

# Channel-aware and Queue-aware Scheduling for Integrated WiMAX and EPON

by

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I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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## Abstract

By envisioning that the future broadband access networks have to support many bandwidth consuming applications, such as VoIP, IPTV, VoD, and HDTV, the integration of WiMAX and EPON networks have been taken as one of the most promising network architecture due to numerous advantages in terms of cost-effectiveness, massive-bandwidth provisioning, Ethernet-based technology, reliable transmissions, and QoS guarantee. Under the EPON-WiMAX integration, the development of a scheduling algorithm that could be channel-aware and queue-aware will be a great plus on top of the numerous merits and flexibility in such an integrated architecture.

In this thesis, a novel two-level scheduling algorithm for the uplink transmission are proposed by using the principle of proportional fairness for the transmissions from SSs over the WiMAX channels, while a centralized algorithm at the OLT for the EPON uplink from different WiMAX-ONUs. The scheduler at the OLT receives a Report message from each WiMAX-ONU, which contains the average channel condition per cell, queues length, and head-of-line (HOL) delay for rtPS traffic. The EPON data frame is then scheduled based on these Report messages. Numerical results show that the proposed scheme could satisfy the end-to-end real-time QoS requirements. In addition, the centralized scheduler at the OLT can achieve high throughput in presence of traffic load variation.

## Acknowledgements

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## Dedication

*To my parents...*

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# List of Acronyms

NGN	Next Generation Networks
IPTV	Internet Protocol Television
EPON	Ethernet Passive Optical Networks
QoS	Quality of Service
MAN	Metropolitan Access Networks
PON	Passive Optical Networks
BER	Bit Error Rate
OLT	Optical Line Termination
ONU	Optical Network Unit
SS	Subscribe Station
MAC	Medium Access Control
LOS	Line of Sight
NLOS	Non-Line of Sight
OFDM	Orthogonal Frequency Division Multiplexing
BS	Base Station
PDU	Protocol Data Unit
SDU	Service Data Unit
UGS	Unsolicited Grant Service
VoIP	Voice over IP
rtPS	Real-time Polling Service

nrtPS	Non-real-time Polling Service
BE	Best Effort
CSI	Channel state information
FDD	frequency-division duplex
TDD	time-division duplex
PS	physical slot
GPSS	Grant per Subscriber Station
WiMax	Worldwide interoperability for microwave access

# Chapter 1

## Introduction

### 1.1 Motivation

Access and backbone networks are going to be an important point of Next generation packet-based or IP-based networks (NGN). Instead of carrying traffic using circuit switching networks, IP-based networks will deliver them efficiently (Figure 1.1). In addition, IP-based networks will be used for other functionalities such as mobility for mobile IP, QoS, and IPTV [1]. As a result, many networks or technologies will lead to converge and become completely IP-based. Our focus in this thesis is on wired/wireless convergence in access networks, specifically WiMAX and EPON technologies.

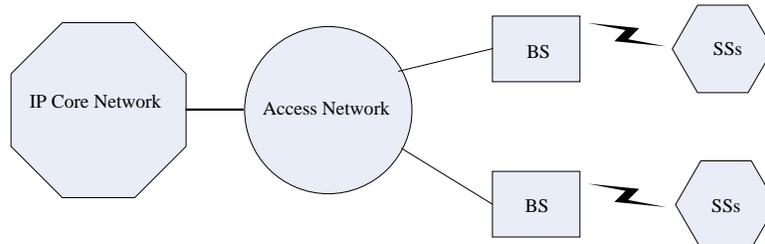


Figure 1.1: Next Generation Networks (NGN)

One of the most desirable broadband wireless technologies in Metropolitan Access Networks (MANs) is World Interpretability for Microwave Access (WiMAX). WiMAX has advantages to be an important solution in the last mile or first mile from a provider or user's location. WiMAX's ability to cover large areas, support quality of service, and utilize radio resources have successfully attracted vendors and research communities to consider it in the last mile. Another candidate for WiMAX broadband wireless access technology is Passive Optical Networks (PONs). Specifically, Ethernet Passive Optical Network (EPON), is a cost-effective technology with available bandwidth that offers low-cost fiber cable and less maintenance and management. In addition, EPON can carry IP packets easier than other PON technologies [2].

However, EPONs are inappropriate from a cost prespective if they are used to connect to homes, schools, and malls. WiMAX has a high Bit Error Rate (BER) due to channel fluctuation. In NGN or all-IP, EPON and WiMAX should be integrated in a way that combines their advantages. In other words, an integrated EPON and WiMAX would provide not only tremendous bandwidth to users but also support mobility and large coverage areas.

## 1.2 Objectives

Recently, the possibility of WiMAX and EPON integration has gained attention in research communities. A centralized scheduling algorithm at Optical Line Termination (OLT) is a challenging problem in converged networks. A conventional scheduler algorithm for EPON assumes that the channel condition from the user to its attached ONU is constant. In WiMAX and EPON integration, the channel is known to be time-varying because each user or Subscribe Station (SS) experiences different channel condition. Therefore, our objective is to study an efficient

scheduler algorithm that considers channel conditions and traffic load for SSs.

Obviously, a scheduler in either wired or wireless networks has performance metrics. The most important performance metrics for schedulers are:

- Throughput– is a ratio of total sending bits to channel capacity. An efficient scheduler should try to maximize the throughput as much as possible.
- Fairness– allocating resources fairly among users is one of a scheduler’s objectives.
- QoS provision– a good algorithm supports different types of traffic. In addition, the scheduler aims to meet the delay bound for all services.
- Complexity– a scheduling algorithm must be easy to implement since the hardware has limited computational power.
- Scalability– a scheduler should be adaptive when the number of users to be scheduled increases.

### 1.3 Thesis Contribution

The main contribution of this thesis is to propose two-level scheduling algorithms for integrated EPON and WiMAX. In the first stage, from SSs to WiMAX, we use proportional fairness algorithm to coordinate the transmissions over the WiMAX channel. At the next level, a centralized algorithm at the OLT is proposed for the EPON uplink to schedule transmissions among WiMAX-ONUs. Even though a few papers have studied scheduling in converged WiMAX and EPON, to the best of our knowledge, none of them consider jointly link adaption, queue length, and head-of-line delay. Our main performance metrics in this thesis are increasing the

throughput of the uplink in the converged network, and supporting real time traffic. Finally, the proposed model is further verified using computer simulations.

## **1.4 Thesis Organization**

The remainder of this thesis is organized as follows: Chapter 2 reviews the background of EPON and WiMAX, especially the MAC protocol and QoS requirements in both technologies. Chapter 3 introduces state-of-the-art scheduling algorithms that exist in the literature. Chapter 4 focuses on the related work for scheduling in converged architectures, and explains the proposed scheme in much detail. The numerical simulation results and parametric studies are presented in Chapter 5. Finally, Chapter 6 concludes this work and offers some preliminary ideas for future work.

# Chapter 2

## Metropolitan Area Networks (MANs)

### 2.1 Overview for the Integration of WiMAX and EPON

To the best of our knowledge, few proposals exist that discuss the integration of WiMAX and EPON. The authors in [3] proposed three architectures for integrating WiMAX and EPON or WiMAX and optical fiber. In the first scheme, an edge node is connected to each WiMAX base station without using a splitter, so it is not PON architecture. In other words, there is a fiber link between the edge node and each WiMAX base station with the capacity of  $1Gbps$ . The first scheme can achieve high throughput and support QoS yet has a major drawback; it is very expensive to deploy. The second proposed architecture takes advantage of PON networks in which there is a splitter for the link between the OLT and all integrated Optical Network Units (ONUs) and WiMAX antenna. Thus, all integrated ONUs and WiMAX antenna share the link between the splitter and the OLT. The advantages

of this architecture are: efficient throughput, QoS support, and low cost to deploy. The third approach suggests that the OLT is connected to a centralized WiMAX base station, which the latter connected to all WiMAX base stations. It does not achieve good throughput, nor does it support QoS. As a result, the best architecture is the one based on PON architecture because it provides efficient throughput, controls end-to-end delay, and is inexpensive to deploy. However, the authors did not state how the integration between the two technologies works in terms of messages exchange, bandwidth allocation, and scheduling the uplink stream.

The authors in [4] proposed four system models for integrating WiMAX and EPON. In the first scheme, the WiMAX base station connects to ONU the same as any other user. Thus, WiMAX and EPON are working independently, so this system is costly because two technologies have to be deployed. The authors solved the independence of the two systems by combining both of them in one system box. The second architecture integrates the hardware and software and, as a result, has more advantages than the independent scheme example. This hybrid proposal highly reduces the cost of converged technologies and, in addition to, each WiMAX-ONU has all information on the required bandwidth from the users. In the third scheme, the MAC layer for EPON has to be modified in order to carry the WiMAX frame or MAC PDUs instead of the Ethernet frame. The last architecture is not of interest to us as it is microwave over fiber.

## **2.2 Overview of WiMAX**

WiMAX is a promising technology in broadband wireless access in MANs. In order to support fixed broadband wireless and mobile access, several standards have been published to include them. In the following sections, brief introductions for fixed and mobile broadband wireless access technologies are provided.

### 2.2.1 WiMAX Broadband Wireless Access

Originally, WiMAX network was designed for fixed broadband wireless access in order to provide similar services as traditional wired access. The physical layer standard supports Line of Sight (LOS) wireless access and operates between 10GHz-66GHz. In addition, the MAC layer of this standard has two modes: mesh access, which defines air interfaces from subscriber station to subscriber station, and Point-to-Multi-Point access (PMP), which defines air interfaces from the base station to subscriber stations. The multiplexing of this standard includes only time division along with single carrier for air interface. In the beginning of 2001, IEEE 802.16a standard was published which was an improvement over the previous standard, IEEE 802.16. The important characteristic of the new standard is that it supports Non-Line of Sight (NLOS) between the sender and receiver, and operates from 2GHz-11GHz band. IEEE 802.16a uses Orthogonal Frequency Division Multiplexing (OFDM) for air interfaces, rather than single carriers with time division as in IEEE 802.16. The final standard for fixed broadband wireless was published in 2004. IEEE 802.16d or IEEE 2004 is based on IEEE 802.16a with amendments to enhance the uplink traffic. Figure 2.1 illustrates an example of IEEE 802.16d for broadband wireless networks where the base station (*BS*) provides access to fixed *SSs*. In order to support mobility, a new standard or modification for previous standards had to be published. Therefore, Mobile WiMAX or IEEE 802.16e which aims to support mobile and nomadic users, was released in 2005. Table 2.1 summarizes the most important releases of IEEE 802.16 family. In this thesis, we only consider the fixed broadband wireless access in the integration with EPON. In addition, we will only discuss the MAC layer for WiMAX and the quality of service classes that WiMAX supports.

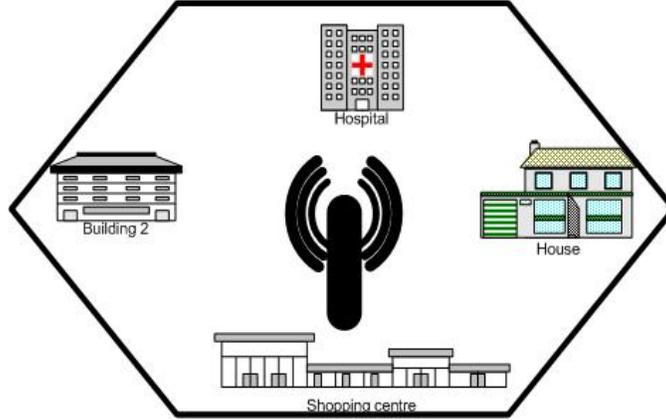


Figure 2.1: Fixed Broadband Wireless Networks

Table 2.1: Important IEEE 802.16 Standards

Standard	Spectrum or Frequency	Purpose	Completion
802.16a	$2GHz - 11GHz$	Support NLOS	2001
802.16d	$2GHz - 11GHz$	For fixed stations	2004
802.16e	$2GHz - 6GHz$	Support mobility	2005
802.16j	$2GHz - 6GHz$	Increase the coverage using relays	late 2007
802.16m	Less than $6GHz$	Support high data rate	late 2008

### 2.2.2 MAC Layer in WiMAX

MAC layer in WiMAX is subdivided into three layers as proposed in IEEE 802.16. The first layer, shown in Figure 2.2, is the service specific Convergence Sublayer (CS) that makes the MAC protocol in WiMAX independent of the higher layers, e.g., Ethernet, ATM. When the CS receives external data from a higher level, it converts them into proper MAC Service Data Units (SDUs) and assigns each SDU with flow and connection identifiers. The main functions of a common part sublayer are offering bandwidth allocation for fragmented SDU or Protocol Data Unit (PDU), meeting QoS requirements, scheduling for uplink and downlink, and maintaining connection. Security is considered one of the important aspects in

IEEE 802.16, so the MAC layer has a sublayer to take care of the encryptions and authentications.

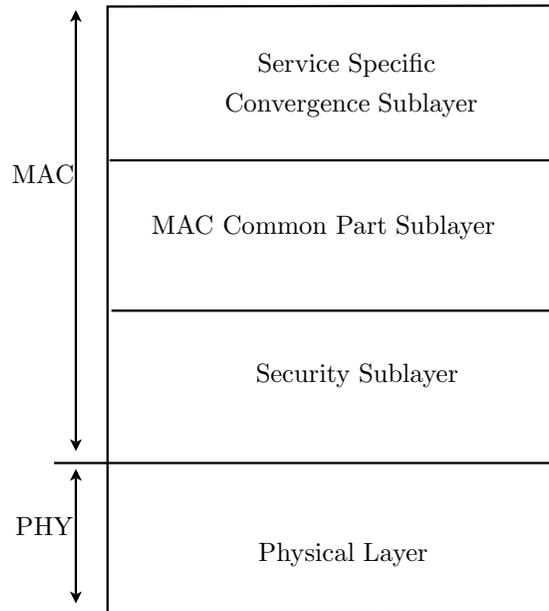


Figure 2.2: IEEE 802.16 Reference Mode

### 2.2.3 Quality of Service

The lack of support of QoS in Wireless Local Area Networks (LANs) has motivated IEEE 802.16 Working Group to consider QoS provisioning as a major objective. Each service flow of SDUs has QoS requirements such as delay, throughput, and maximum jitter delay [5][6]. When the BS receives SDUs from SSs, it uses QoS parameters associated with each SDU in order to efficiently schedule and allocate bandwidth for the transmission of SSs. WiMAX divides the SDUs into four classes of services, each of which has some QoS requirements that have to be met by the BS. The followings are the QoS classes, together with an example of each class (Table 2.2 summarizes all the services):

- Unsolicited Grant Service (UGS), where it supports real-time constant bit rate or fixed packet size such as T1/E1 line or Voice over IP (VoIP) traffic. This service does not need to request a bandwidth from BS since the latter periodically allocates bandwidth for UGS. For UGS, BS has to guarantee delay, jitter, and throughput.
- Real-time Polling Service (rtPS), is similar to UGS in term of generated traffic at periodic interval such as video conferencing, video streaming, and MPEG. However, rtPS is different from UGS as the SS has to request BS for bandwidth allocation. In addition, the packet length is variable, not constant like UGS. Thus, this service guarantees maximum latency and throughput.
- Non-real-time Polling Service (nrtPS), does not guarantee delay or jitter. However, it requires minimum throughput for its traffic. An example of this service is File Transfer Protocol (FTP).
- Best effort (BE) service, provides no QoS guarantee. Its applications include web or HTTP and electronic mail.

Table 2.2: QoS Requirements for IEEE 802.16

Service name	QoS parameter	Example	Request bandwidth
UGS	Delay, Jitter, throughput	VoIP	No
rtPS	Maximum delay, throughput	MPEG, Video Conference	YES
nrtPS	Minimum throughput	FTP	YES
BE	No QoS provision	Email, HTTP	YES

## **2.3 Ethernet Passive Optical Network Standards (EPON)**

Passive optical networks (PON) is considered as an important solution in broadband access networks. In this context, "passive" means that the devices between the OLT and ONUs, such as splitters and combiners are passive. The feature of passive devices has motivated IEEE 802.3 and International Telecommunication Unions Standardization Sector (ITU-T) to form working groups for PON technology in first mile from a user's perspective or last mile from a service provider's perspective. Based on the multiplexing, the standards of PON can be divided into two classes: TDM-based and WDM-based. We will discuss TDM-PON standards in this thesis. Asynchronous transfer mode (APON) and broadband PON (BPON), released by ITU-T, encapsulate the stream of data from the OLT to ONUs or vice versa in ATM cells. However, their applications focus on businesses given their high deployment cost in homes or buildings. On the other hand, Ethernet PON (EPON) or Gigabit PON(G-PON), published by IEEE Ethernet First Mile (IEEE/EFM), seems to be the most attractive solution when compared to APON or BPON due to its cost effectiveness and better bandwidth utilization. Table 2.3 summarizes the important standard for the PON technology [7].

### **2.3.1 TDM-PON Architecture**

TDM-PON networks are implemented in different topologies such as star, tree, and ring. In Figure 2.3, the OLT connects with 32 ONUs in a tree topology manner where the packets are broadcasted from point-to-multipoint or from multipoint-to-point. The downstream link is broadcast, thus there is no problem in downstream because there is only one sender (OLT) and many receivers (ONUs). Every ONU distinguishes its packets coming from the OLT using its MAC address under PMP.

Table 2.3: Passive Optical Networks Standards

Standard	IEEE/ITU-T	Ethernet/ATM/WDM data unit	Bandwidth
EPON	IEEE 820.3ah	Ethernet	1Gb/s downstream 1Gb/s upstream
10GPON	IEEE 802.av	Ethernet/ATM/GEN	10 Gb/s downstream 10Gb/s upstream
BPON /APON	ITU-T G.983	WDM/ATM	622Gb/s downstream 155 upstream
GPON	ITU-T G.984	Ethernet/ATM/GEN	2.48 Gb/s downstream 1.24Gb/s upstream

After that, each ONU will resend its received packets to the users attached to it. On the other hand, upstream link, multipoint-to-points, is shared among all ONUs to send their packets to the OLT. Since packets from each ONU are transmitted directly, no connection among ONUs to the OLT in uplink is required. Collisions may occur when two or more ONUs transmit simultaneously. As a result, the major functionalities of OLT are to schedule the uplink and allocation of the time slots effectively between all ONUs.

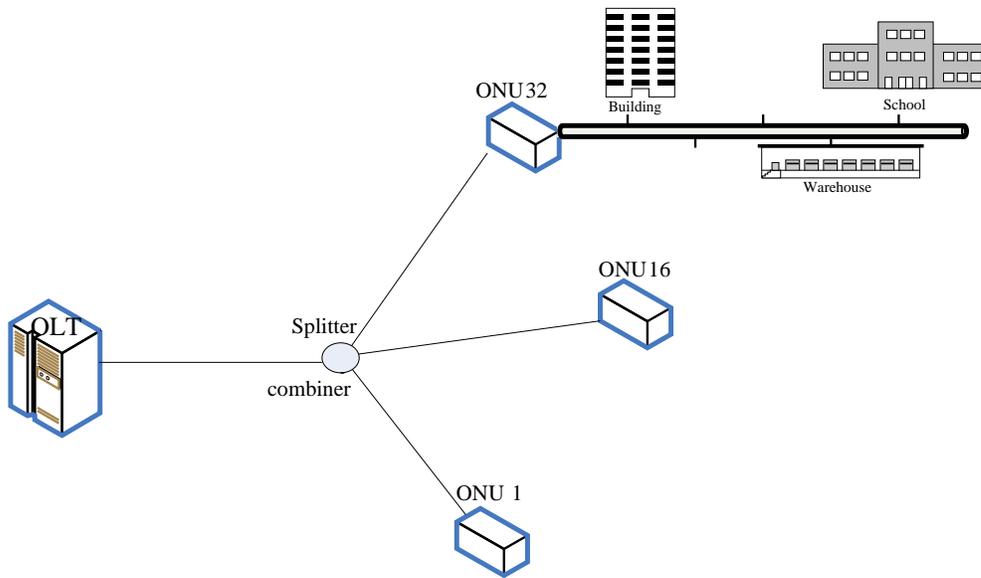


Figure 2.3: Ethernet Passive Optical Network: Tree Topology

### 2.3.2 Medium Access Control in EPON

The standard IEEE 802.3ah for EPON assumes there is no connection between any ONUs. Thus, the Carrier Sense Multiple Access with Collision Detection (CS-MA/CA), which is used in LANs, is not able to be deployed in EPON. The transmitted ONUs do not have any information about the collided packets at the OLT. Although the OLT could inform ONUs about the collided packets, the distance between OLT and each ONU may decrease the efficiency of the system. An alternative solution would be using Time Division Multiple Access (TDMA), where the centralizing OLT coordinates the transmission data from ONUs in a timely manner. Even though TDMA is currently the best solution for EPON, it has some issues to be addressed, such as dynamical allocation of time slots, transmission scheduling among ONUs, and support/differentiation of different QoS classes.

### 2.3.3 Multi-point Control Protocol

IEEE 802.3ah for EPON specifies the MAC sublayer control protocol, called Multi-Point Control Protocol (MPCP). Figure 2.4 illustrates the frame structure of MPCP. MPCP has two important messages: GATE message and REPORT message. Both are used for bandwidth assignment, and each has the same frame structure as the MPCP frame. The REPORT message is sent by an ONU which contains destination address, source address, length (up to eight queues), opcode ID for REPORT message, and time that the message was sent. The GATE message conveys the destination address, source address, grant size, timestamp of the GATE message, and start time for transmitting frames from a particular ONU [8].

MPCP Frame Format

Destination Address	Source Address	Length	Opcode	Timestamp	Padding	Frame Check Sequence
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Figure 2.4: MPCP Frame Structure

### 2.3.4 Fixed and Dynamic Bandwidth Allocation

The OLT divides time resources into time slots. These slots may be allocated statistically or dynamically. In static or Fixed Bandwidth Allocation (FBA), time slots are equally distributed to each ONU in the network. Fixed or static bandwidth allocation achieves fairness between all the ONUs. However, sometimes the ONU does not efficiently use its time slots because there is no high traffic or the queues are empty. Therefore, FBA is not an efficient algorithm since it cannot support QoS and maximize throughput. Dynamic Bandwidth Allocation (DBA) is a more attractive solution. DBA can be divided into QoS support and statistical multiplexing [2]. DBA algorithms can achieve either QoS assurance or statistical multiplexing by assigning time slots to ONUs on a polling mechanism. Each ONU sends a Report message to the OLT about the buffer occupancy. The latter allocates time slots using DBA time slot size for each Report. In [9] the authors proposed DBA algorithm for EPON which is based on interleaved polling with adaptive cycle. Prior to each cycle, the OLT receives Report messages from all active ONUs. Based on the collected Report messages, the OLT grants resources to each ONU according to the DBA algorithm. The author in [9] proposed four DBA algorithms to grant the Reports messages. First, the limited service algorithm grants each ONU its Reported bandwidth, but no more than a maximum transmission window is given. The maximum transmission window prevents the ONU that has high traffic demand to consume all the available bandwidth. Second, the credit constant

algorithm grants the ONUs with the requested time slots and extra bytes up to the maximum window size. The limited algorithm assumes no more packets arrive after the Report message is sent, whereas the credit constant does not. The other two algorithms are similar to the previous mentioned algorithms.

### 2.3.5 Quality Of Service

EPON is capable of delivering different applications such as video conferencing, Internet Protocol Television (IPTV), and non-real time traffic such as File Transfer Protocol (FTP) [10]. Each service must meet some QoS requirements such as delay, throughput, packet loss ratio, or jitter. Each service has a priority to be served based on QoS requirements. As shown in Figure 2.5, the packets coming from the users to each ONU are prioritized by packet prioritizer, so the packets either correspond to class 1, class 2, or class 3. Class 1 corresponds to high-priority traffic such as voice or VoIP; class 2 has high traffic with longer delay than that in class 1, such as video services; and class 3 has no guarantee for QoS. Priority queues can be preemptive or non-preemptive. If the high-priority traffic found its queue full, the low-priority queue will be dropped to allow high-priority traffic to enter the queue. However, when the low-priority traffic finds the system full, it will not preempt any other traffic so it will be dropped.

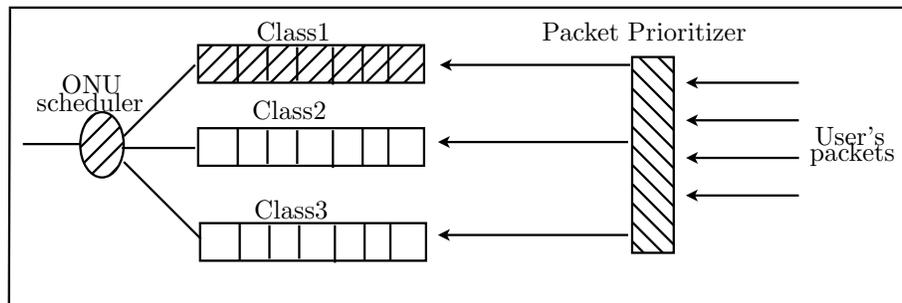


Figure 2.5: Priority Queues

### 2.3.6 Scheduling

As shown in the previous section, each ONU should have priority queues that correspond to the service that each of them is supposed to provision. In addition, an efficient scheduler should be implemented in each ONU to guarantee the service constraints. This scheduling mechanism is called intra-ONU since the scheduler only coordinates the transmission in each time slot among all the priority queues. On the other hand, inter-ONU implements at the OLT, which is responsible for arbitrating the uplink data streams among all the active ONUs. Figure 2.6 illustrates the inter-ONU and intra-ONU schedulers.

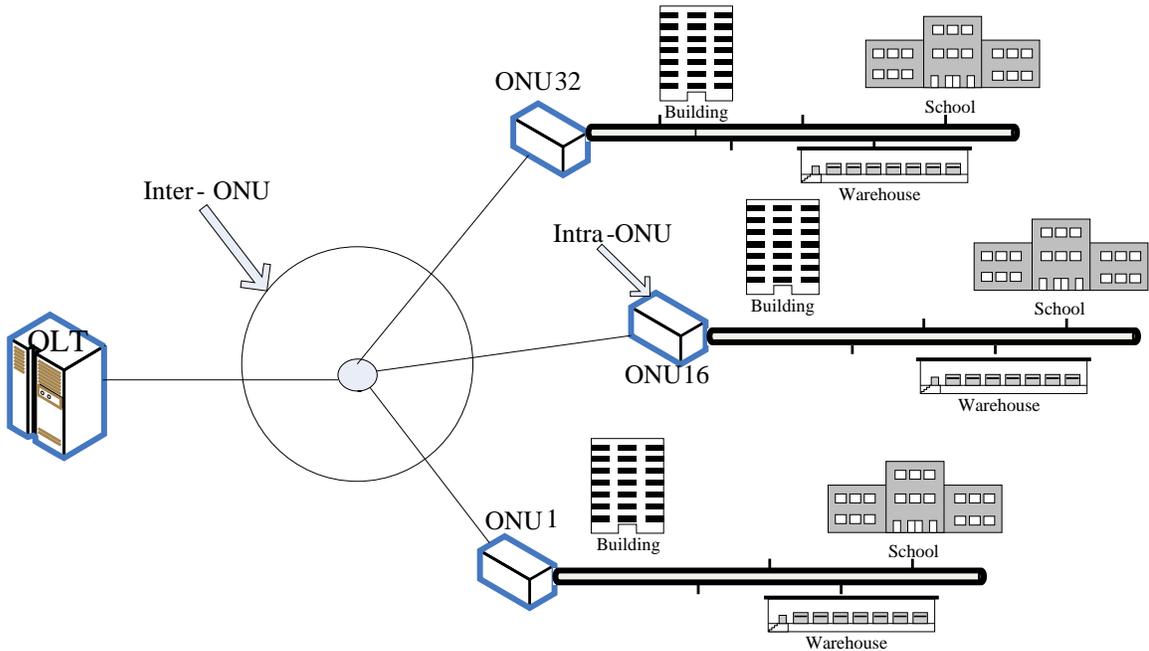


Figure 2.6: Intra-ONU and Inter-ONU Scheduler

The OLT may use an online or offline algorithm for uplink scheduling. Online means that the OLT assigns the uplink resources for a given ONU once the ONU's Report arrives at the OLT. Thus, the OLT has less information on the traffic conditions of ONUs. On other hand, when the OLT waits for all Reports to arrive before performing scheduling, the scheduling algorithm is called offline. In order

for the OLT to schedule the queues for all the ONUs, the Report messages have to contain the buffer occupancy for all queues in an ONU. Thus, IEEE 802.3ah formed MPCP to be able to carry up to eight Reports. After the OLT receives the Report messages from all ONUs, it has all the information necessary to improve the transmission efficiently. The drawback of this scheme is that the number of grant messages will increase with the number of queues and, also, the OLT will be subject to a larger computation overhead [2][11].

The other type of scheme is based on a two-layer scheduler algorithm, where the OLT is only responsible for arbitrating the uplink traffic among the ONUs and granting the bandwidth requested for each ONU. The latter will then divide the bandwidth among the queues according to a certain policy. The policy could be strict or non-strict. In the strict scheduling, the low-priority packets will not be selected as long as the high-priority queues are not empty. For the non-strict scheduling algorithm, the ONUs do not schedule traffic after sending the Report message.

## 2.4 Summary

In this chapter, an overview of the state-of-the-art architectures for EPON and WiMAX is given. In addition, the important standards for WiMAX and EPON are briefly discussed. We also mention the reference model for MAC layer in WiMAX, and QoS classes that WiMAX supports. For EPON, we discuss the MAC protocol along with MPCP protocol. Finally, we discuss the MAC layer and QoS provision for EPON and WiMAX that is supported by each of them. In the next chapter, details for related work of scheduling in hybrid WiMAX and EPON networks is provided. We will also propose a scheduling scheme for integrating the two technologies. Specifically, the system model, channel model, and scheduling algorithm for integration of EPON and WiMAX networks.

# Chapter 3

## Overview of Scheduling Algorithms

### 3.1 Scheduling Algorithms

A scheduling algorithm plays an important role in wired and wireless networks, aiming to achieve efficient network resource allocation and satisfy performance metrics. Scheduling algorithms can be classified as: channel-aware, queue-aware, or channel-aware and queue-aware [12]. In this chapter, we review some of the scheduling algorithms that have been proposed in the literature.

### 3.2 Round Robin

Round Robin (RR) is well known as the most naive fair algorithm. RR at Base Station (BS) divides the cycle into time slots and each  $SS$  is assigned a time slot by BS. Thus, every  $SS$  transmits its packets in its time slot, while the cycles and service sequence are fixed. One of the pros of RR is its fairness between all the users, WiMAX-ONU, and  $SS$ . Even though an  $SS$  has bad channel condition, it

would reserves the channel in its time slot. On the other hand, the RR algorithm may fall short in terms of the ability of maximizing the overall throughput.

### 3.3 MaxSNR or Max-Sum

The MaxSNR was proposed to achieved high throughput since RR had failed to achieve this goal. The scheduler assigns adaptively to a user with the best channel condition in each time slot in order to maximize the throughput. However, the MaxSNR cannot be fair among all the users because the algorithm always selects the user with the strongest channel condition.

In [13][14], the authors proposed absolute SNR-based scheduling by using the following equation:

$$m = \operatorname{argmax}_{i \in M} \gamma_i \quad (3.1)$$

where  $M = \{1, 2, \dots, M\}$  is the set of user indices, and  $\gamma_i$  is the instantaneous *SNR* of user  $i$ . When each user experiences different average *SNR* values, the algorithm schedules users based on normalized *SNR* [15]. The normalize-SNR scheduler aims to balance throughput and fairness. Normalized SNR-based scheduling can be expressed as follows:

$$m = \operatorname{argmax}_{i \in M} \left( \frac{\gamma_i}{\Gamma_i} \right) \quad (3.2)$$

where  $\Gamma_i$  is the average *SNR* of user  $i$ . In other words,  $E[\gamma_i] = \Gamma_i$

### 3.4 Proportional Fairness

Proportional Fairness (PF) aims to jointly consider two performance metrics: fairness and throughput. PF selects the user with the highest value of the following preference metric:

$$\frac{S_k[t]}{R_k[t]} \quad (3.3)$$

where  $S_k[t]$  is the current data rate for user  $k$  at time slot  $t$ , and  $R_k[t]$  is the average rate perceived by the user  $k$  up to time slot  $t$ . The scheduler updates average rate  $R_k[t]$  for each user  $k$ . If user  $k$  is served at time slot  $t$ , it averages service rate update as

$$R_k[t + 1] = \left\{ \left( 1 - \frac{1}{t_c} \right) R_k(t) + \left( \frac{1}{T_c} \right) S_k[t] \right\}$$

Otherwise,

$$R_k[t + 1] = \left( 1 - \frac{1}{t_c} \right) R_k(t)$$

where  $t_c$  is time constant usually chosen to be 1000 slots.  $t_c$  is a critical factor in the PF scheduler since the user  $k$  will be visited frequently when  $t_c$  is small [16].

### 3.5 Modified Largest Weighted Delay First (M-LWDF)

In [17], the authors proposed a scheduling algorithm, called Modified Largest Weighted Delay First, in order to support QoS and maximize the channel capacities. M-LWDF has been proven to be throughput optimal. Each time slot  $t$ , the scheduler is serving queue  $m$  for which  $\nu_m W_m(t) r_m(t)$  is maximal, where  $W_m(t)$  a length or head-of-line packet delay for queue  $m$ ,  $r_m(t)$  is the channel capacity, and  $\nu_m$  is an arbitrary non-negative constant. Thus, the scheduling algorithm considers not only queue length but also channel conditions [18].

# Chapter 4

## Proposed A Scheduling Algorithm for the Hybrid Architecture

### 4.1 Scheduling for Hybrid Networks

Link scheduling is an essential component in both homogeneous and heterogeneous networks. In hybrid WiMAX and EPON networks, the scheduler must adopt a policy that takes into account the wireless channel condition of WiMAX and network availability of EPON. In addition, the scheduler should be either centralized at the OLT or completely distributed as multi-hop scheduling.

Without an efficient scheduler, the performance metrics such as throughput, delay, or fairness will not be met. Our centralized scheduler is channel-aware and queue-aware for integrated EPON and WiMAX systems. In other words, the scheduler not only considers the queue length and head-of-line delay of the WiMAX-ONU queues, but also takes into account channel fluctuation in WiMAX. In the next section, we will review related work for scheduling schemes in integrating the WiMAX and EPON. After that, we will outline the system architecture, WiMAX and EPON channel models, and scheduling algorithms that we use in this work.

## 4.2 Related Work

In [19], the authors proposed a QoS-aware scheduling mechanism for hybrid optical and wireless network considering quality of service (QoS) requirements. They proposed two approaches for QoS-aware scheduling. Firstly, the scheduling algorithm acts as a multi-hop network, in which each hop forwards data packets based on the network resource availability along the way to the OLT. However, the distributed algorithm does not reduce latency and provide QoS. Therefore, the authors proposed a centralized scheduling algorithm located at the OLT, which receives all the requests from each *SS* such that only the OLT can schedule all *SSs* based on the QoS requirements. This scheduling algorithm takes advantage of MPCP message protocol, specifically Report and Gate messages, for bandwidth allocation. However, the authors did not consider two-level scheduling algorithms and the queue length of ONU queues.

## 4.3 System Model for Hybrid Network

We consider a tree topology for the hybrid WiMAX and EPON integrated networks. The OLT connects to each WiMAX-ONU by a splitter [4]. In this model, the OLT is responsible for scheduling the up-link traffic among all the WiMAX-ONUs since they share the up-link resources from the splitter/combiner to the OLT, as seen in Figure 4.1.

Since each WiMAX-ONU is accessed by multiple *SSs*, a scheduling scheme is needed at the WiMAX-ONU to arbitrate the up-link channel among all *SSs* in its cell. We assume that there is no inter-cell interference. For the up-link transmission, each WiMAX's MAC layer receives the traffic from its *SSs* and puts them in the corresponding queues. Internally, traffic in each WiMAX queue is aggregated and

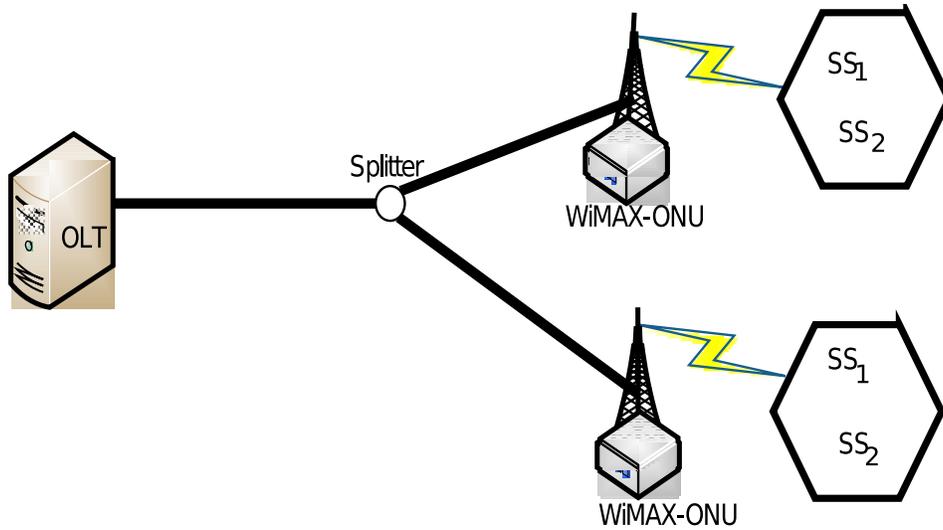


Figure 4.1: Hybrid Network

then moved to the ONU's queues. Without loss of generality, suppose we have two *SSs* in a cell as exemplified in Figure 4.2. Each *SS* has four queues in WiMAX's BS. So, the traffic in all queues at the WiMAX's BS will be aggregated into just four queues in the ONU to be sent to the OLT. Then, the OLT may or may not schedule those traffic in the next time slot depending on the scheduling algorithm.

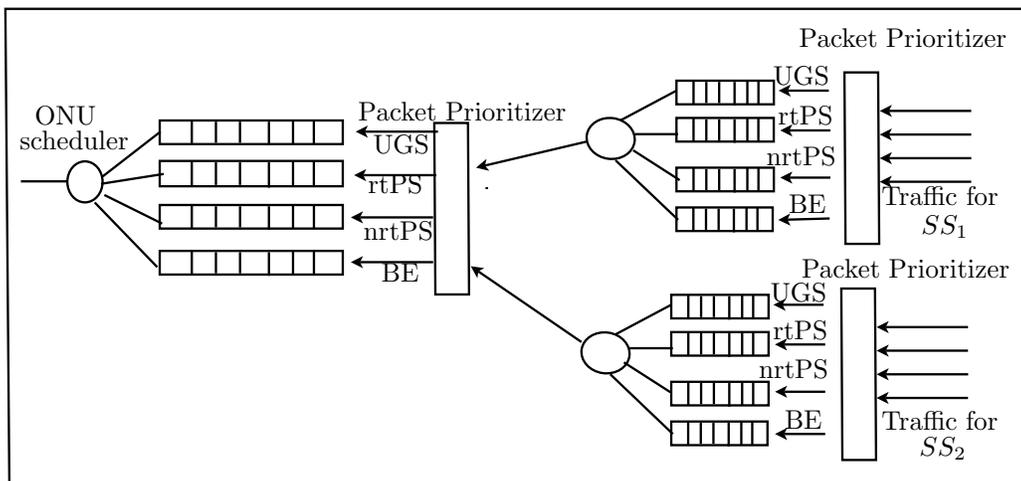


Figure 4.2: Queues Mapping

## 4.4 Channel Model

### 4.4.1 Wireless Channel

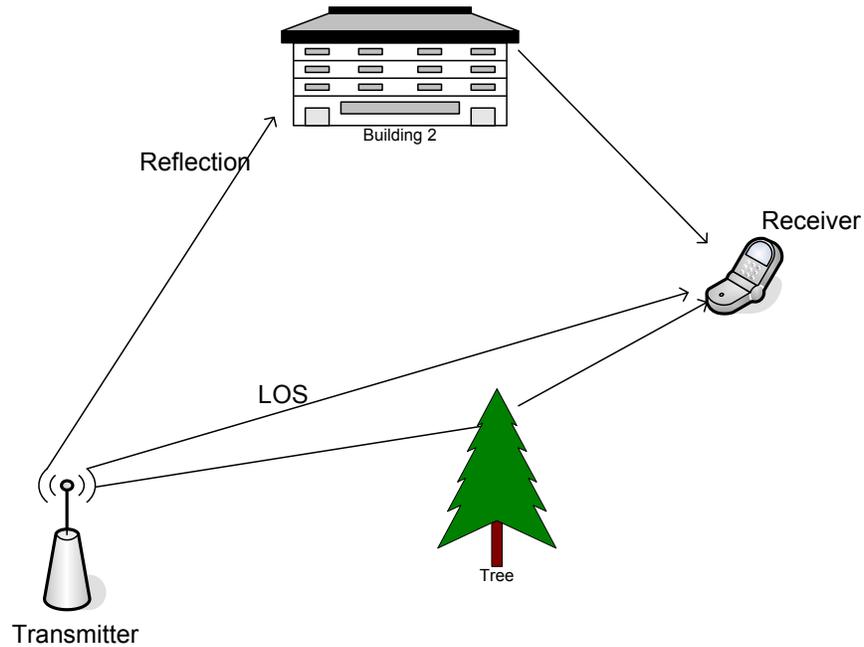


Figure 4.3: Path loss and Shadowing

Two sources of impairments on received signals are identified in the study: large scale effects and small scale effects. Large scale effects for the received signal can be classified into two factors: path loss and shadowing effects. For the Pathloss, the received power is decreasing inversely proportional to the distance between the transmitter and the receiver. The power received affected by path loss can be written as

$$P_r = P_t P_0 \left( \frac{d_0}{d} \right)^\alpha \quad (4.1)$$

where  $P_0$  is the reference path loss at reference  $d_0$ , and  $\alpha$  is the path loss exponent. Usually, the path loss exponent varies from 2 to 6. In addition to path loss,

obstructions such as trees, buildings, and hills, may cause the received power to fluctuate. The effects due to obstacles are called shadowing, so the received power varies due to path loss and shadowing modeling as

$$P_r = P_t P_0 \left( \frac{d_0}{d} \right)^\alpha + S \quad (4.2)$$

where  $S$  is random variable follows log-normal distribution with zero mean and standard deviation  $\sigma$  in dB.

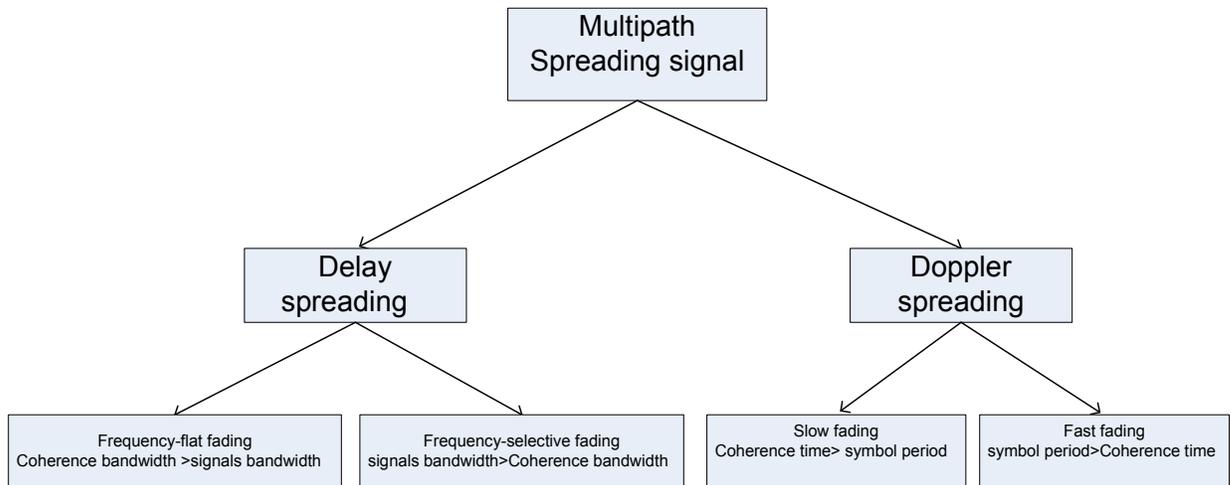


Figure 4.4: Multipath Spreading Signals

Multipath effects happen when the receiver receives many versions of the same transmitted signal from different paths. The signal from each path could be different in amplitude, phase, and delay from that of other paths. The multipaths effects affect the signals to be spreading as delay or Doppler spreading, which is illustrated in Figure 4.4. In summary, we can have four fading channels: fast fading, slow fading, flat fading, and selective fading, as shown in Figure 4.5 [20] [21] [22].

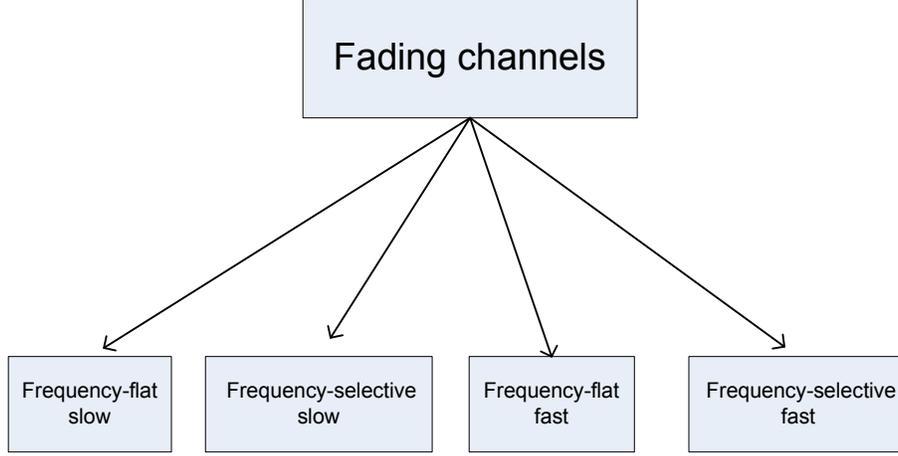


Figure 4.5: Fading Channels

#### 4.4.2 WiMAX Channel

We consider multiuser diversity in a single cell governed by a single WiMAX-ONU. We assume that the wireless channel is modeled as Rayleigh fading channel. Each  $SS$  measures its instantaneous  $SNR$  and feeds it back to the WiMAX-ONU, which takes advantage of the received  $SNR$  to collect Channel State Information (CSI).

Received Signal of  $user_{ss}$

$$r_{ss}(t) = h_{ss}(t)x(t) + n_{ss}(t), \quad ss = 1, 2, \dots, M \quad (4.3)$$

where  $x(t)$  is the transmitted signal in time slot  $t$ ,  $r_{ss}(t)$  is the received signal of user  $ss$  in time slot  $t$ ,  $n_{ss}$  is background noise, and  $h_{ss}$  is the channel gain by jointly considering the multipath effects, shadowing effects, and path loss exponents. The channel gain can be expressed as:

$$h_{ss} = \left( \frac{c}{d_{ss}^\alpha} \right)^{\frac{1}{2}} (k_{ss})^{\frac{1}{2}} m_{ss} \quad (4.4)$$

where  $c$  is a constant for transmission and receiver antenna,  $d_{ss}$  is the distance between  $user_{ss}$  and the associated WiMAX-ONU,  $\alpha$  is path loss exponent. For a

given  $k_{ss}$ , the amplitude of  $h_{ss}$  follows Rayleigh distribution. If the power transmission of the WiMAX-ONU is  $P_t$ , the receiving power by the  $SS$  is  $P_{ss} = |h_{ss}|^2 P_t$ . It is a valid assumption that the transmitted power  $P_t$  is always constant for all  $SSs$ , and the  $SNR$  at each  $SS$  is expressed as:

$$SNR_{ss} = \frac{P_{ss}}{P_n} \quad (4.5)$$

where  $P_n$  is the noise power.

The average received  $SNR$  for user  $ss$  can be expressed as:

$$\overline{SNR_{ss}} = \rho (D/d_{ss})^\alpha k_{ss} \quad (4.6)$$

where  $\rho$  is median  $SNR$  and  $\alpha$  is the path loss exponent. Since the noise power is constant, the received  $SNR$  will be modeled as an exponential random variable. Further details can be found in [23] [24] [25].

## 4.5 Adaptive Modulation and Coding

With Adaptive Modulation and Coding (AMC), each  $SS$  measures its CSI to feedback to the WIMAX-ONU in the downlink direction by which an appropriate modulation and coding rate is selected. For uplink, the WIMAX-ONU could determine the quality of the channel based on the channel condition of each  $SS$ . By assuming uplink and downlink directions are subject to the same channel, both directions take the transmission rate based on Table 4.1. We have OFDM as air interface with 256 carriers, the bits per OFDM symbol can be calculated as Equation 4.7 given 192 data carriers and 8 pilot carriers.

Table 4.1: Adaptive Modulation and Coding (AMC)

Mode K	1	2	3	4
Modulation	BPSK	QPSK	16 QAM	64 QAM
Coding rate	$\frac{1}{2}$	$\frac{1}{3}$ $\frac{3}{4}$	$\frac{1}{2}$ $\frac{3}{4}$	$\frac{2}{3}$ $\frac{3}{4}$
bits/ OFDM symbol	88	184 280	376 568	760 856
Receiver SNR (dB)	6.4	9.4 11.2	16.4 18.2	22.7 24.4

$$|Bits/OFDMsymbol| = \begin{cases} (192 * 1 * \frac{1}{2}) - 8 & \text{if BPSk } \frac{1}{2}, \\ (192 * 2 * \frac{1}{2}) - 8 & \text{if QPSk } \frac{1}{2}, \\ (192 * 2 * \frac{3}{4}) - 8 & \text{if QPSK } \frac{3}{4}, \\ (192 * 4 * \frac{1}{2}) - 8 & \text{if 16QAM } \frac{1}{2}, \\ (192 * 4 * \frac{3}{4}) - 8 & \text{if 16QAM } \frac{3}{4}, \\ (192 * 6 * \frac{2}{3}) - 8 & \text{if 64QAM } \frac{2}{3}, \\ (192 * 6 * \frac{3}{4}) - 8 & \text{if 64QAM } \frac{3}{4}, \end{cases} \quad (4.7)$$

## 4.6 Multiuser Diversity

The phenomena of multiuser diversity appears only in time-varying fading wireless channels. In a system with a transmitter and  $N$  receivers of independently varying channels, it is highly possible that some users with better channel conditions than that of the others. Thus, if the the scheduler always opportunistically selects the users with better channel conditions, the overall throughput will be much improved [26].

## 4.7 IEEE 802.16 Frame Structure

A WiMAX frame is divided into uplink and downlink subframes. There are two duplex techniques for a subframe: either frequency-division duplex (FDD) or time-division duplex (TDD). In FDD, an *SS* allows to transmit and receive packets simultaneously. However, with the TDD technique, uplink and downlink subframes share the same medium in different intervals [27]. The TDD frame structure for IEEE 802.16 is illustrated in Figure 4.6. The whole frame consists of integer physical slots (PS). The number of PSs depends on the system parameters such as frame length and symbol rate. By assuming that each PS has four symbols, the number of  $n$  PS can be found using the following equation:

$$n \text{ PS} = \frac{\text{SymbolRate} \times \text{FrameLength}}{4} \quad (4.8)$$

where  $n$  is an integer number, and the frame length may range from  $2ms$  to  $20ms$  [28].

## 4.8 Physical Slots Allocation

In uplink transmission, a BS uses a grant-per-SS scheme for PS allocation. For instance, a scheduler at BS's MAC layer selects one of the SSs for the first PS, and again repeats choosing one of the SSs until the PSs are allotted. The procedure considered in this study is described as follows:

- We adopt proportional fairness (PF) in our scheduling algorithm at WiMAX's MAC layer. In each frame, PF uses the current channel conditions and exponential moving average to assign resources to each SS as defined in Equation 3.3. Firstly, PF selects one of the SSs for the first PS and updates the

moving average for all  $SSs$ . Then, PF chooses one of  $SSs$  for second PS and updates the exponential moving average, and so on.

- When an  $SS$  wins a slot, all data carriers assigned to this  $SS$ . All connections at the  $SS$  share the resources of the assigned time slot.

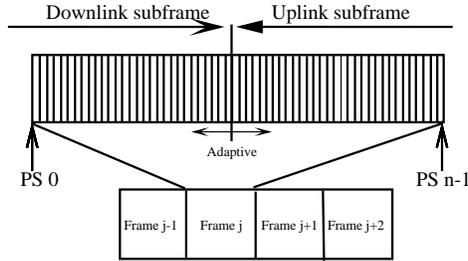


Figure 4.6: TDD Frame Structure

### 4.8.1 EPON Channel

IEEE 802.3ah suggests only one optical fiber for upstream and downstream links. In other words, the topology of EPON is a single fiber point-to-multi-point (P2MP), from the OLT to the ONUs via a splitter, and multi-point to point from the ONUs to the OLT via combiner. EPON operates in a full duplex mode with two different wavelengths for upstream and downstream. The wavelength for upstream is at  $1310\text{ nm}$ , and for downstream is at  $1490\text{ nm}$ , as shown in Figure 4.7 [29] [7].

## 4.9 The Proposed Scheme

An centralized scheduling algorithm is proposed for EPON uplink transmission. The scheduler at the OLT considers the WiMAX channel condition, ONU queues length, and rtPS head-of-line delay, in order to allocate the frames for WiMAX-ONUs. For bandwidth allocation, EPON's frame is divided into two slots. Usually,

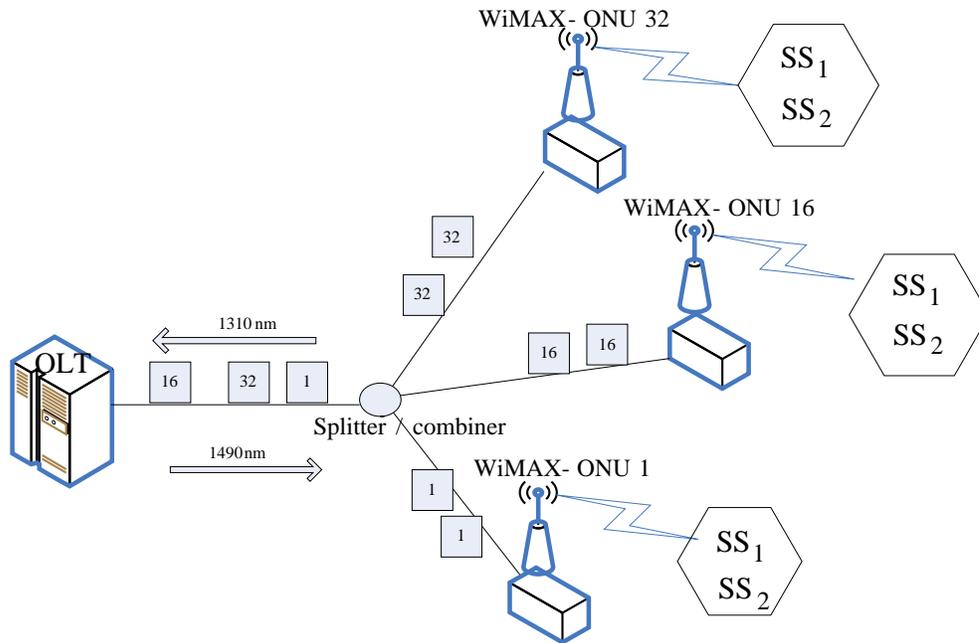


Figure 4.7: EPON Channels

the UGS queues will be assigned the first slot of the frame, and rtPS or nrtPS queues will take the second slot. In addition, each slot further divides into mini-slots as illustrated in Figure 4.8.

The length of an EPON's frame is the same as the length of WiMAX frame. In the beginning, the OLT polls each WiMAX-ONU, which sends the Report message containing information about each cell condition, length of rtPS and nrtPS

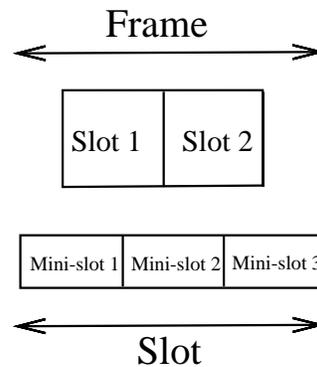


Figure 4.8: EPON Frame Structure

queues, and the head-of-line delay for the rtPS queue. The scheduler does not make a scheduling decision in a scheduling cycle until it receives all Report messages. Once all reports are received, the scheduler starts choosing some UGS queues for transmission in a Round Robin fashion. Each UGS queue is granted with fixed number of mini-slots from the first slot of the EPON's frame. The remaining slots are allocated for rtPS and nrtPS. After all UGS packets are received, the scheduler selects rtPS queue  $m$  for transmission if it maximizes the following equation:

$$m = \underset{i \in M}{\operatorname{argmax}} W_i(t) r_i(t) h_i(t) \quad (4.9)$$

where  $i = \{1, 2, \dots, M\}$  is set of WiMAX-ONUs indices,  $r_i(t)$  is cell condition of WiMAX-ONU  $i$  at time  $t$ ,  $W_i$  is length for rtPS queues at WiMAX-ONU  $i$  at time slot  $t$ , and  $h_i(t)$  is ONU  $i$  the head of line delay of rtPS queue. If the capacity of the first mini-slot, maximum slot size, larger than the length of rtPS  $m$ , the bandwidth allocation grants the selected queue its report bandwidth. Otherwise, the BA grants the whole size of the first mini-slot to rtPS  $m$ . Then the scheduler repeats Equation 4.9 over and finds new rtPS  $m$ . The new rtPS  $m$  is granted the minimum of its requests and the size of the second mini-slot. The scheduling for Grant messages repeats Equation 4.9 over and over until all the mini-slots are exhausted or there is no further request. Possibly, the same ONU's rtPS queue wins all the mini-slots if it could maximize Equation 4.9, and the queue length larger than the size of mini-slots.

Since nrtPS is not delay sensitive, Equation 4.9 cannot be applied. Instead, the queue length of nrtPS is used to determine the winner of uplink transmission. nrtPS queues are scheduled for uplink transmission in two ways

1. The reminder slots must not be wasted after the rtPSs traffic are settled. The nrtPS's queues share the excess slots.

2. After some predefined threshold cycles, the OLT scheduler selects nrtPS queues for transmission and assigns the second slot of EPON's frame to the nrtPS queues. The procedure of assigning the mini-slots is similar to that for rtPS mini-slots. However, neither cell condition nor head-of-line delay is considered.

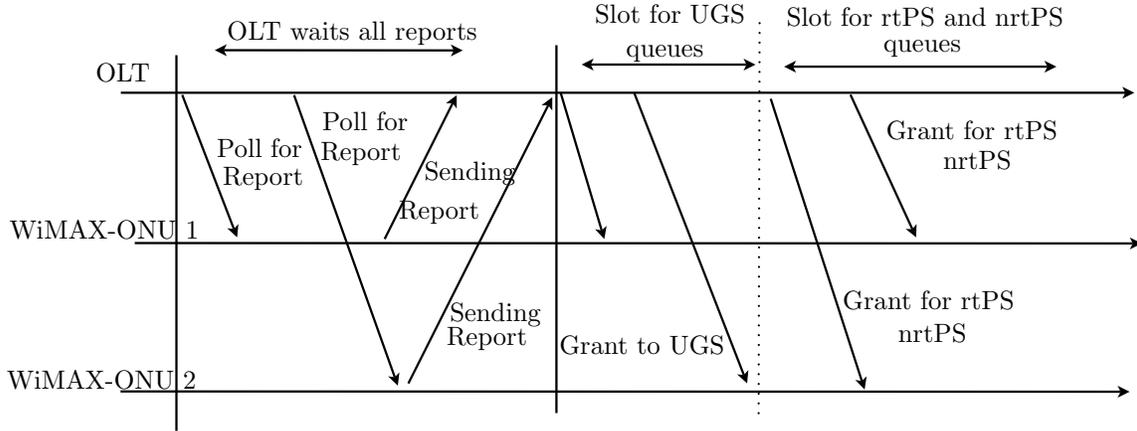


Figure 4.9: Scheduling Process

Without loss of generality, the proposed scheduling process for two WiMAX-ONUs and OLT is illustrated in Figure 4.9. At time  $t = 0$ , the centralized scheduler at the OLT polls WiMAX-ONU 1 and WiMAX-ONU 2 to send their Report messages. Upon receiving the Report messages, the scheduler allocates fixed bandwidth for the UGS's queues for both WiMAX-ONUs in a Round-Robin fashion. As shown in Figure 4.9, the OLT schedules WiMAX-ONU 1, and then WiMAX-ONU 2 and so on. As soon as WiMAX-ONU 1 receives the grants, WiMAX-ONU 1 sends its UGS's packets to the OLT, including packet overhead for Ethernet packet. The same procedure as for WiMAX-ONU 1 is taken by WiMAX-ONU 2. When the OLT receives all UGS's packets from the WiMAX-ONUs, the scheduler begins granting the second slot of EPON's frame for rtPS, as discussed in Section 4.9.

## 4.10 Traffic Model

It is highly important that the integrated architecture supports different types of services. We have three types of traffic for video, voice, and data at each *SS*. So, each *SS* needs to send its traffic to WiMAX-ONU. We assume all traffic always come to *SSs* prior to the beginning of each frame with the arrival process follows Poisson distribution.

- UGS traffic generator is modeled as constant bit rate (CBR). A new packet for one UGS connection is generated every 2.4 milliseconds with packet size *3bytes*. Thus, the average arrival rate for UGS traffic is *10kbps*
- It has been shown that most of the Internet traffic is generated by http, VBR, and FTP. As a result, rtPS traffic consumes most of WiMAX's bandwidth compared with the UGS traffic. Here, the rtPS traffic average arrival rate is *64kbps* and the payload can be calculated as follow  $2.25ms * 64kbps = 18bytes$ .
- nrtPS traffic is not sensitive to delay as UGS and rtPS; however, it is subject to a minimum bandwidth requirement. Also, its packet size is *24bytes* with an average arrival rate equal to *80kbps*. Table 4.2 [30] [31] [32] summarizes the traffic arrival rates and the delay bound for each type of traffic.

Table 4.2: QoS Requirements for Real Time Traffic

Type of traffic	QoS requirements	Average Arrival rate
UGS	<i>150ms</i>	<i>10kbps</i>
rtPS	<i>250ms</i>	<i>64kbps</i>
nrtPS	Flexible	<i>80kbps</i>

## 4.11 Summary

In the chapter, the proposed hybrid system architecture for EPON and WiMAX was presented. The channel model for wireless network was discussed in terms of channel impairments. For EPON, we mentioned the wavelength for upstream and downstream links and topology system. The frame, slot structure, and allocation for the two technologies were introduced and explained. Then, the proposed scheduling algorithms for upstream links regarding UGS, rtPS, and nrtPS was presented, where we have detailed the procedure of the algorithms. Finally, we discussed the traffic model and QoS of service for the system model.

# Chapter 5

## Performance Evaluation and Simulation Results

### 5.1 Introduction

In this chapter, the centralized scheduling algorithm at the OLT is studied and its performance is evaluated. In order to simulate the proposed algorithm, simulation based on the discrete events is conducted using C++. In our implemented model, one OLT is connected to 14 WiMAX-ONUs in a tree topology. The distance from the OLT to each WiMAX-ONU, including the splitter, is kept constant. The upstream link capacity of EPON is  $1Gbps$ , while each WiMAX-ONU maximum data rate is  $75Mbps$  with a channel width of  $20MHz$ . In addition, each WiMAX-ONU has three queues for differentiated classes of service. Those queues share  $10Mbit$  buffer for traffics coming from all *SSs* within the same cell. In IEEE 802.16d, the total number of carriers is 256, but only 192 are used for data [33]. Moreover, the duration of the OFDM symbol is  $12.6 \mu s$  where each physical slot consists of four OFDM symbols [34].

We set the time duration for the WiMAX frame and the EPON frame to be

2.5ms. Thus, 50 PSs are available for uplink subframe since only uplink transmission is implemented in this work. Maximum mini-slot size of the EPON frame can be found as:

$$T_s = U \left[ \frac{T_C}{M} \right] \quad (5.1)$$

where  $T_s$  is maximum mini-slot size,  $U$  is uplink EPON capacity,  $T_C$  is slot duration,  $M$  is number of WiMAX-ONUs [35] [9]. The simulation parameters are summarized in Table 5.1 [36] [25].

Number of WiMAX-ONU	14
Number of SSs in each cell	10
Number of PSs	50
Number of OFDM symbols in a slot	4
WiMAX maximum data rate	75Mbps
EPON maximum data rate	1Gbps
Buffer size in ONU	10Mbyte
$t_c$	100000
Frame length	2.5ms
Symbol duration	12.6us
UGS arrival rate	10kbps
rtPS arrival rate	64kbps
nrtPS arrival rate	80kbps
Pathloss exponent	2

As discussed previously in Chapter 4, the received  $SNR$  can be modeled as an exponential random variable with average  $\overline{SNR} = \rho \left( \frac{D}{d_{ss}} \right)^\alpha S_{ss}$ . We assume that the average channel condition among  $SSs$  is represented as a cell condition during one frame. Therefore, Table 4.1 is used in order to determine the appropriate coding rate and bits/symbol. Cell condition can be determined as:

$$R_{cell} = \frac{\sum_{i=0}^n C_i M_i}{\sum_{i=0}^n C_i} \quad (5.2)$$

where  $R_{cell}$  is the average channel per cell,  $C_i$  maximum number of bits  $SS_i$  can transmit,  $M_i$  is the traffic load of  $SS_i$ , and  $n$  is the total number of  $SS$ s in a single cell.

In the following sections, simulation results for the proposed scheduling algorithm are presented and discussed. Parametric analysis based on varying the traffic load,  $SS$ s, and their effects on the delay sensitive traffic is studied in more detail. Moreover, numerical results for the average delay of the transmitted packet from  $SS$  until received by the OLT are presented. Packets drop ratio, which is also an important factor, is discussed along with overall achievable throughput by all the traffic types.

## 5.2 Performance Analysis of Proposed Scheduling Algorithm at OLT

The scheduler at the OLT aims to maximize the throughput and support differentiated classes of service. EPON's uplink throughput can be calculated in two ways: carried load of EPON link times the link capacity of EPON, or number of transmitting bits over the simulation time. Each *nrtPS* and *rtPS* traffic at each *SS* starts with two connections, and we add two connections when millions of packets have been sent to the OLT. For UGS traffic, the number of connections is set to one for each *SS*. Figure 5.1 shows the throughput of the proposed scheme when traffic load is increased. Starting with two connections for *rtPS* and *nrtPS*, the

maximum transmitted bits from UGS, rtPS, and nrtPS queues are 4% of the total capacity. When the traffic load is 16, the maximum number of bits is almost 17% of EPON's capacity. The scheduler serves all UGS queues in each frame, so almost all packets in the queues will be transmitted to the OLT. For rtPS queues, the scheduler first chooses non-empty queues with relatively best channel conditions, thus the throughput is sharply increased. Therefore, the proposed scheme efficiently utilizes the uplink capacity.

The comparison of throughput between rtPS and nrtPS traffic is shown in Figure 5.2. From load 2 to 4, the remaining mini-slots of rtPS allocation is large, resulting more nrtPS traffic scheduled for transmission. As a result, nrtPS achieves better throughput than rtPS. As the load increases, more rtPS packets are received by WiMAX-ONUs. Thus the throughput improves since mini-slots are exhausted with rtPS traffic. So, less nrtPS packets are then transmitted in the rtPS's allocation slot.

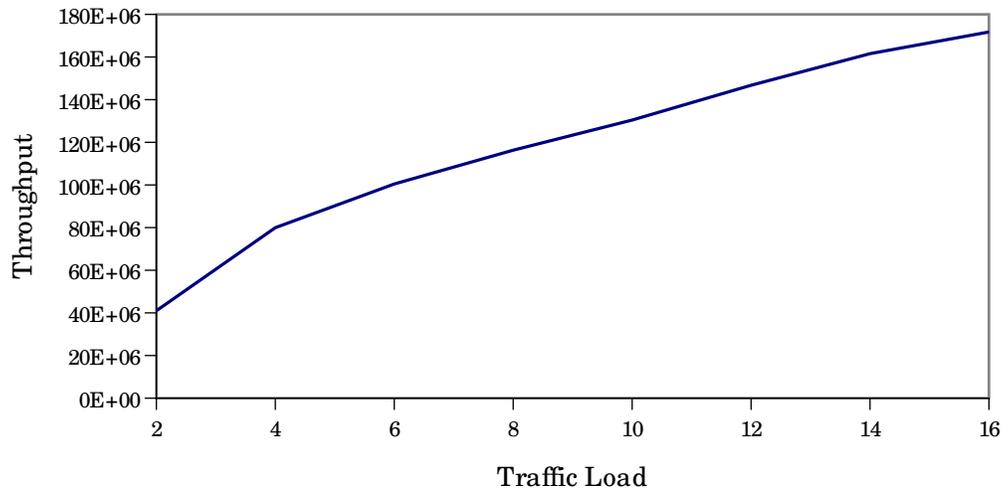


Figure 5.1: Achievable Throughput versus Traffic Load

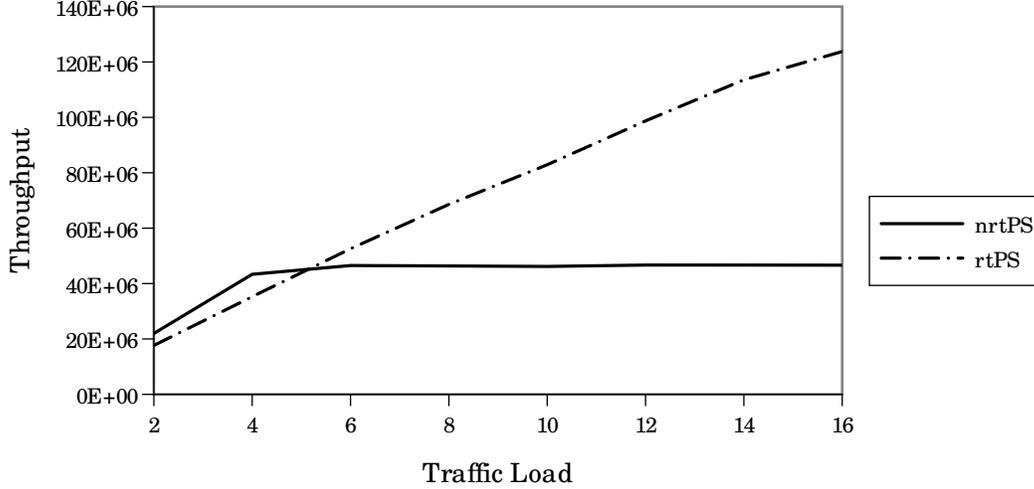


Figure 5.2: Comparison of nrtPS and rtPS Throughput

### 5.2.1 Performance Analysis of Real Time Traffic

In this section, the impact of increasing traffic load on the average delay and dropping ratio is presented. Packets delay are measured from packets generation starting at SSs until they arrive at OLT. Thus, the delay includes queue time at SS, transmission time from SS to WiMAX-ONU, queue time at ONU, and EPON link delay. UGSs connections are fixed, and only rtPS and nrtPS connections are varying. The proposed scheduler can provide QoS for real time traffic as shown in Figure 5.3. UGS average delay slightly increases with traffic load since the UGS traffic has less load. At early stages, the average time delay for UGS is around  $5ms$  at load 2, while it is around  $7ms$  at load 16. Figure 5.4 shows rtPS average delay versus traffic load. The scheduler considers the rtPS queue with the highest queue length and delay close to the delay bound to schedule first. As a result, there is almost no noticeable delay difference, as the load is increases from 2 to 12. When the traffic load above 12, the average delay for rtPS traffic is linearly increasing.

Real time packets can be dropped in two ways. First, if the packets exceed the predefined delay bound, the packets will be immediately dropped. Thus, each

ONU checks the delay bound for each real time packet before it is sent to the OLT. Second, when the capacity of queues at ONUs is consumed by real time traffic, the new arrival real time packets will be dropped. Since each SS has only one connection for UGS, the dropping percentage is around 0.1% (Figure 5.5). On the other hand, using the proposed scheduling for rtPS traffic, the dropping ratio increases slowly with the addition of more rtPS connections. In other words, by serving the rtPS queue that will expire soon and has larger number of packets, we can achieve a low dropping rate for all rtPS packets from WiMAX-ONUs. As shown in Figure 5.5 the dropping percentage for rtPS packets starts from around 1.5% when the load is 2 to 8% when load is 16.

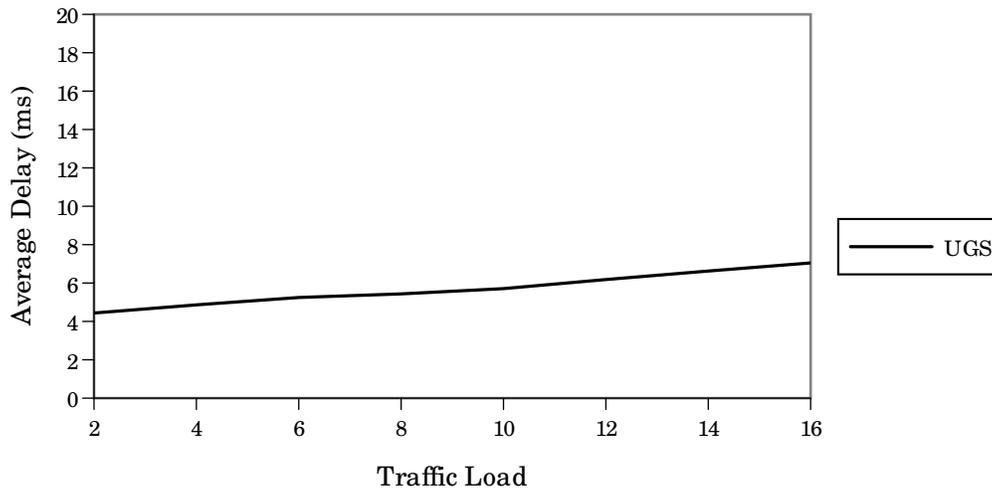


Figure 5.3: UGS Average Delay versus Traffic Load

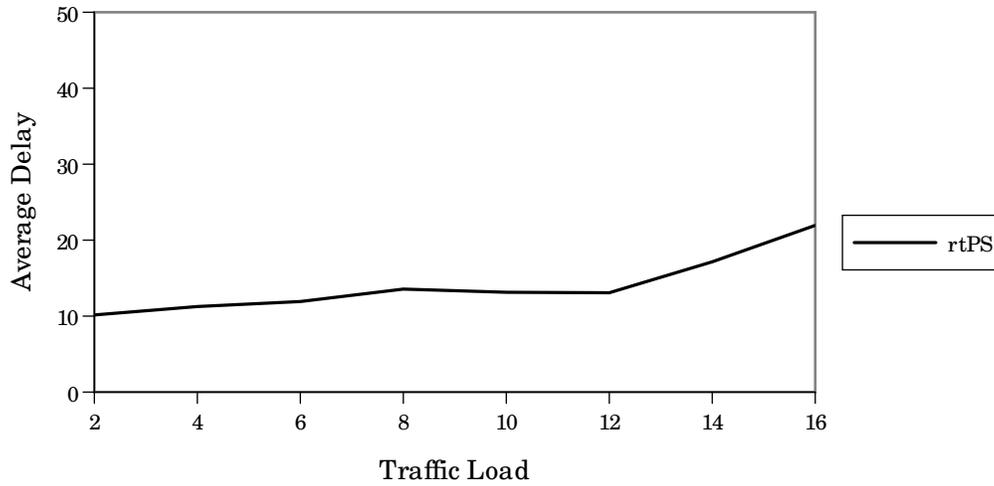


Figure 5.4: rtPS Average Delay versus Traffic Load

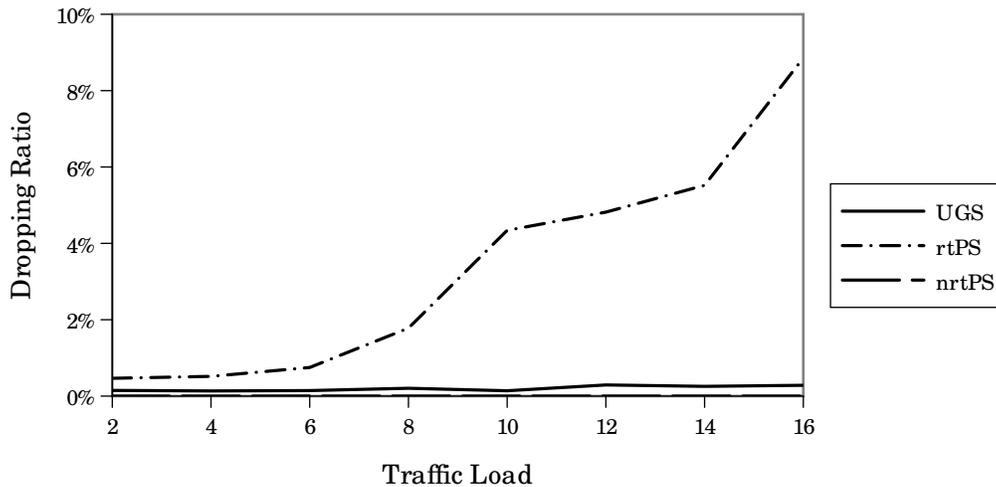


Figure 5.5: Dropping Rate for Real Time Traffic versus Traffic Load

### 5.2.2 Impact of Increasing UGS Traffic Load

In this section, the effect of having a heavy UGS traffic load on the proposed scheme is studied, by adding more UGS connections in each SSs. Note that the size of the EPON frame and mini-slot allocations are fixed. Figure 5.6 shows the obtained throughput for fixed and varying UGSs. As shown in the Figure, the throughput is improved with the varying UGSs. At light load, there is no noticeable difference, but the throughput of the two numerical simulation models starts to behave differently

when the load above 10. The two simulation models are compared here in terms of average delay. As can be seen from Figure 5.7, the average delay is slowly increasing when the load varies. As a result, the scheduler scheme satisfies the delay bound for UGS traffic. However, the packet loss ratio for the case of varying load is much higher than that of a fixed load.

As shown in Figure 5.8, the percentage of packet dropping ratio for load 12 is around 3.3% for the varying load whereas it is around 0.1% for the fixed load. Intuitively, the limit on the shared buffer among queues at each ONU is an important reason for having high packet loss ratio when UGS load is increased. In case of heavy load, UGS packets coming to WiMAX-ONUs find the buffer is occupied by real time traffic, so they will not be allowed to enter the system. In addition, the mini-slot allocated to each UGS queue by bandwidth allocation, is less than the UGS queue length at high load.

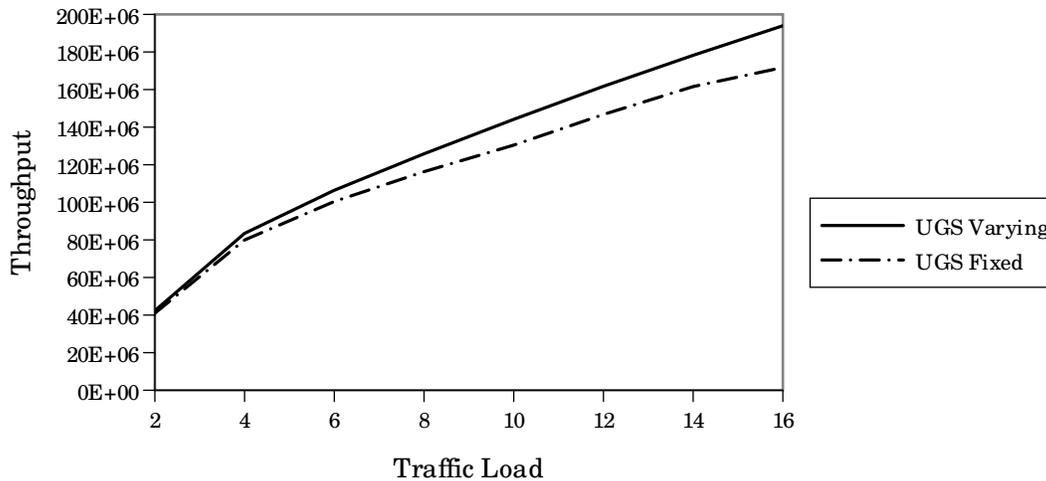


Figure 5.6: Achievable Throughput when all Traffic Varies

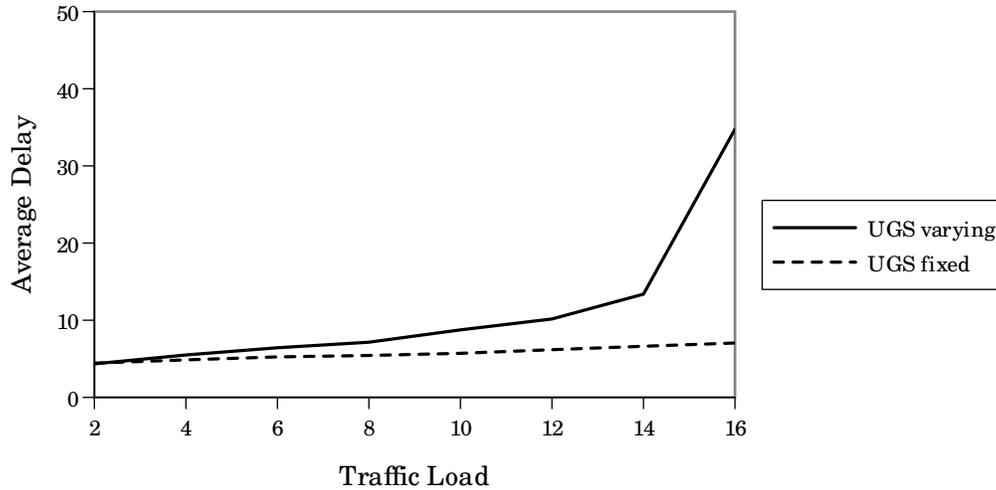


Figure 5.7: Comparison of UGS Traffic

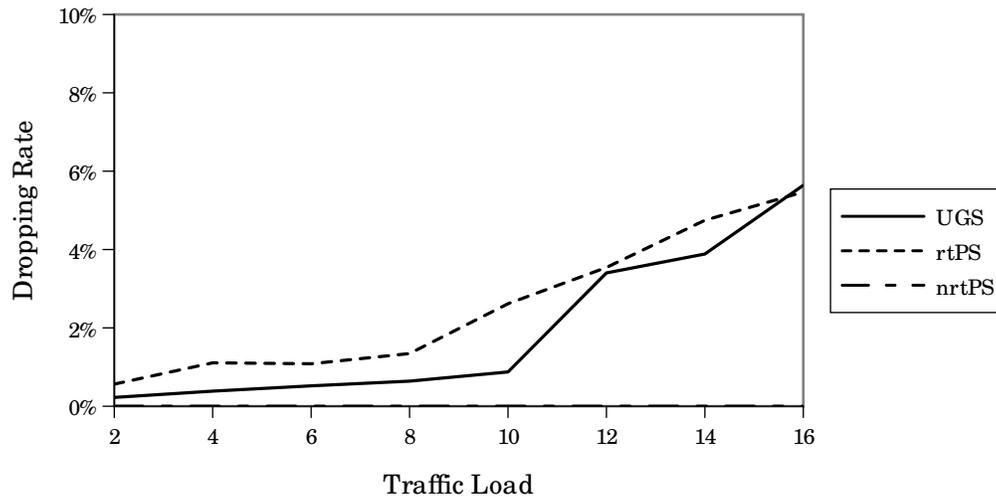


Figure 5.8: Packet Loss Ratio of UGS Traffic

### 5.2.3 Impact of Increasing SSs

To validate our work, it is an important to investigate the proposed scheduling scheme with SSs varying. In the simulation model, we reduce the number of connections for UGS, rtPS, and nrtPS at each SS to balance the system. Then, we increase the number of SSs in each cell from 10 to 40. It is observed from Figure 5.9 that the obtained throughput is 0.106 Gbps when SSs equal 10. Above 10 SSs, the throughput is actually improving with the increase of SSs because our scheduling

scheme can carry efficiently most packets in ONUs. Noticeably, the scalability of the scheduler algorithm can be achieved.

Figure 5.10 shows the average delay for UGS and rtPS traffic as the number of SSs is increasing. When there are 10 SSs in each cell, the average delay for UGS traffic is similar to the one in Figure 5.7 when the traffic load is 6. In addition to UGS, the rtPS average delay is similar to Figure 5.4 when the number of SSs is 10. The average delay for UGSs increases sharply when there are more than 25 SSs in the WiMAX cell. If there are 40 SSs in each cell, the average delay for UGS traffic will probably be above 100 *ms*. On the other hand, the scheduler significantly keeps the rtPS average delay under 40 *ms* when there are 40 SSs. Therefore, the benefit of considering the head of line delay, queue length, and channel condition for rtPS can be realised.

Another QoS requirement that needs to be studied here is the packets drop ratio with increasing SSs in each cell. We depicted the packet loss ratio for all types of traffic in Figure 5.11. At light load, UGS and rtPS dropping packet ratio is less than 1%, while it is zero for the case of nrtPS. Even though WiMAX-ONUs can receive more packets from rtPS traffic than UGSs when the load varies from 10 to 35, their packet loss is very close, providing an evidence of the efficiency of rtPS scheduling. When there are more than 35 SSs, the packet loss ratio for both UGS and rtPS is above 15%, and for nrtPS is around 10%. At high load (more than 35 SSs) the high-priority traffic preempts low-priority traffic, consequently, the enqueued and incoming nrtPS traffic are dropped.

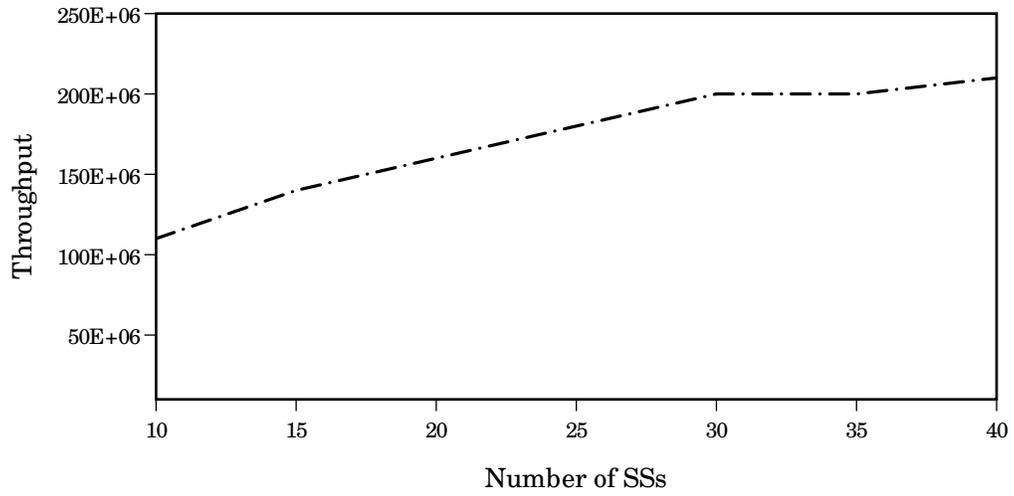


Figure 5.9: Achievable Throughput versus SSs

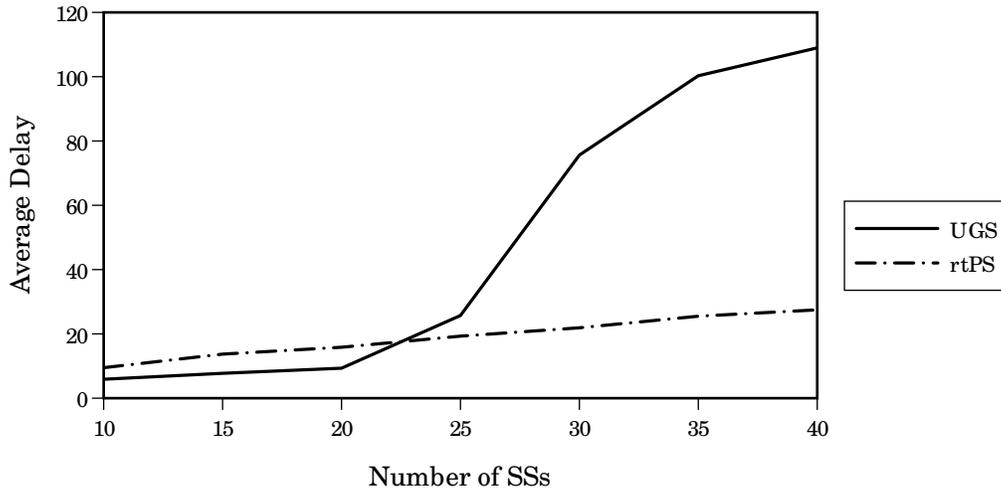


Figure 5.10: Average Delay for Real Time Traffic versus SSs

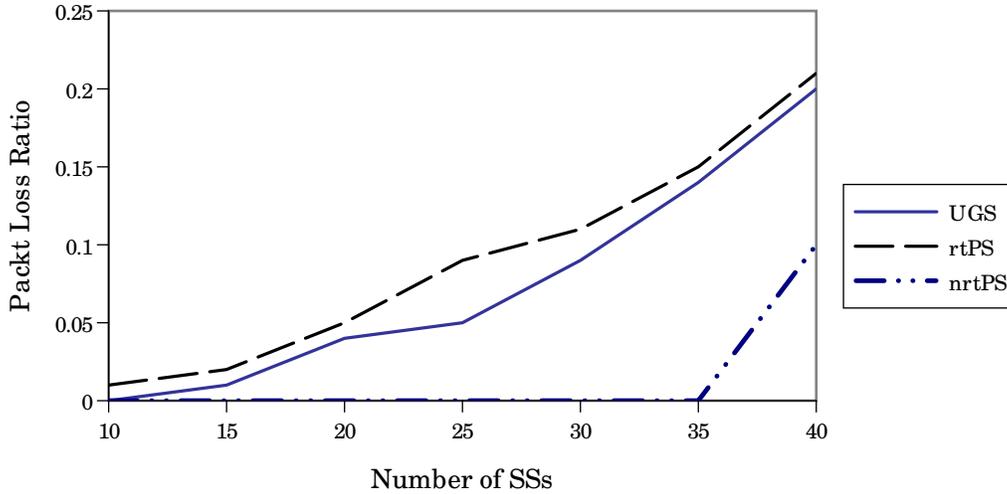


Figure 5.11: Packet Loss Ratio versus SSs

### 5.3 Summary

In this chapter, the proposed scheduling algorithm for WiMAX and EPON integrated networks is evaluated. Firstly, we presented the achievable throughput, average delay, and packet loss ratio when the number of connections for nrtPS and rtPS varies. The simulation results showed that the throughput is improved when adding more connections to each SS. Moreover, the average delay for UGS and rtPS are below the delay boundary since the former has low connections and the latter is scheduled based on HOL, queue length, and average channel condition. In case of varying UGS traffic, the results showed that the throughput can be improved with more UGS packets in the system, but the average delay and dropping ratio were increased. Finally, the impact of increasing SSs in each cell was demonstrated. The numerical results showed that the throughput is enhanced with more SSs in the cell. In addition, the impacts due to channel condition, queue length, and HOL delay were discussed in terms of packet average delay and loss ratio.

# Chapter 6

## Conclusions and Recommendations

### 6.1 Thesis Summary

In this thesis, two-level uplink scheduling schemes for converged WiMAX and EPON are presented. First, proportional fairness is adopted to be the scheduler for uplink transmission at the BS. In the second level, a centralized scheduler for the uplink transmissions with QoS provisioned at the OLT is proposed. Three priority queues at each ONU for UGS, rtPS, and nrtPS are modeled with QoS requirements for each type of service. The performance of the scheduler for the uplink transmission is studied in terms of the throughput, average delay, and dropping packets. The proposed scheme could satisfy delay requirement for real time traffic, specifically rtPS. In addition, the scheduler utilized EPON uplink capacity in the aspects of achievable throughput in a highly loaded system.

## 6.2 Thesis Contribution

The primary contributions of this thesis are as follows:

- It provides a survey of state-of-art converged WiMAX and EPON architectures.
- It suggests an new slot structure for EPON frame.
- It proposes a scheduling policy to effectively schedule WiMAX-ONUs for transmission.
- Link adaption is used to capture the channel condition in each cell.
- Its proposed scheduling scheme guarantees QoS requirements for real time traffic.
- Its simulation model studies the perforce of scheduling scheme to arbitrate the uplink.

## 6.3 Future Work

There are many avenues that should be further studied for EPON as a Mobile backhaul specifically, all packets converged over EPON architecture. The following are some of the open issues

- The bandwidth allocation for mini-slots needs to be dynamic instead of fixed.
- The performace of the centralized scheduler with other traffic, such as BE, IPTV,...etc need further study.
- Investigation of the performance when OFDMA is the air interface in WiMAX might suggest advantages.

- Comparison of the scheduling process with other scheduling algorithms which consider channel condition as a factor in coordinating the transmission could suggest new potential topics for Investigation.

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