dfrac{QL_{curr} - QL_{thr1}}{QL_{thr2} - QL_{thr1}} (W_{\max} - W_{\min}) & \\ \qquad if\ QL_{thr1} < QL_{curr} < QL_{thr2} & \\ W_{\max} & if\ QL_{curr} \geq QL_{thr2} \end{cases} \tag{4.1}$$

In WIMAX networks, bandwidth requests are done in two modes: incremental mode and aggregate mode. In the aggregate bandwidth requests, each bandwidth request of an SS represents the instantaneous queue size of the related service class of the SS. In the incremental bandwidth requests, the instantaneous queue size may need to be calculated based on the bandwidth requests. We used aggregate bandwidth requests for our simulations.

The weights are updated at the beginning of every frame according to the instantaneous rtPS bandwidth requests of SSs.

4.2 Intra-Class Scheduling

At the beginning of every frame, weights of the SSs are set based on their bandwidth requests and SNR values. The weights of SSs are calculated as:

$$W_i = \frac{C}{2} \frac{SNR_i}{Total\,SNR} + \frac{C}{2} \frac{BW_i}{Total\,BW} \tag{4.2}$$

where C is the capacity, SNR_i is the SNR of the i^{th} SS, BW_i is the bandwidth request of the ith SS and W_i is the weight calculated for SS_i.

The time slots are allocated to SSs according to their weights. The SNR values of SSs may vary a little in time due to weather conditions or interference [16]. An SS that has greater SNR value can transmit more data in a time slot.

The pseudo code of inter-class and intra-class scheduling of the proposed scheduler is given in Figure 4.2. The complexity of the proposed scheduler is O (N) where N is the number of connections.

Pseudo code of Proposed Inter-class Scheduling:

```
For each uplink sub frame
{
    Calculate Total Aggregate BW Requests & Total SNR of rtPS connections
    Calculate Total Aggregate BW Requests & Total SNR of nrtPS
    connections
    Calculate Total Aggregate BW Requests & Total SNR of BE connections

    //Calculation of Weight for rtPS service class
    If the sum of rtPS BW Request <= threshold1
        Assign Weight for rtPS service class as $W_{min}$
    If the sum of rtPS BW Request > threshold1 &
    the sum of rtPS BW Request < threshold2
        Assign Weight for rtPS service class as $W_{dyn}$
    If the sum of rtPS BW Request >= threshold2
        Assign Weight for rtPS service class as $W_{max}$

    Set $W_{total} = W_{rtPS} + W_{nrtPS} + W_{BE}$

    Schedule $W_{rtPS} / W_{total}$ of time slots for rtPS connections
    Schedule $W_{nrtPS} / W_{total}$ of time slots for nrtPS connections
    Schedule $W_{BE} / W_{total}$ of time slots for BE connections
}
```

Pseudo code of Proposed Intra-class Scheduling:

```
Schedule (A type of connections with $SNR_{total}$, $BW_{total}$)
{
    For each $i^{th}$ SS
    {
        Assign $W_i$ for the SS based on Equation (4.2).
        Allocate $W_i/W_{total}$ of time slots for the SS.
    }
}
```

Figure 4.2 : Pseudo-code of the proposed scheduler

5. SIMULATIONS AND RESULTS

5.1 Network Simulator-2 (NS-2)

Network Simulator-2 (NS-2) is an open source network simulator [17]. It is popular in academic researches in the literature due to its extensibility and open source model. NS is licensed for use under version 2 of the GNU General Public License [18].

5.2 Simulation Environment

The simulations are performed on NS-2 simulator [17]. We used the WIMAX QoS patch which is designed based on NIST WIMAX module [19, 20]. We added nrtPS service class to the patch. The fundamental simulation parameters are shown in Table 5.1.

The simulation topology consists of five UGS, four rtPS, two nrtPS, and two BE subscriber stations. SSs 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. In the simulation scenario, SNR values of the SSs fluctuate ±1dB for the periods of 10 seconds for more realistic environment modeling. We choose these values considering our measurements [21]. We consider these short periods as *short term* and the entire simulation duration as *long term*. Network elements are sketched in Figure 5.1.

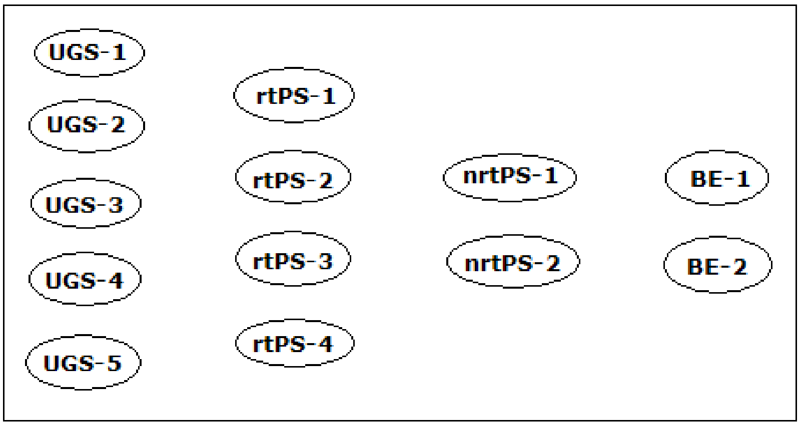

Figure 5.1 : Network elements

Table 5.1 : Simulation parameters

Parameter	Value
PHY specification	WirelessMAN-OFDM
Frequency band	5 MHz
Antenna model	Omni antenna
Antenna height	1.5 m
Propagation model	TwoRayGround
Transmit antenna gain	1
Receive antenna gain	1
System loss factor	1
Transmit power	0.25
Frame duration	20 ms
Cyclic prefix (CP)	0.03125
Simulation duration	100 s
Packet length	1000 bytes
Frame Structure	TDD
SNR of SS rtPS1	21 ±1dB
SNR of SS rtPS2	8 ±1dB
SNR of SS rtPS3	13 ±1dB
SNR of SS rtPS4	24 ±1dB
SNR of SS nrtPS1	20 dB
SNR of SS nrtPS2	25 dB
SNR of SS BE1	20 dB
SNR of SS BE2	25 dB

The scheduler parameters used throughout the simulations are given in Table 5.2.

Table 5.2 : Scheduler parameters

Parameter	Value
W_{min}	10500
W_{max}	1500
W_{nrtPS}	300
W_{BE}	200
QLthreshold1	22% of maximum Queue Length of rtPS connections.
QLthreshold2	90% of maximum Queue Length of rtPS connections.

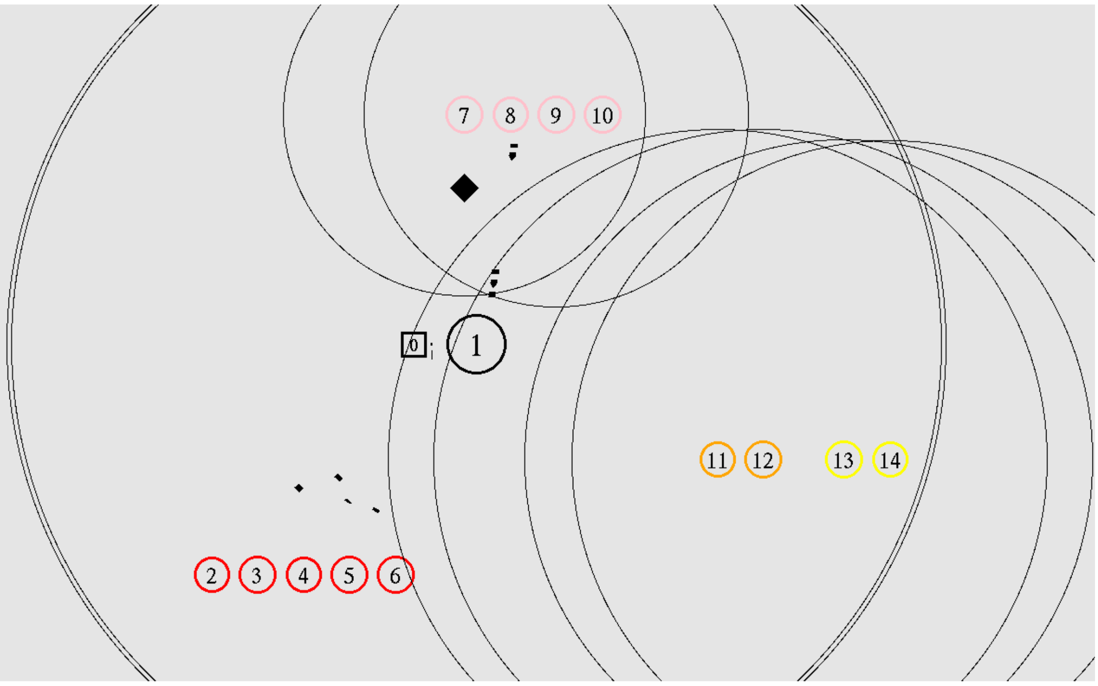

Figure 5.2 : Simulation topology

Figure 5.2 shows the simulation topology. Nodes 2,3,4,5,6 are SSs with UGS traffic load; nodes 7,8,9,10 are SSs with rtPS traffic load; nodes 11, 12 are SSs with BE traffic load, nodes 13, 14 are SSs with nrtPS traffic load. Node 0 is sink node and node 1 is the BS.

5.3 Performance Metrics

We measured throughput of rtPS, nrtPS and BE service class flows. We also calculated queue lengths corresponding to the queuing delays, since we propose an uplink scheduler.

We compared the following schedulers with each other:

- RED-Based Weighted Fair Priority Queuing (inter-class) combined with Proportional Fair mSIR (intra-class), RED_WF-PFmSIR
- Strict Priority (inter-class) combined with RR (intra-class), SP-RR
- Strict Priority (inter-class) combined with mSIR (intra-class), SP-mSIR

We have run each simulation 5 times to achieve results with 95% confidence interval. Simulation results for each scheduler with confidence interval are shown in Appendix A.1 and Appendix A.2.

5.4 Results

We consider the rtPS throughput versus increasing rtPS traffic load in Figure 5.3. SP-RR and SP-mSIR achieves higher throughput than RED_WF-PFmSIR algorithm under heavy rtPS traffic, since they allocate the entire bandwidth for rtPS class and the proposed algorithm allocates bandwidth for nrtPS and BE service classes also. Under lower rtPS traffic, all schedulers produce close rtPS throughputs.

Figure 5.4 shows nrtPS throughput of SP-RR and SP-mSIR schedulers under increasing rtPS traffic approximating to zero. This is due to the intent of the schedulers, allocating the entire bandwidth for rtPS service class. SP-RR and SP-mSIR schedulers starve the nrtPS throughput under heavy rtPS traffic. However, our proposed scheduler has enough nrtPS throughput to support QoS for nrtPS class.

In Figure 5.5, BE throughput of the schedulers is shown under increasing rtPS traffic. SPRR and SP-mSIR schedulers starve the BE connections, too, under heavy rtPS traffic.

Total throughputs of the schedulers are illustrated in Figure 5.6. The proposed scheduler achieves higher throughput than the other two schedulers, as it takes variations in SNR values into account. It allocates more time slots for the SS that has higher SNR value and can transmit more data in a given transmission period.

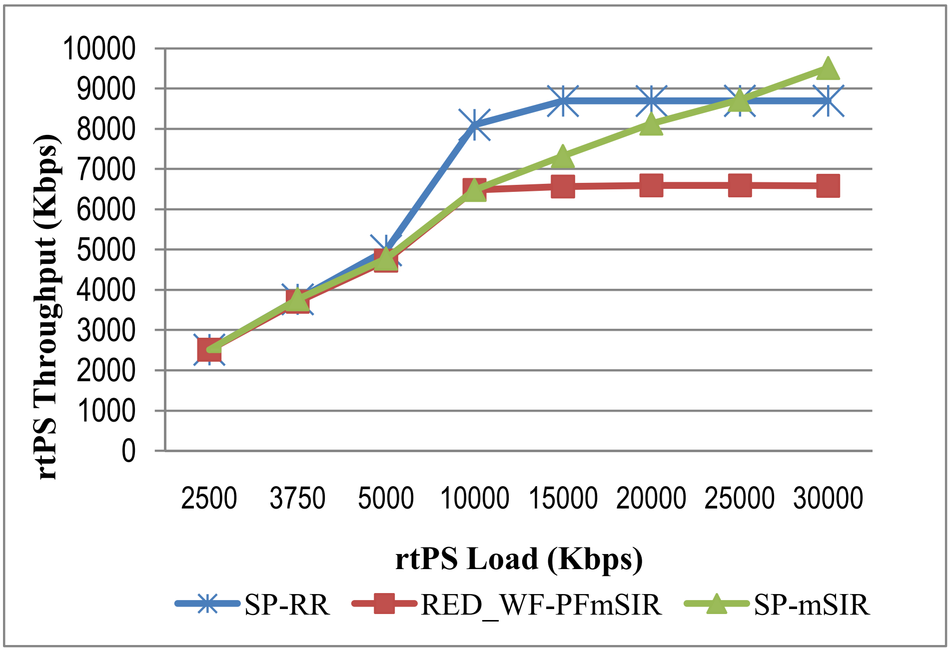

Figure 5.3 : rtPS throughput vs. rtPS load for variable SNR

The average queue length for rtPS service class, achieved by the schedulers, is illustrated in Figure 5.7. In low rtPS traffic, the proposed scheduler produces smaller average queue length than the others. In high rtPS traffic, the queue length achieved by the proposed scheduler is greater, as it does not allocate the bandwidth for rtPS class only, but also for nrtPS and BE classes to prevent starvation.

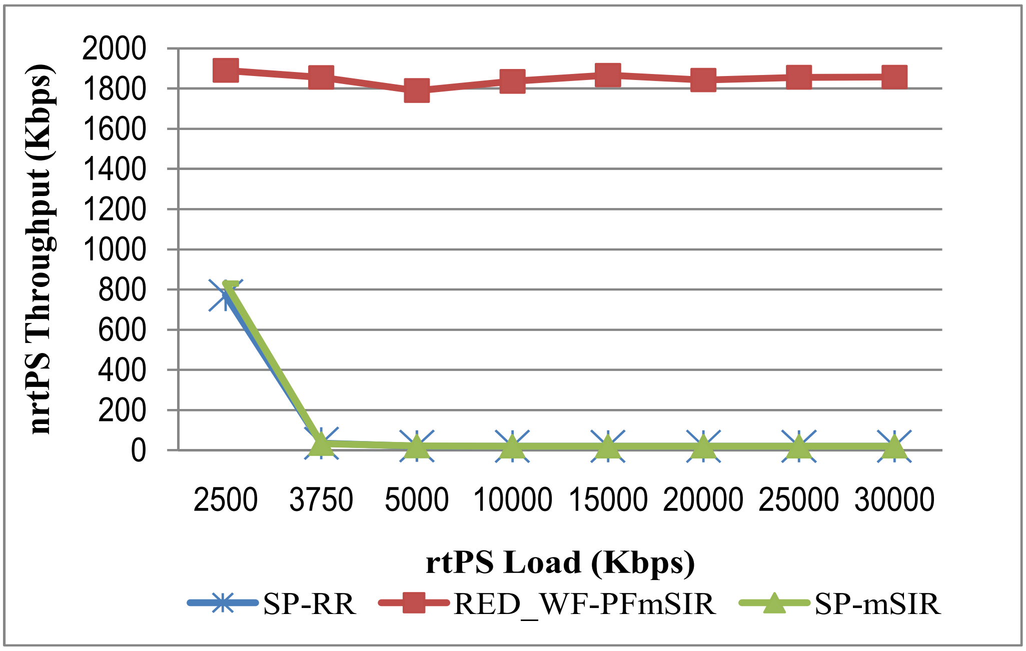

Figure 5.4 : nrtPS throughput vs. rtPS load for variable SNR

The proposed scheduler decreases the nrtPS average queue length. Figure 5.8 shows the average nrtPS queue length for the schedulers. Queue lengths for SPRR and SP-mSIR are high, as they allocate all of the time slots for rtPS service class. Their queue sizes are not maximized due to the TCP congestion avoidance mechanism.

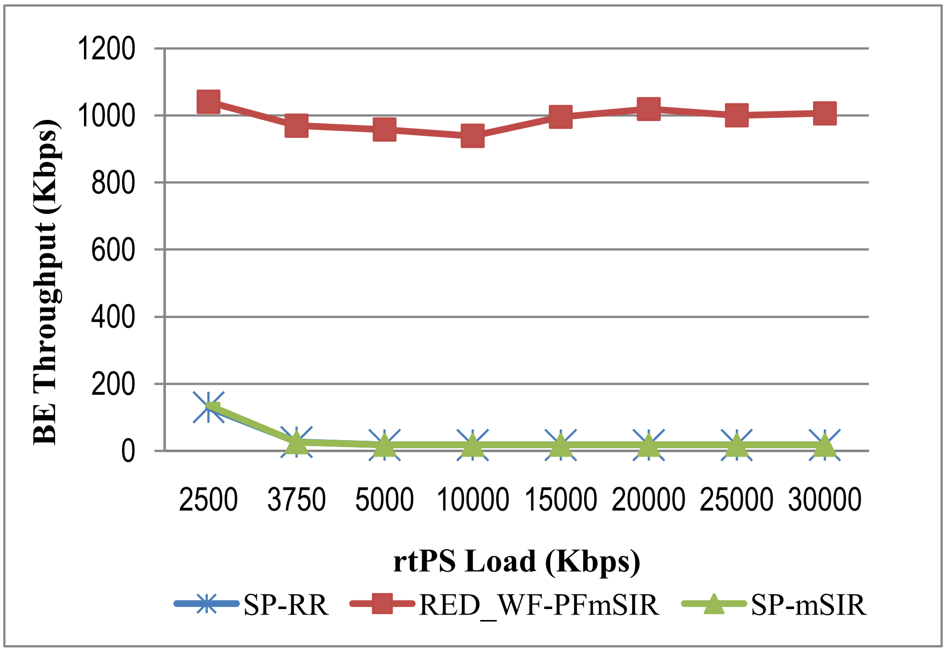

Figure 5.5 : BE throughput vs. rtPS load for variable SNR

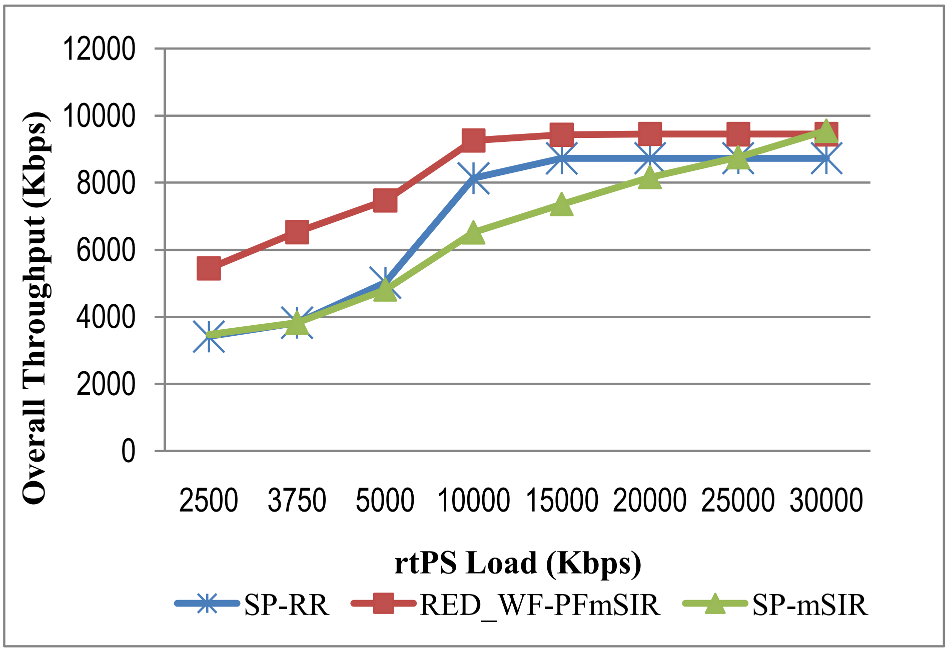

Figure 5.6 : Total throughput vs. rtPS load for variable SNR

Average BE queue lengths for the schedulers are shown in Figure 5.9. Similar to the results obtained for nrtPS service class, SP-RR and SP-mSIR schedulers cause higher queue lengths than the proposed scheduler. Queue length achieved by the proposed scheduler is consistent under increasing rtPS traffic load.

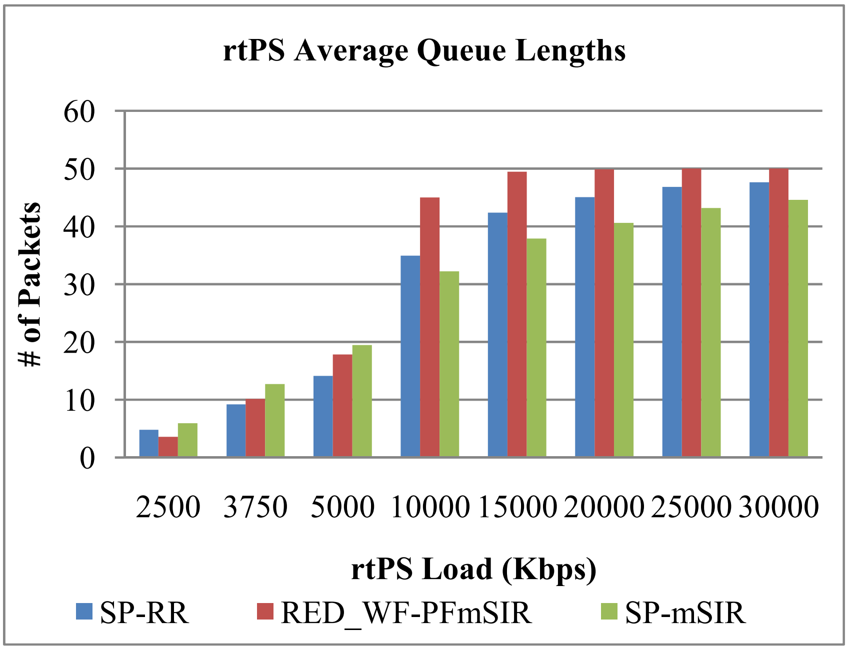

Figure 5.7 : rtPS average queue lengths vs. rtPS load for variable SNR

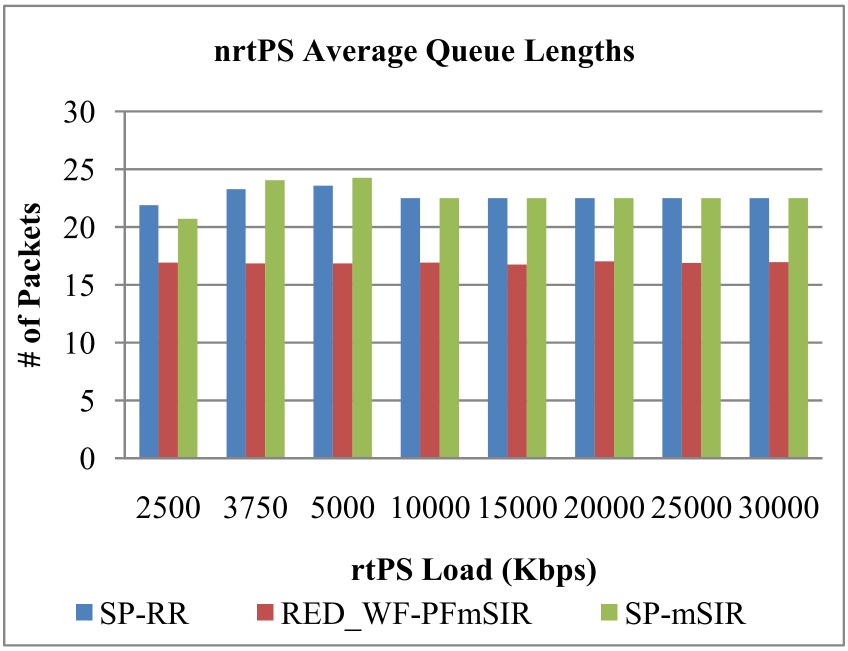

Figure 5.8 : nrtPS average queue lengths vs. rtPS load for variable SNR

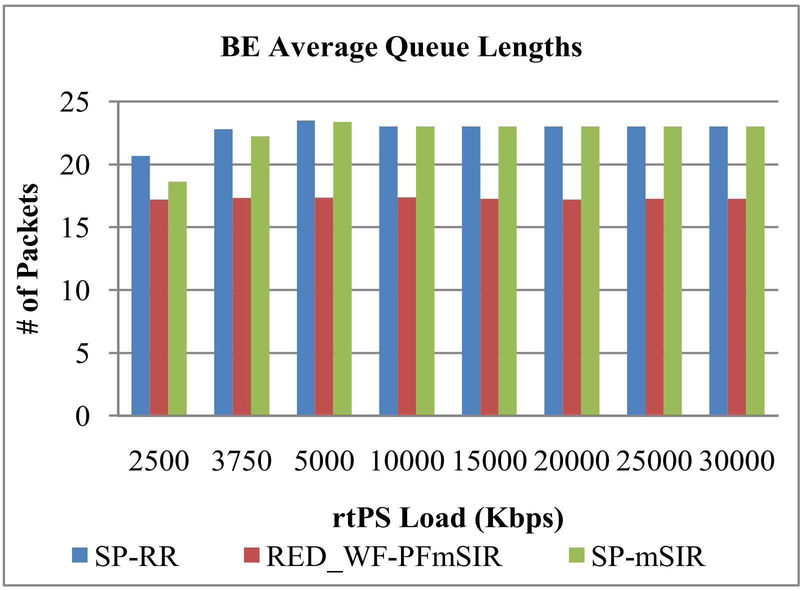

Figure 5.9 : BE average queue lengths vs. rtPS load for variable SNR

Average end-to-end delay of rtPS traffic for the schedulers are shown in Figure 5.10. SP-RR and SP-mSIR schedulers cause better delay values than the proposed scheduler. The values obtained for the proposed scheduler could be accepted for the real time applications. End-to-end delay of transmitted packets by the proposed scheduler is consistent under increasing rtPS traffic load.

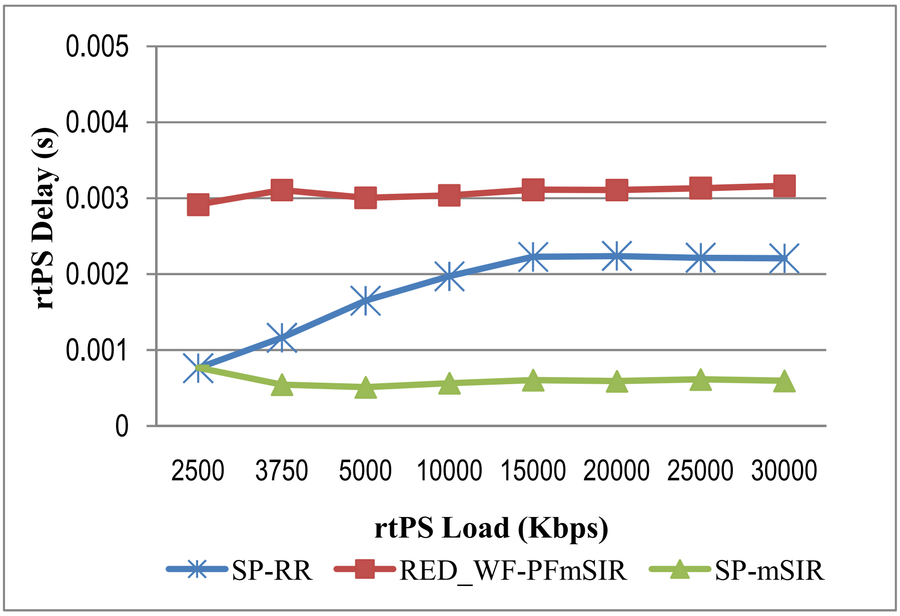

Figure 5.10 : rtPS average delay vs. rtPS load for variable SNR

Average end-to-end delay of nrtPS traffic for the schedulers are shown in Figure 5.11. SP-RR and SP-mSIR schedulers allocates entire bandwidth for rtPS service class and hence they do not transmit any nrtPS packet under high rtPS load. Since the SP-RR and SP-mSIR schedulers do not trasmit any nrtPS packet under high rtPS load, they are not shown in the figure.

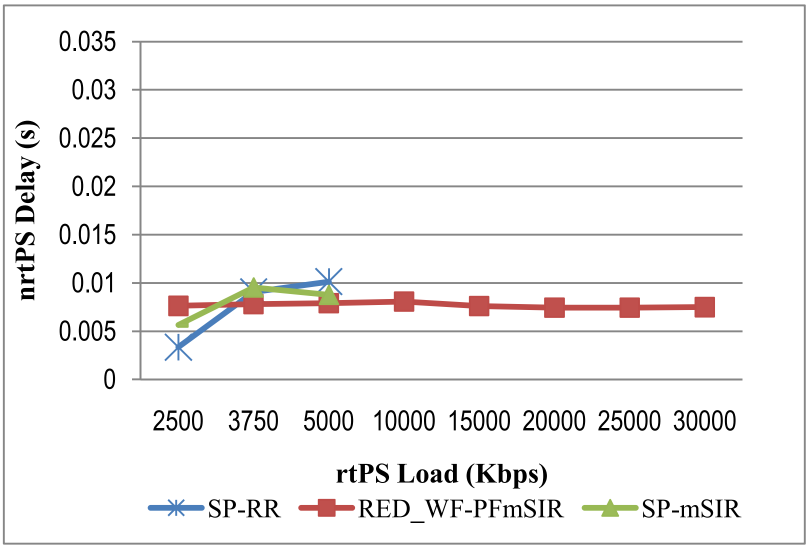

Figure 5.11 : nrtPS average delay vs. rtPS load for variable SNR

Average end-to-end delay of BE traffic for the schedulers are shown in Figure 5.12. SP-mSIR has 30 ms average BE delay for 2500Kbps rtPS load. Since the SP-RR and SP-mSIR schedulers do not trasmit any BE packet under high rtPS load, they are not shown in the figure.

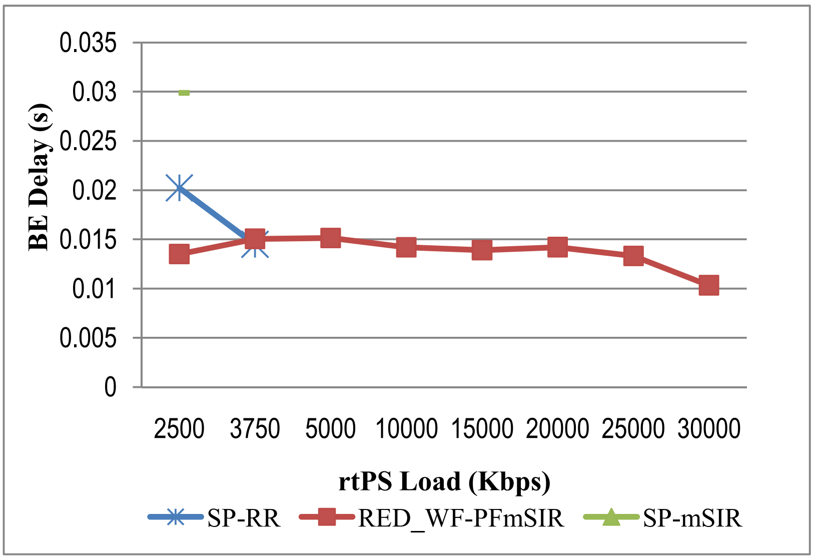

Figure 5.12 : BE average delay vs. rtPS load for variable SNR

Throughput comparison of each SS is shown in Figure 5.13. To analyze fairness between SSs, we have measured the throughput of each SS. All rtPS SSs have equal submitted load. Their SNR values are different and fluctuating during short periods of the simulation duration. Since the SNR values are different and SP-mSIR allocates the entire bandwidth by starving the SSs with lower SNR value, SP-mSIR is not fair in long term. The proposed scheduler and SP-RR are fair in long term. SP-RR and SP-mSIR are not fair between service classes and they starve the nrtPS and BE service flows.

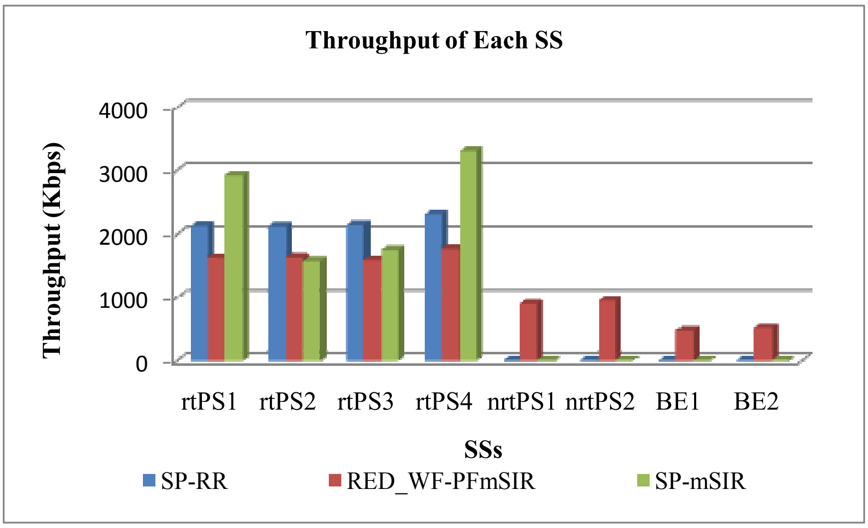

Figure 5.13 : Throughputs vs. SSs

We also performed simulations with constant SNR values of the rtPS SSs to model short term behavior: 7.0dB, 14.0 dB, 20.0 dB, and 25.0 dB. SNR values of nrtPS and BE SSs and other simulation parameters are same with the previous simulation.

Figure 5.14 shows rtPS throughput under increasing rtPS traffic load. Similar to the variable-SNR scenario representing long term model, rtPS throughput of the proposed scheduler is lower than the other two schedulers' since it allocates some bandwidth for nrtPS and BE service classes.

Figure 5.15 shows nrtPS throughput under increasing rtPS traffic load. The proposed scheduler achieves more nrtPS throughput than the SP-RR and SP-mSIR schedulers.

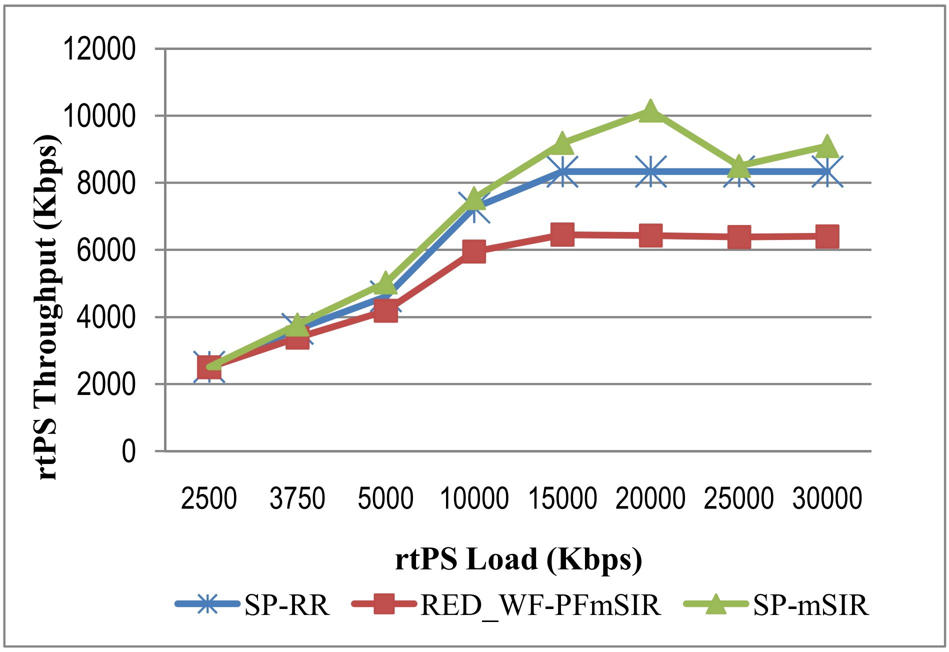

Figure 5.14 : rtPS throughput vs. rtPS load for constant SNR

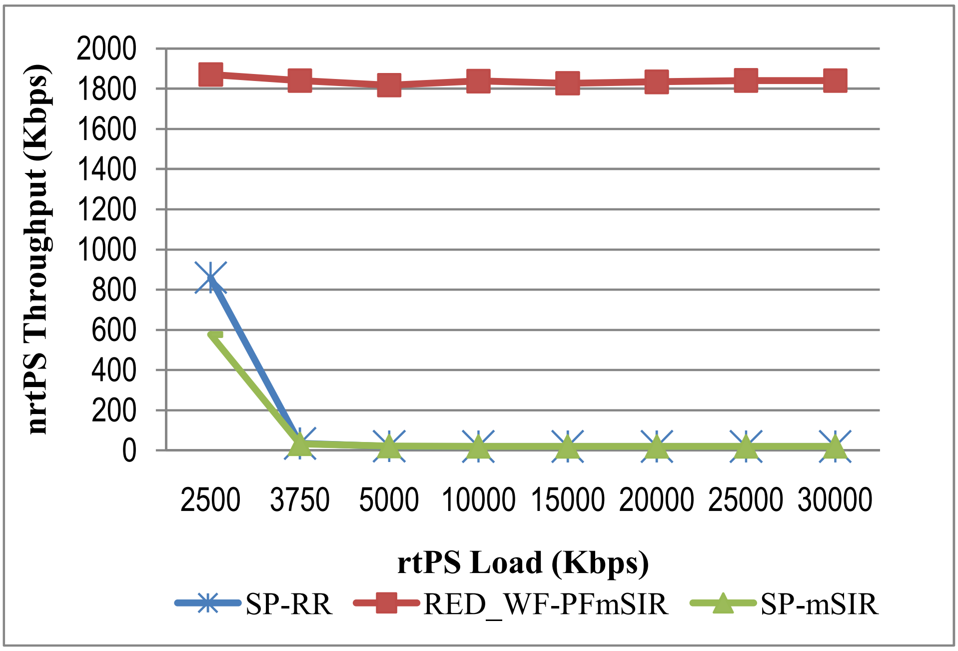

Figure 5.15 : nrtPS throughput vs. rtPS load for constant SNR

Figure 5.16 shows BE throughput of the schedulers under increasing rtPS traffic load. Similarly, SP-RR and SP-mSIR algorithms starve the BE service class. The proposed scheduler achieves higher throughput.

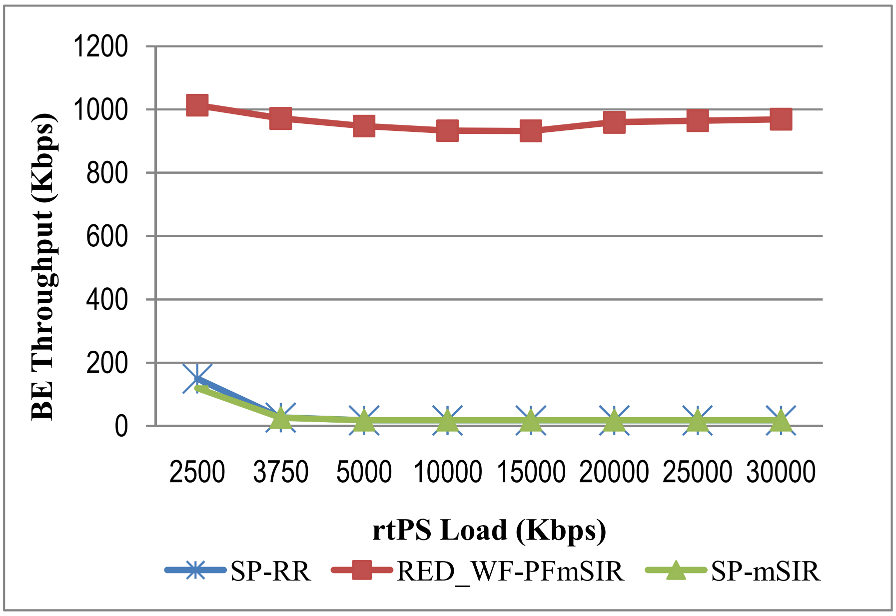

Figure 5.16 : BE throughput vs. rtPS load for constant SNR

Overall system throughput of the schedulers is shown in Figure 5.17. The proposed scheduler achieves more throughput than the other schedulers. So, it improves the overall system throughput.

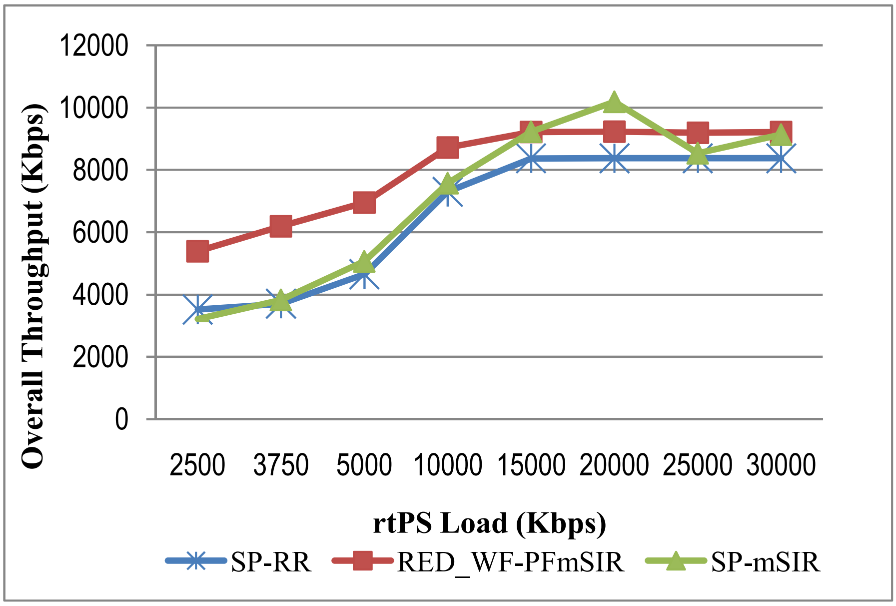

Figure 5.17 : Total throughput vs. rtPS load for constant SNR

Average rtPS Queue Lengths of schedulers increase under increasing rtPS Load as shown in Figure 5.18. The proposed scheduler has more packets in the queue since it allocates some bandwidth for nrtPS and BE service classes to prevent starvation of them.

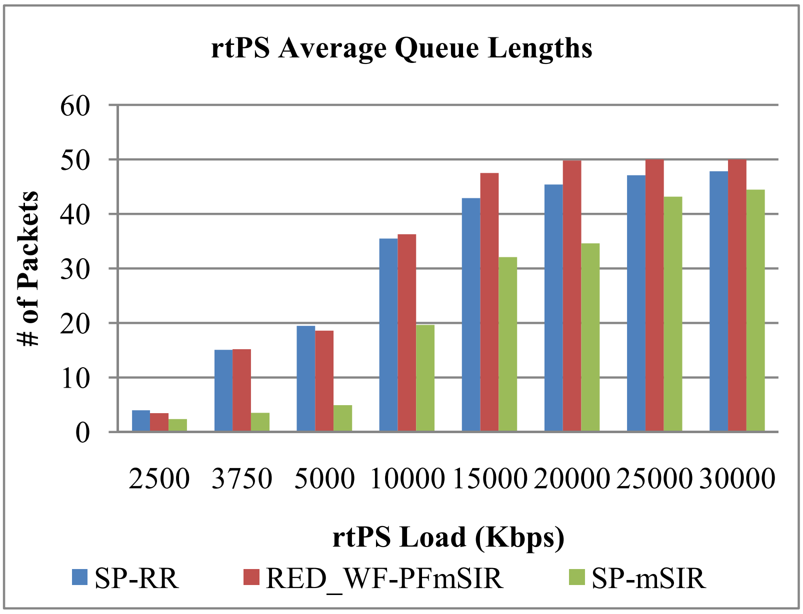

Figure 5.18 : rtPS average queue lengths vs. rtPS load for constant SNR

Figure 5.19 and Figure 5.20 shows nrtPS and BE average queue lengths of the schedulers. SP-RR and SP-mSIR have higher average queue lengths than the proposed scheduler.

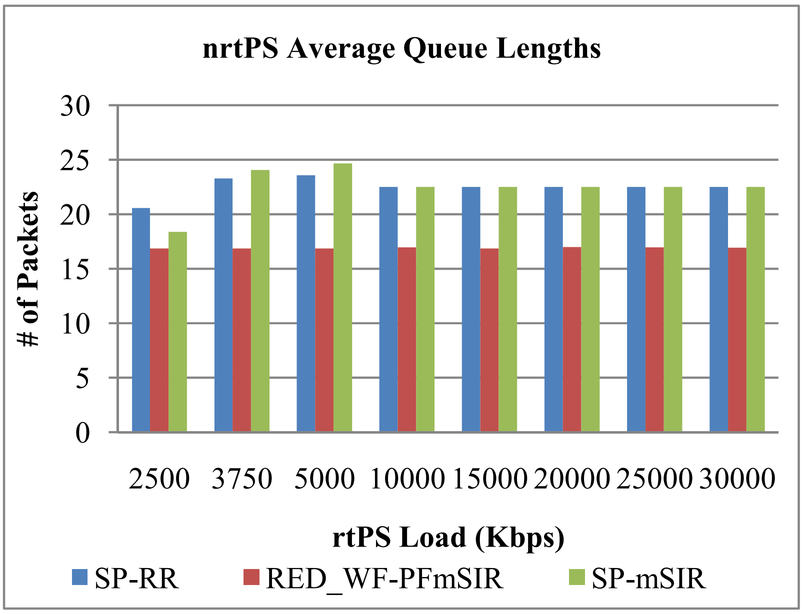

Figure 5.19 : nrtPS average queue lengths vs. rtPS load for constant SNR

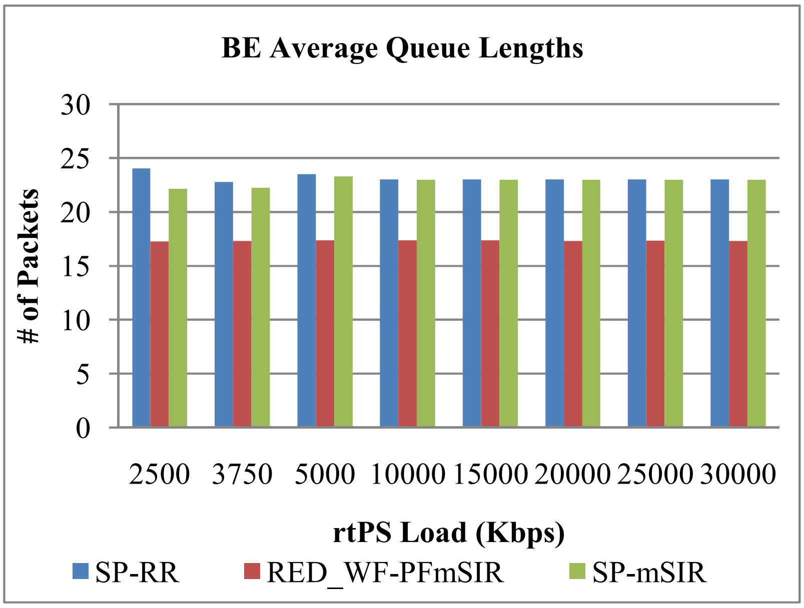

Figure 5.20 : BE average queue lengths vs. rtPS load for constant SNR

6. CONCLUSION

In this thesis, a hierarchical channel aware uplink scheduling algorithm which takes SNR variations into account is proposed and it is observed that the overall system throughput is improved. The hierarchical model maintains both overall bandwidth efficiency and inter-class fairness.

The proposed scheduler's performance is compared with two other schedulers: Strict Priority-Round Robin (SP-RR) and Strict Priority-Maximum Signal to Interference Ratio(SP-mSIR). Simulation results show that in lower rtPS traffic load, all three schedulers achieve similar rtPS throughput. Under heavy rtPS traffic load, since SP-RR and SP-mSIR schedulers allocate the entire bandwidth for rtPS traffic, their achieved rtPS throughputs are higher than that of the proposed scheduler. However, SP-RR and SP-mSIR schedulers starve the nrtPS and BE traffic flows and do not guarantee the QoS. The proposed scheduler does not starve any of the service classes and achieves higher overall system throughput.

For future work, the parameters of the proposed scheduler can be arranged adaptively based on estimation of the other system parameters.

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] **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.

[3] **Ball, C. F., Treml, F., Ivanov, K., Humburg, E**., 2006. Perfermance evaluation of ieee802.16 WiMAX with fixed and mobile subscribers in tight reuse. European Transactions on Telecommunications, 17(1):203 218, March 2006.

[4] **Ball, C. F., Treml, F., Gaube, X., Klein, A**., 2005. Performance analysis of temporary removal scheduling applied to mobile WiMAX scenarios in tight frequency reuse. European Transactions on Telecommunications, 888-894, September 2005.

[5] **Wongthavarawat, K., Ganz, A.**, 2003. Packet scheduling for QoS support in IEEE 802.16 broadband wirelessaccess systems, *International Journal of Communication System*.

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

[7] **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), May 2005.

[8] **Floyd, S., Jacobson, V.**, Random Early Detection gateways for Congestion Avoidance V.1 N.4, August 1993, p. 397-413.

[9] **Yarali, A., Rahman**, **S.,** WiMAX broadband wireless access technology: Services, architecture and deployment models, Canadian Conference on In Electrical and Computer Engineering, 2008, pp. 000077-000082.

[10] **Nuaymi,. L,** 2007**.** *WiMAX*, John Wiley & Sons Publication, Jan 2007.

[11] **Lu, K., Qian, Y., Chen, H., Fu, S.**, WiMAX networks: from access to service platform, *IEEE Network*, Vol. 22, No. 3, pp. 38-45, May 2008.

[12] **Ahson S., Ilyas M.,** 2004. A Survey on Sensor Networks, *IEEE Communications Magazine*, 40, p102-114.

[13] **Ghosh, A., Wolter, D. R., Andrews, J. G., Chen, R**., 2005. Broadband Wireless Access with WiMAX/802.16: Current Performance Benchmarks and Future Potential, IEEE Communication Magazine, pp129-136, Feb. 2005.

[14] **Both, C.B. , Kunst, R.**, 2008. Analysis of WiMAX bandwidth allocation mechanism considering physical conditions, Wireless Communication Systems, ISWCS '08, IEEE International Symposium, 2008.

[15] **Agis, A., et al.,** Global, interoperable broadband wireless networks: extending WiMAX technology to mobility. *Intel Technology Journal*, August 2004.

[16] **Robles Rico, P.F.,** 2007. Performance Evaluation of IEEE 802.16e Standard, MSc Thesis, ITU, Istanbul.

[17] **The network simulator ns-2**, <*http://www.isi.edu/nsnam/ns/*>, last accessed at 23.12.2009.

[18] **GNU General Public License**, <*http://www.gnu.org/copyleft/gpl.html*>, last accessed at 24.12.2009.

[19] **NIST Seamless and secure mobility**, NIST WIMAX Module on NS-2, <*http://www.antd.nist.gov/seamlessandsecure*>, last accessed at 23.12.2009.

[20] **Belghith, A., Nuaymi, L.**, 2008. Design and Implementation of a QoS-included WiMAX Module for NS-2 Simulator, *Simutools*, ACM, 2008.

[21] **Oktug, S., Canberk, B.,** 2009. Self Similarity Analysis and Modeling of VoIP Traffic under Wireless Heterogeneous Network Environment, AICT, pp.76-82, 2009 Fifth Advanced International Conference on Telecommunications, 2009.

APPENDICES

APPENDIX A.1 : Confidence Intervals For Constant SNR Scenario
APPENDIX A.2 : Confidence Intervals For Variable SNR Scenario

APPENDIX A.1 Confidence Intervals For Constant SNR Scenario

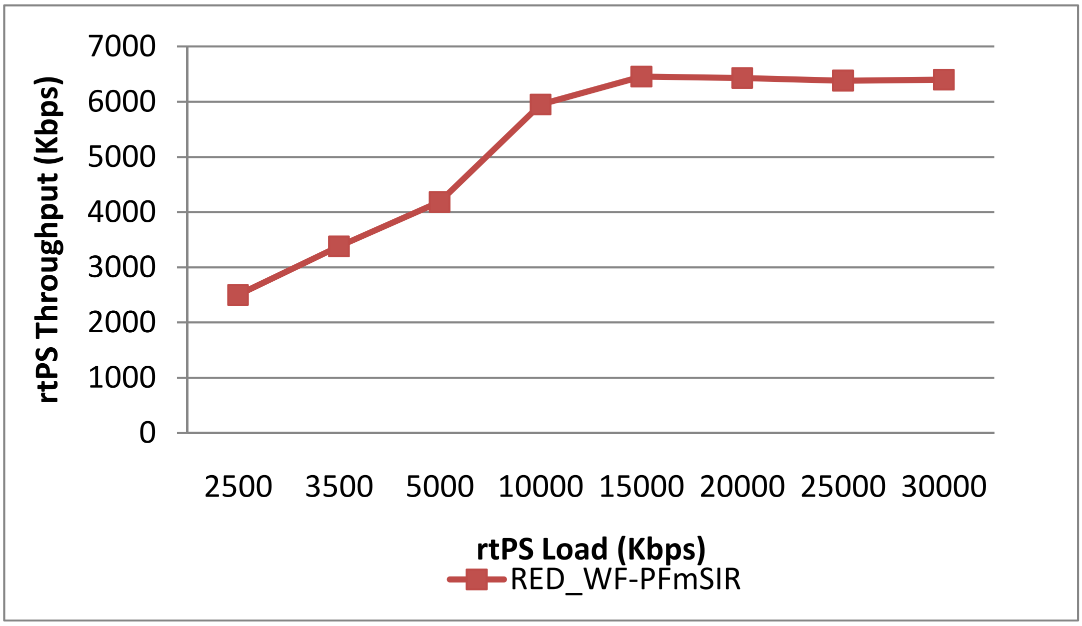

Figure A.1 : rtPS throughput vs. rtPS load for constant SNR (RED_WF-PFmSIR)

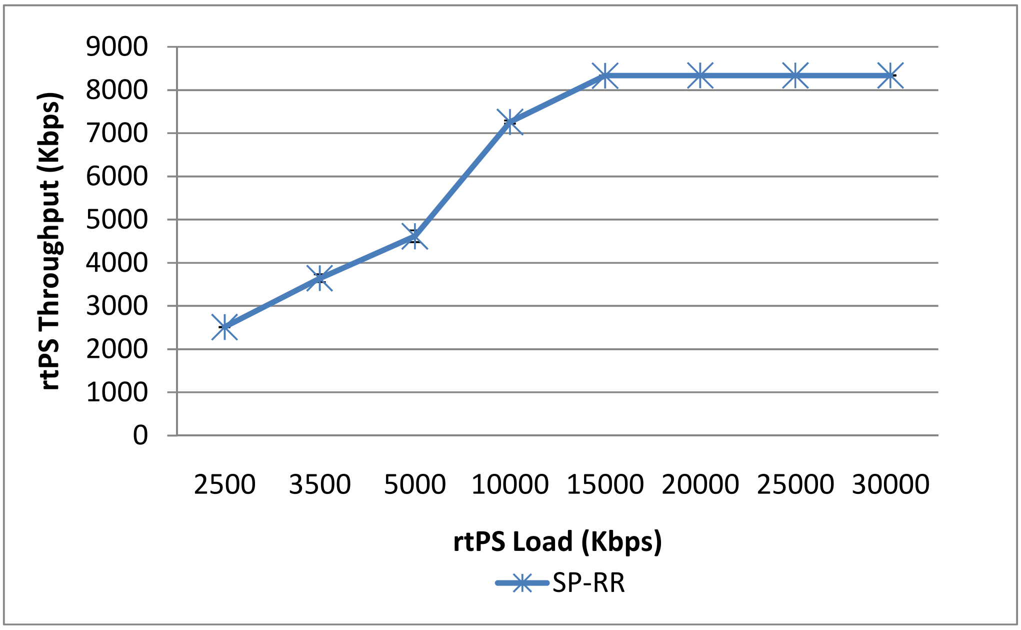

Figure A.2 : rtPS throughput vs. rtPS load for constant SNR (SP-RR)

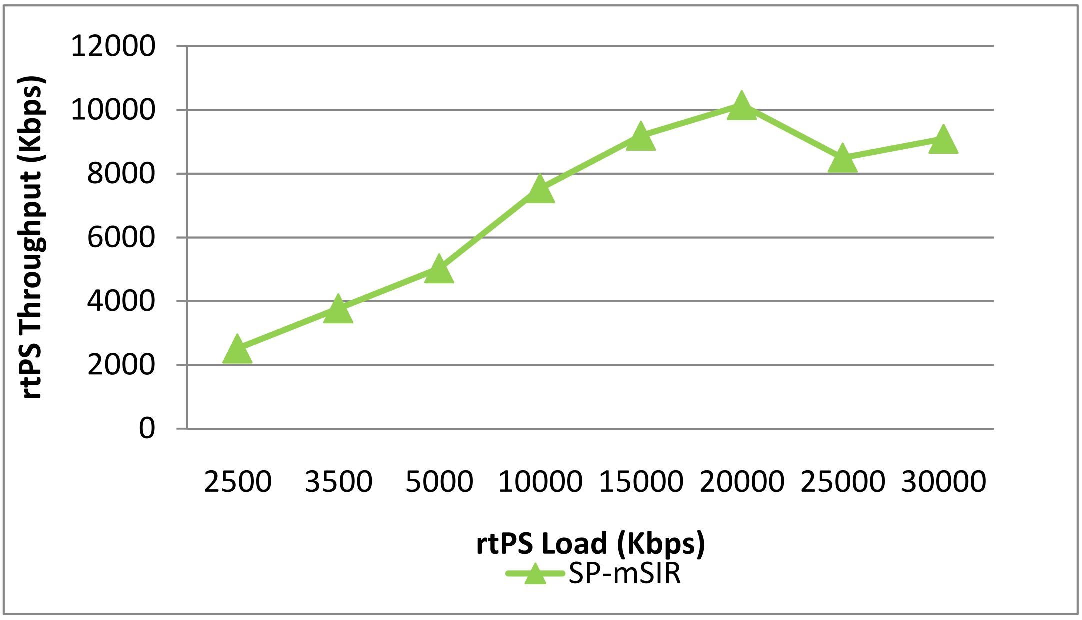

Figure A.3 : rtPS throughput vs. rtPS load for constant SNR (SP-mSIR)

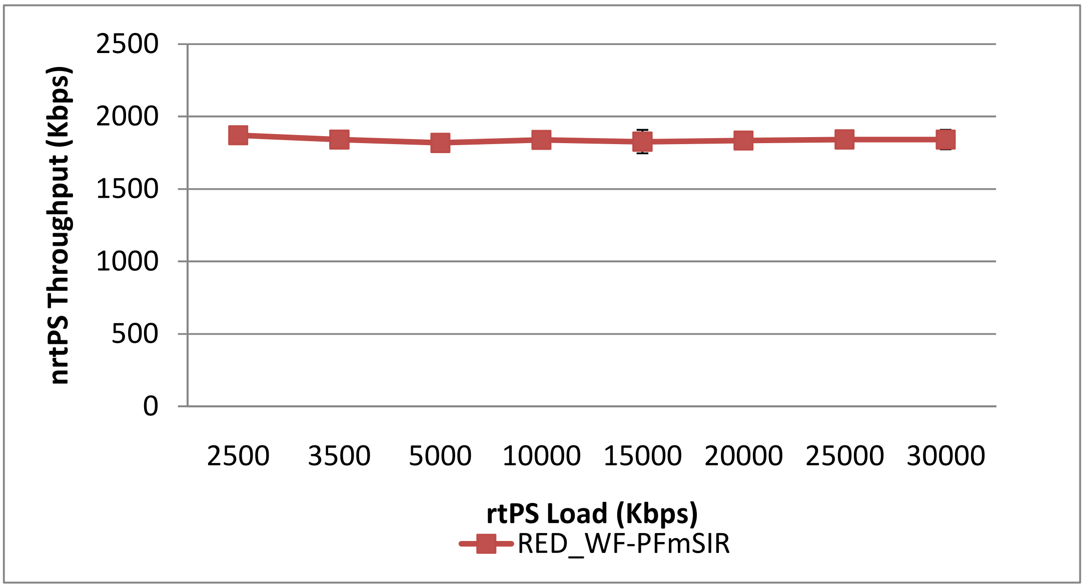

Figure A.4 : nrtPS throughput vs. rtPS load for constant SNR (RED_WF-PFmSIR)

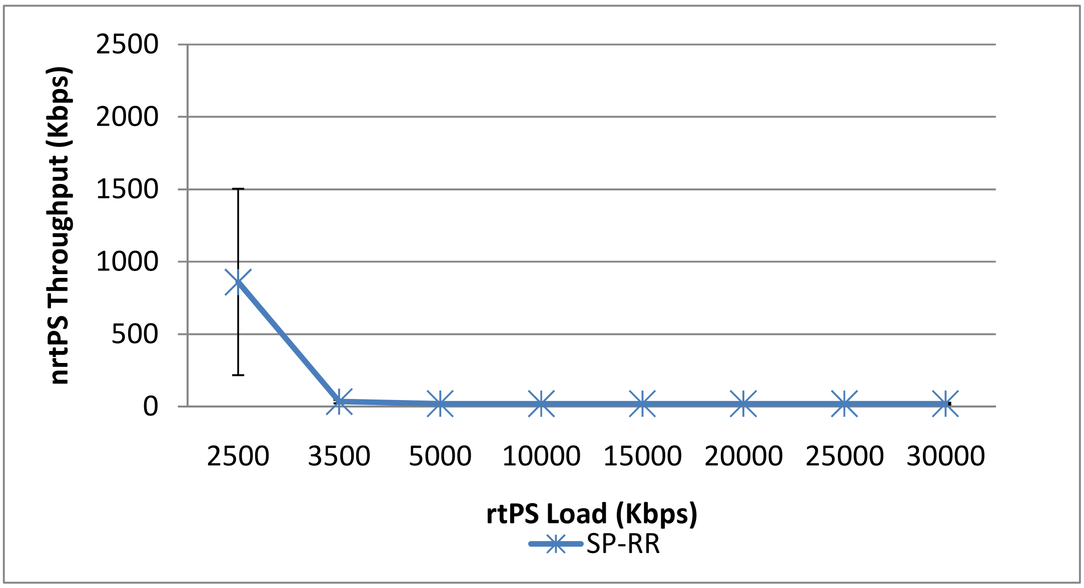

Figure A.5 : nrtPS throughput vs. rtPS load for constant SNR (SP-RR)

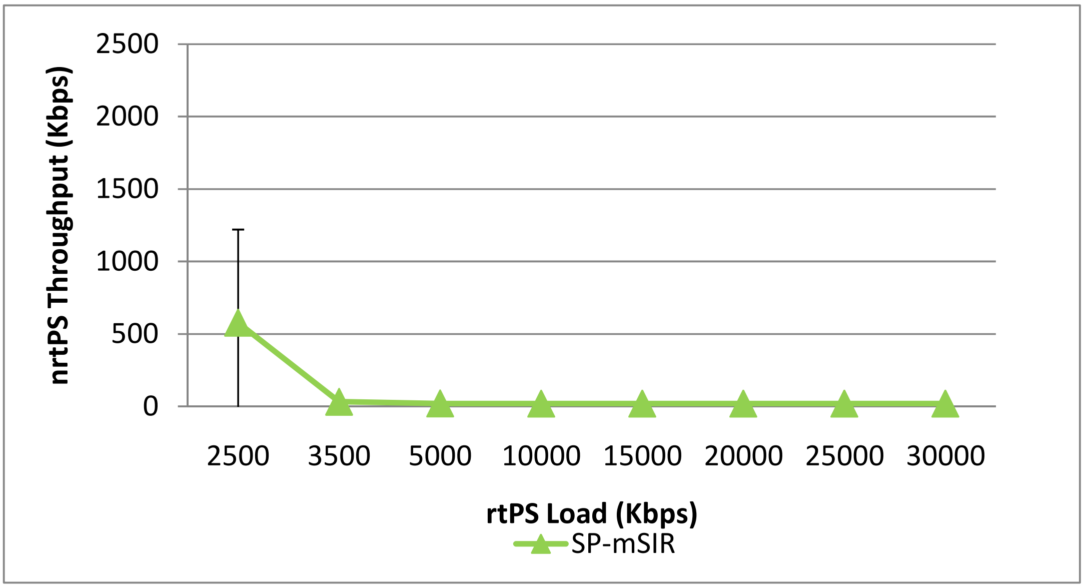

Figure A.6 : nrtPS throughput vs. rtPS load for constant SNR (SP-mSIR)

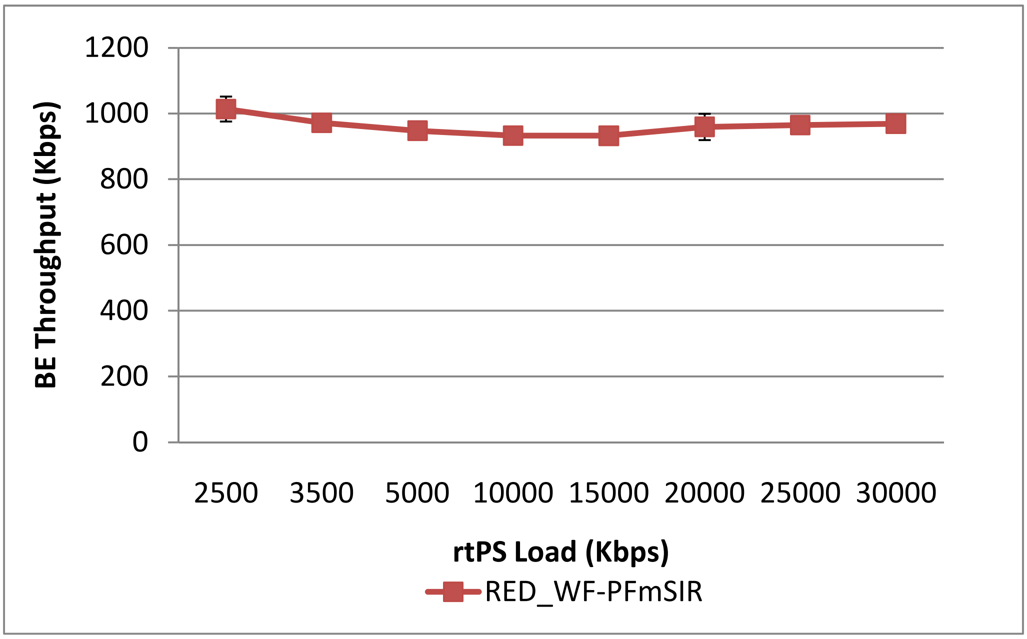

Figure A.7 : BE throughput vs. rtPS load for constant SNR (RED_WF-PFmSIR)

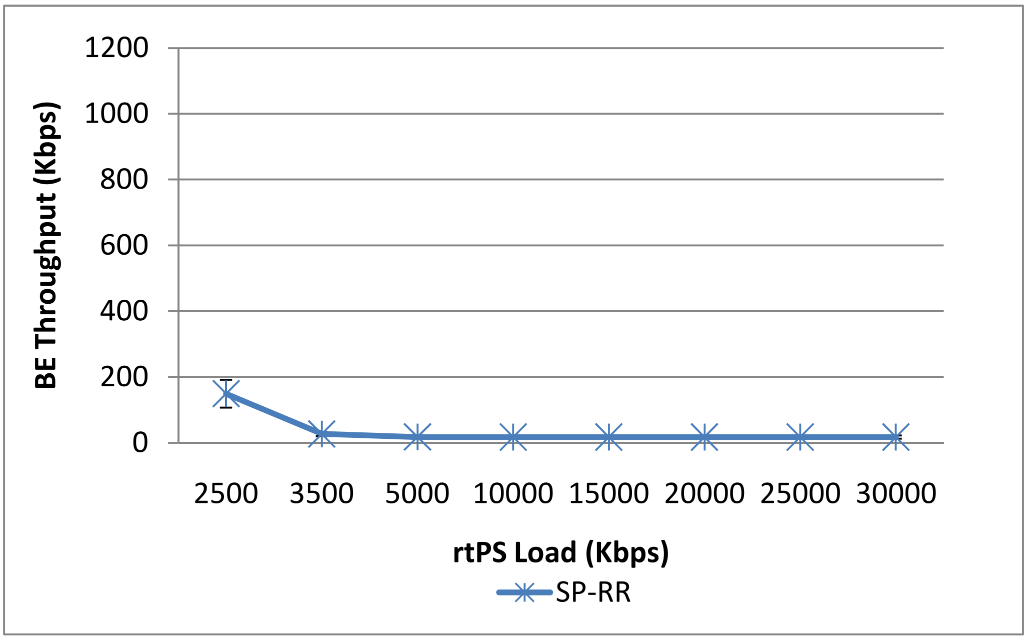

Figure A.8 : BE throughput vs. rtPS load for constant SNR (SP-RR)

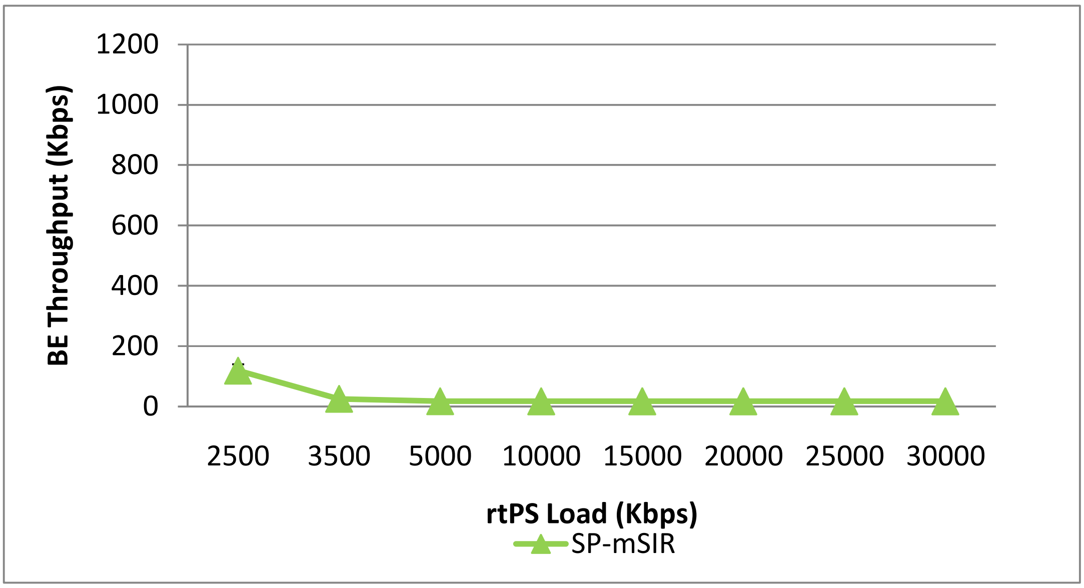

Figure A.9 : BE throughput vs. rtPS load for constant SNR (SP-mSIR)

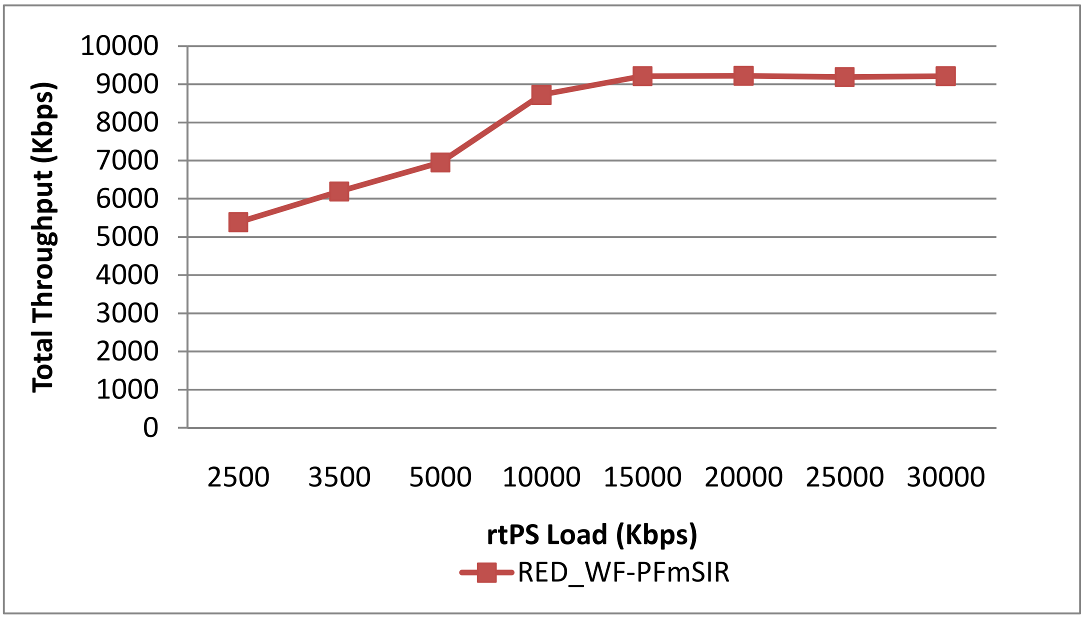

Figure A.10 : Total throughput vs. rtPS load for constant SNR (RED_WF-PFmSIR)

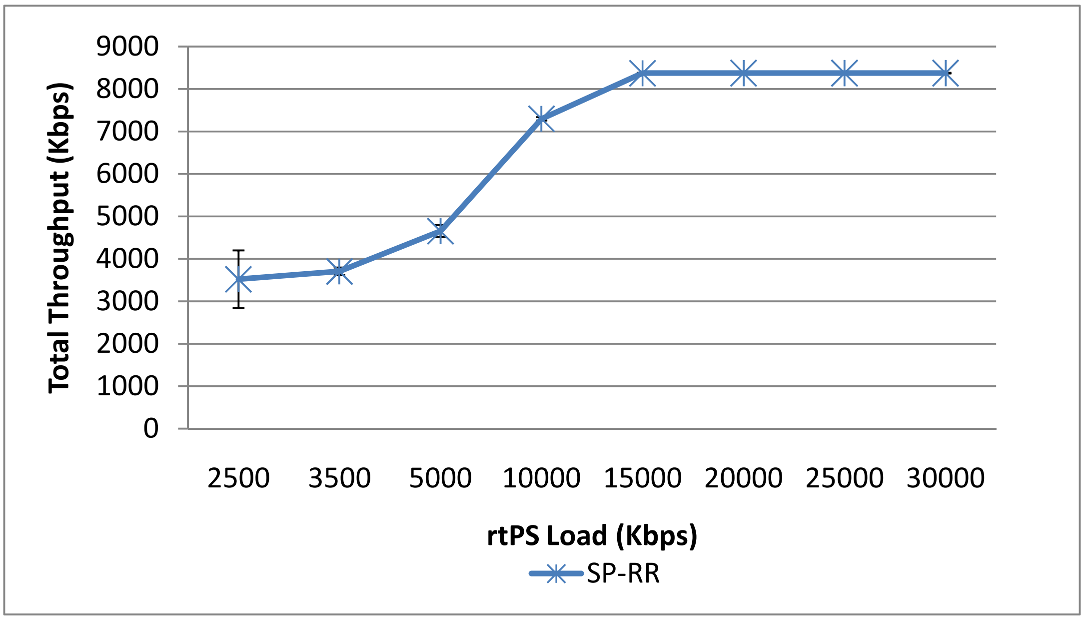

Figure A.11 : Total throughput vs. rtPS load for constant SNR (SP_RR)

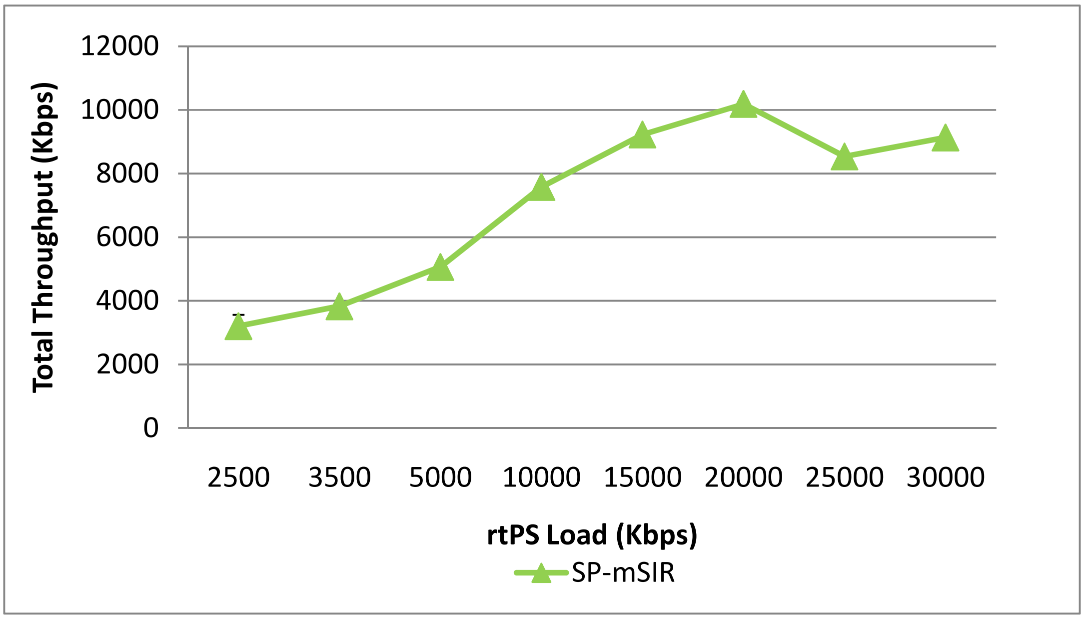

Figure A.12 : Total throughput vs. rtPS load for constant SNR (SP-mSIR)

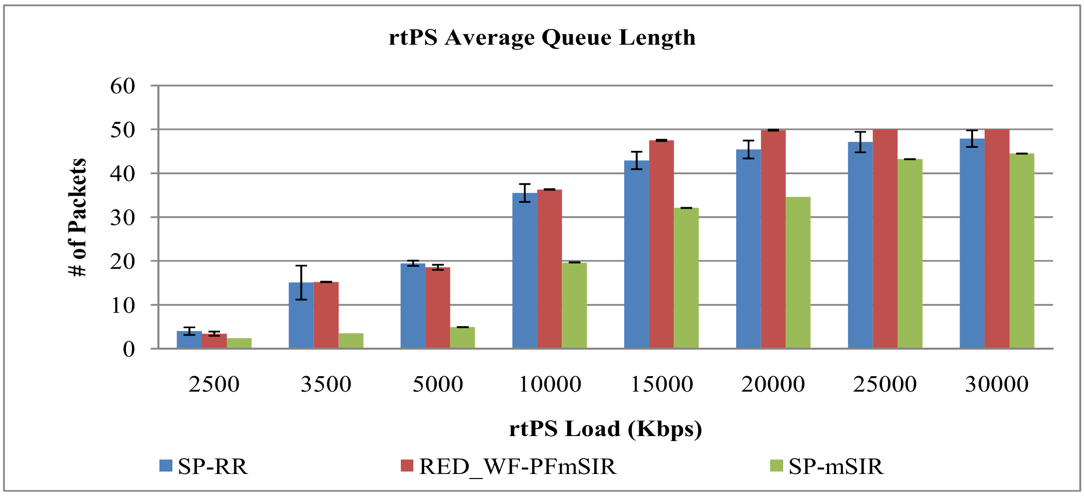

Figure A.13 : rtPS average queue lengths vs. rtPS load for constant SNR

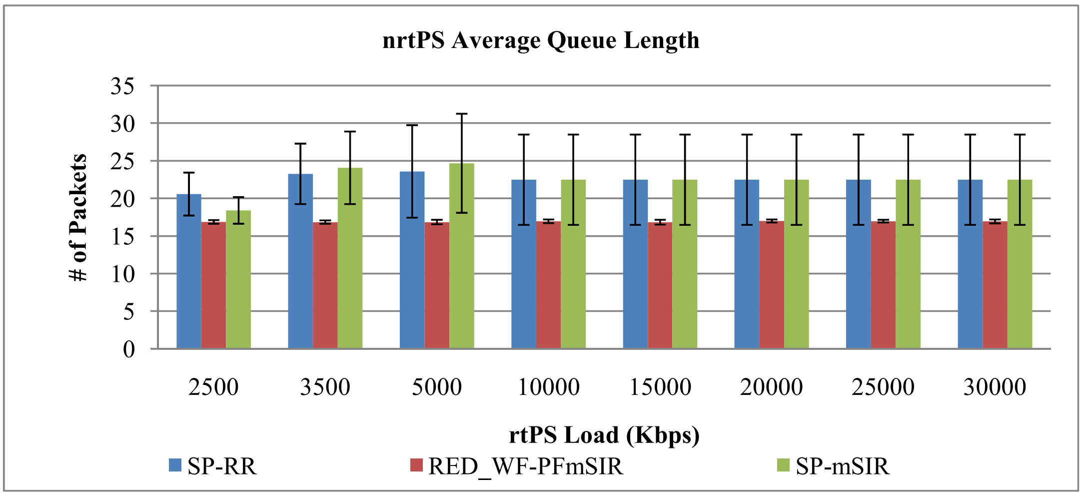

Figure A.14 : nrtPS average queue lengths vs. rtPS load for constant SNR

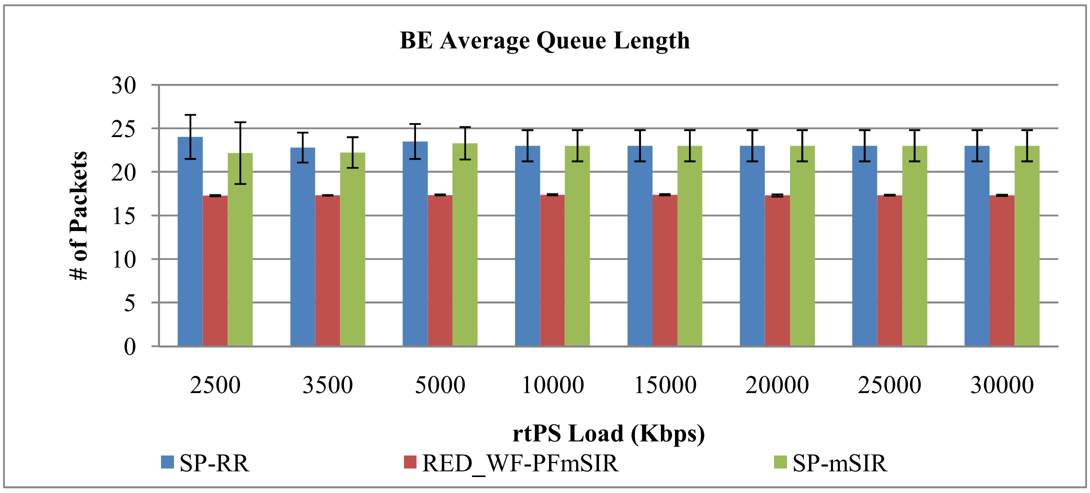

Figure A.15 : BE average queue lengths vs. rtPS load for constant SNR

APPENDIX A.2 Confidence Intervals For Variable SNR Scenario

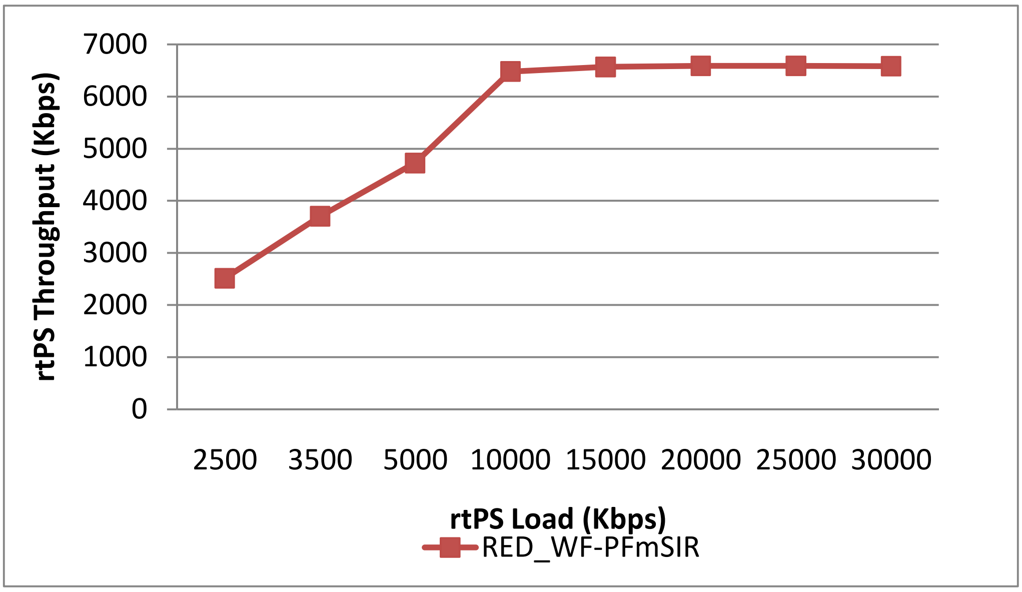

Figure A.16 : rtPS throughput vs. rtPS load for variable SNR (RED_WF-PFmSIR)

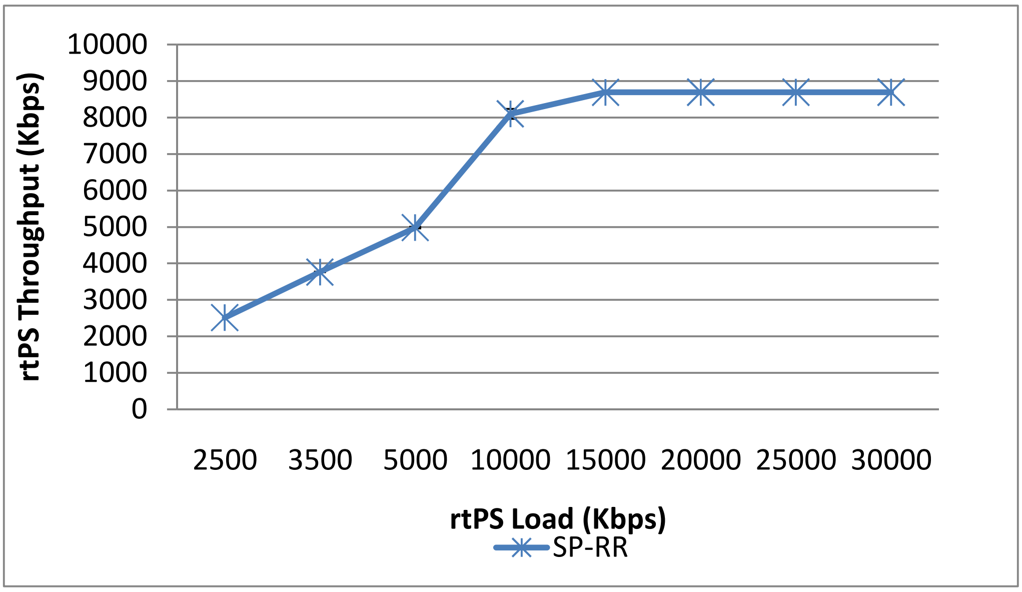

Figure A.17 : rtPS throughput vs. rtPS load for variable SNR (SP-RR)

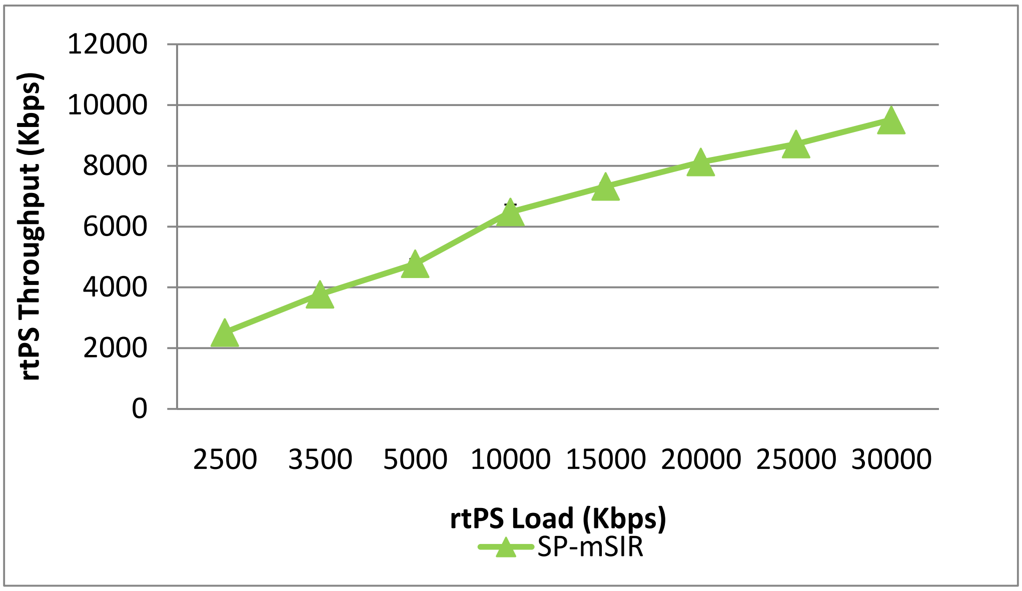

Figure A.18 : rtPS throughput vs. rtPS load for variable SNR (SP-mSIR)

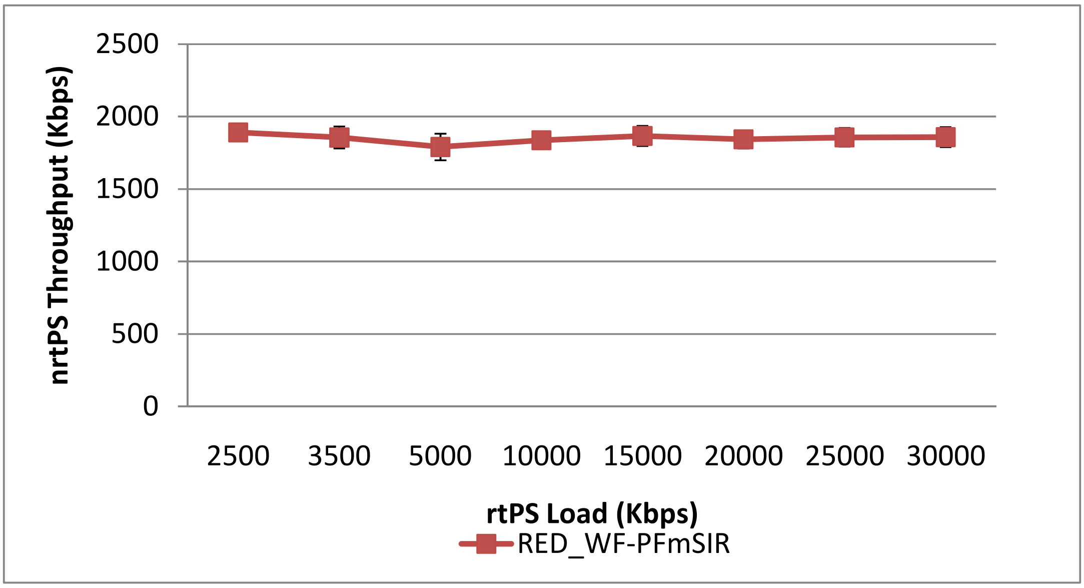

Figure A.19 : nrtPS throughput vs. rtPS load for variable SNR (RED_WF-PFmSIR)

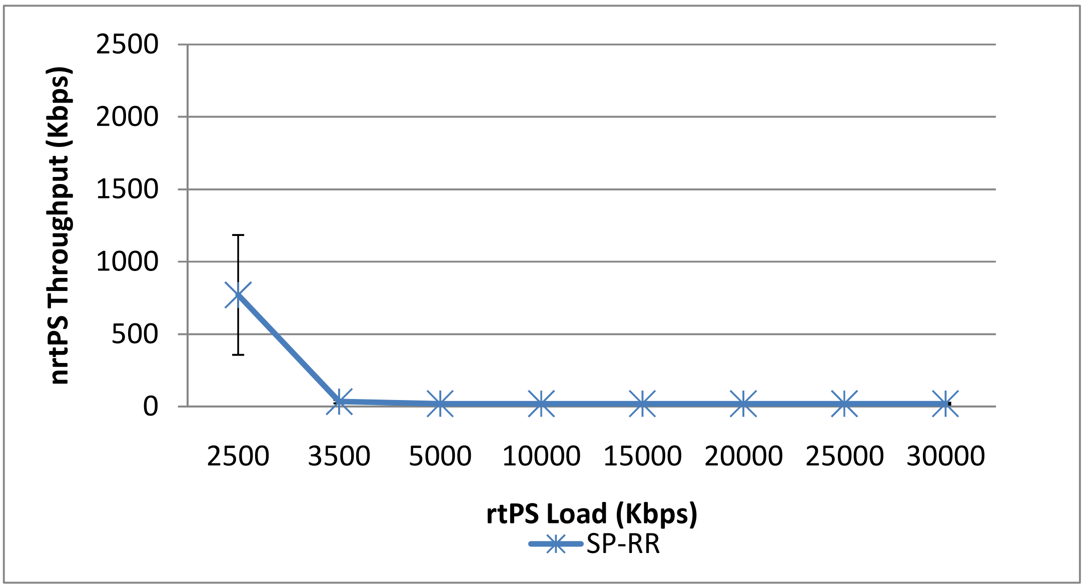

Figure A.20 : nrtPS throughput vs. rtPS load for variable SNR (SP-RR)

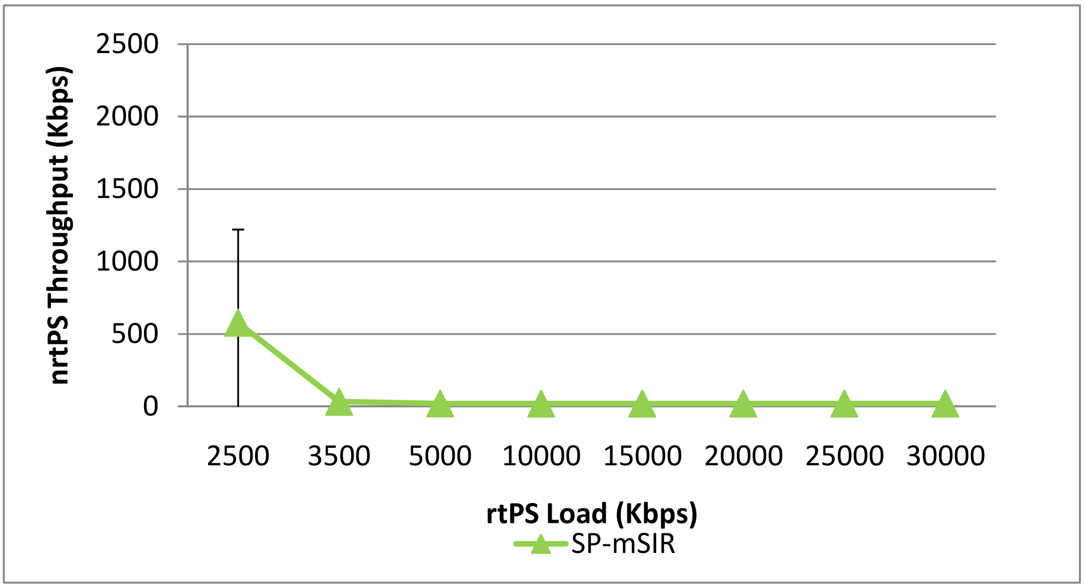

Figure A.21 : nrtPS throughput vs. rtPS load for variable SNR (SP-mSIR)

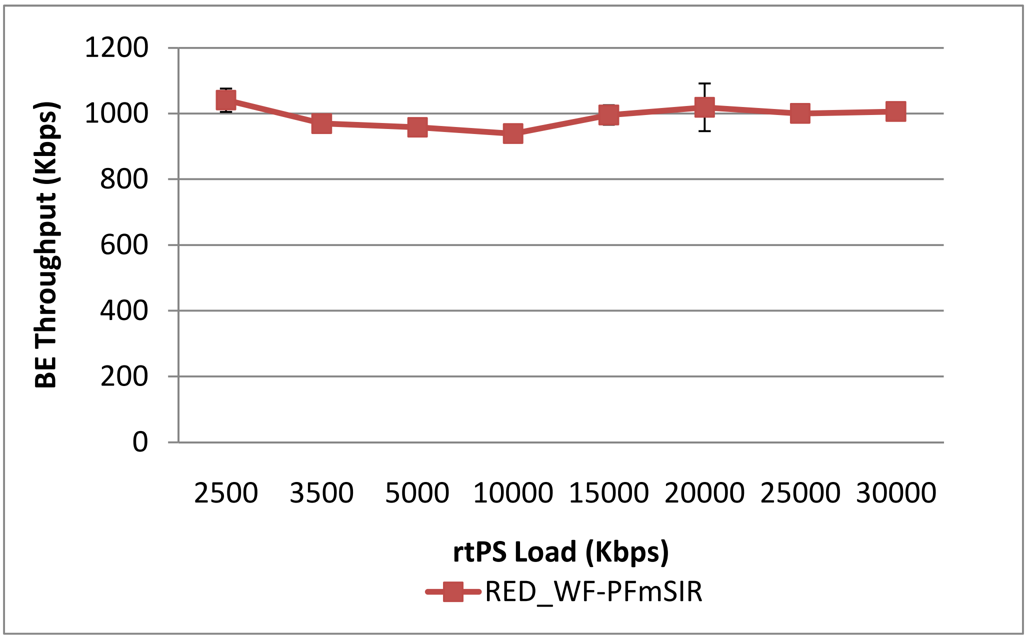

Figure A.22 : BE throughput vs. rtPS load for variable SNR (RED_WF-PFmSIR)

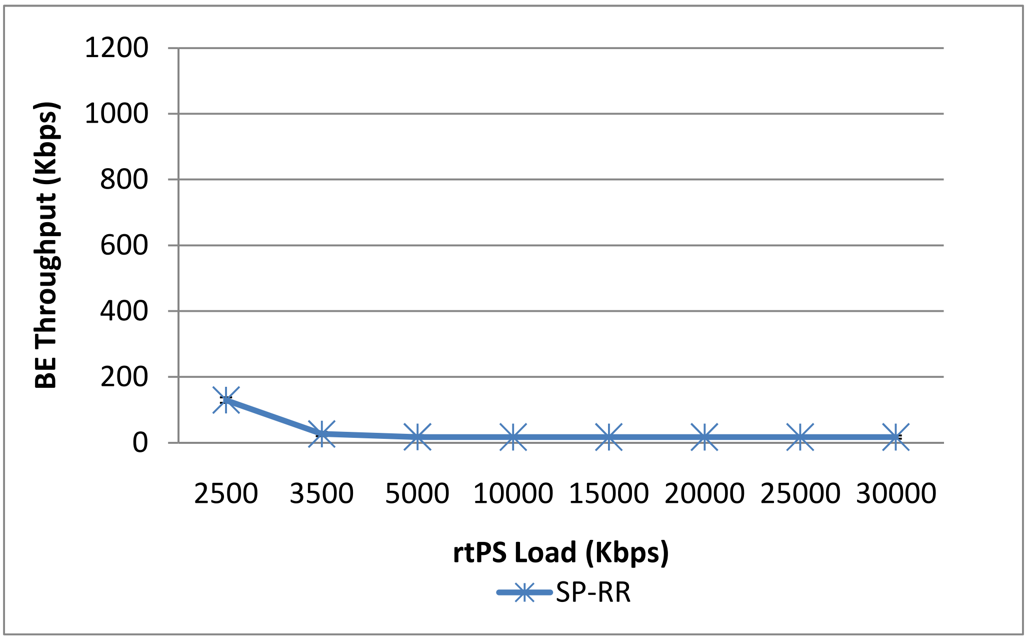

Figure A.23 : BE throughput vs. rtPS Load for variable SNR (SP-RR)

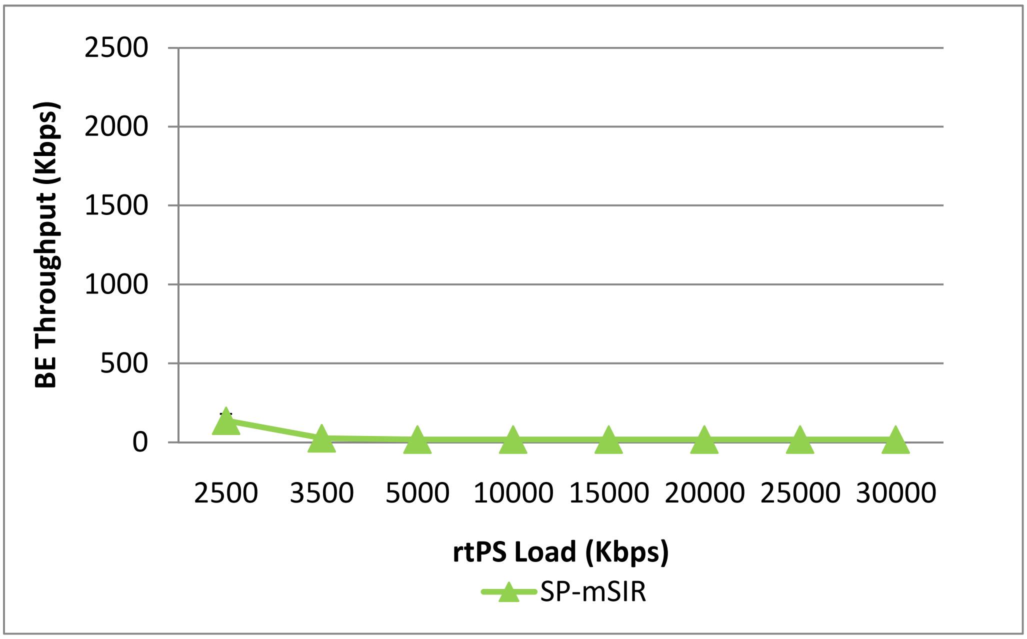

Figure A.24 : BE throughput vs. rtPS load for variable SNR (SP-mSIR)

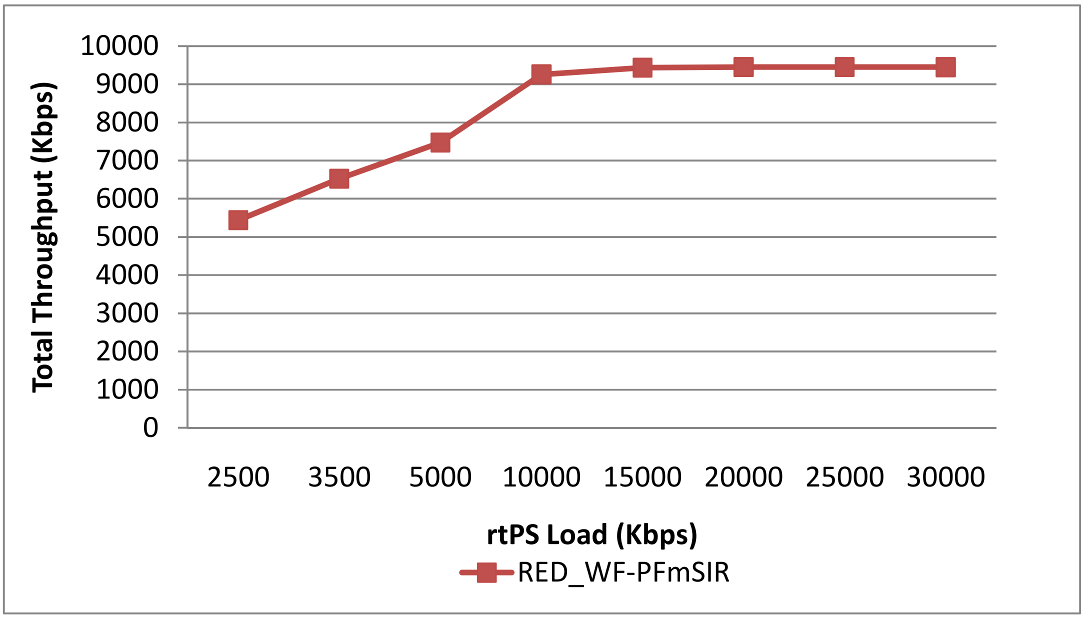

Figure A.25 : Total throughput vs. rtPS load for variable SNR (RED_WF-PFmSIR)

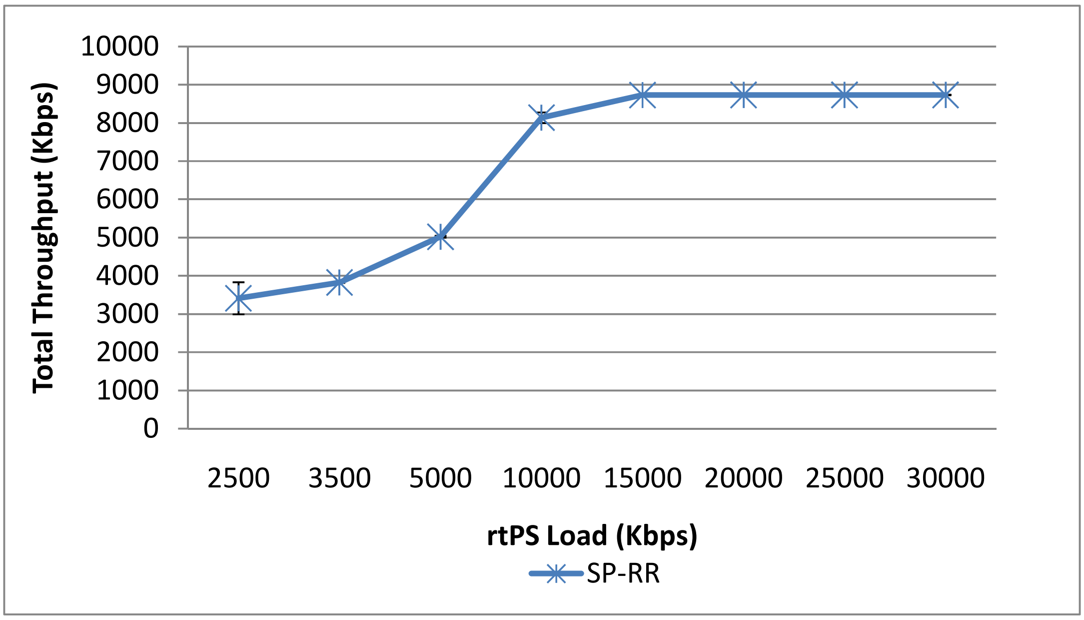

Figure A.26 : Total throughput vs. rtPS load for variable SNR (SP_RR)

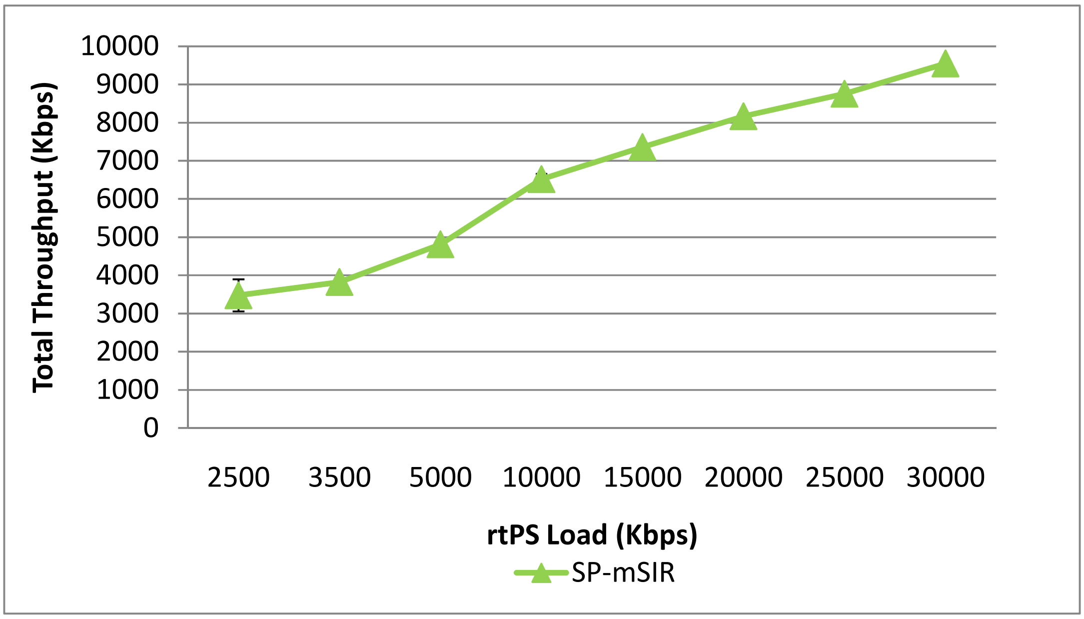

Figure A.27 : Total throughput vs. rtPS load for variable SNR (SP-mSIR)

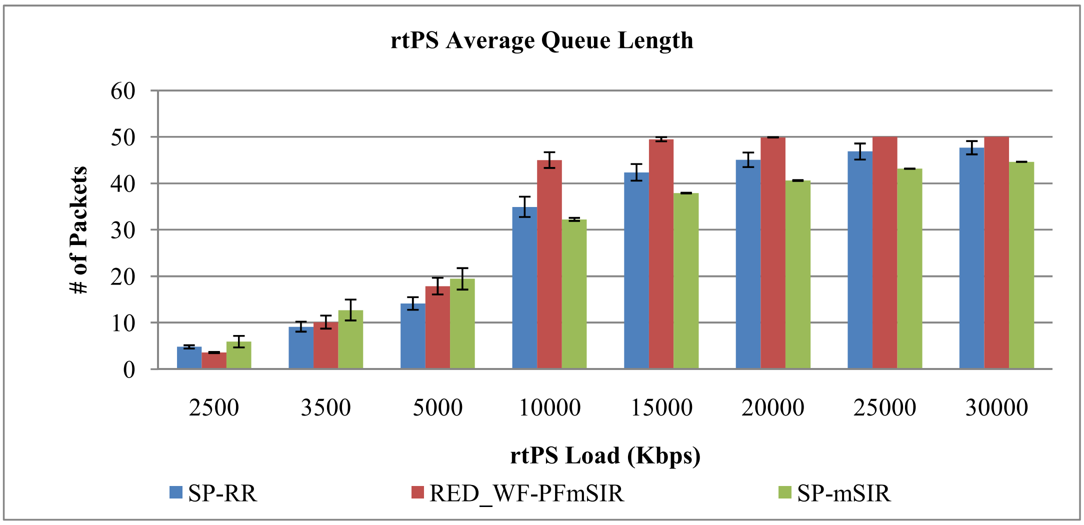

Figure A.28 : rtPS average queue lengths vs. rtPS load for variable SNR

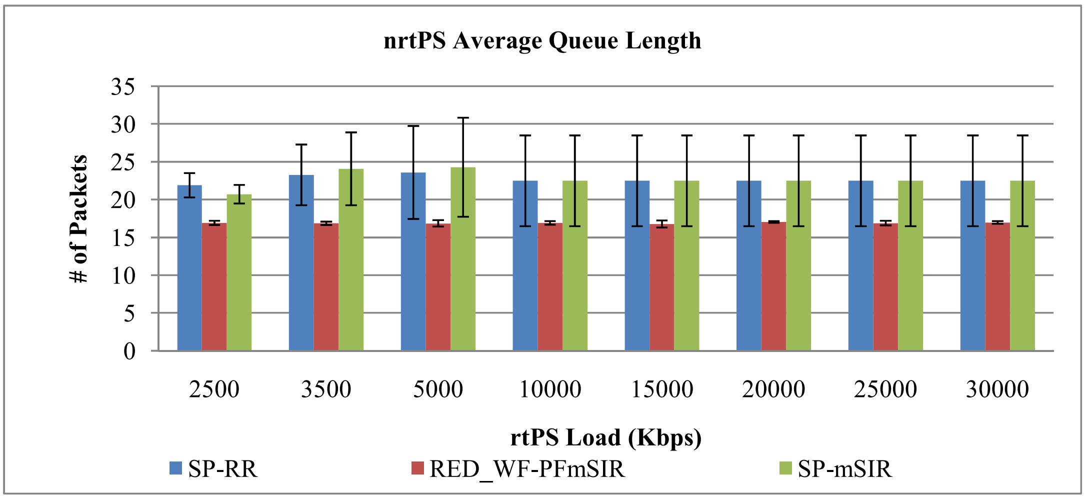

Figure A.29 : nrtPS average queue lengths vs. rtPS load for variable SNR

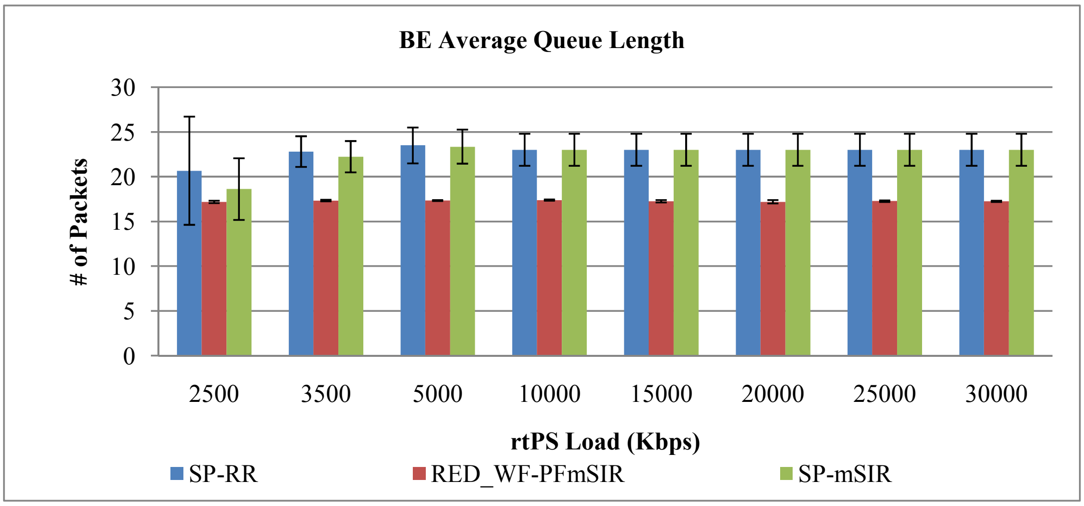

Figure A.30 : BE average queue lengths vs. rtPS load for variable SNR

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