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Optical-WiMAX Hybrid Networks

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Abstract

The emergence of bandwidth-intensive Internet services creates a high demand for a very qualified next-generation access network. The future access networks should provide high bandwidth, improved network availability, flexibility, mobility, reliability, failure protection, Quality of Service (QoS) support and cost-effective access. The integration between optical networks and Worldwide Interoperability for Microwave Access (WiMAX) is a promising solution for future access networks. The integration between the Ethernet Passive Optical Network (EPON) and WiMAX has been proposed but contains several drawbacks and does not yet contain a mechanism for QoS support. Finally, this work describes the Resilient Packet Ring (RPR) standard, which aims to build high-performance metro that interconnect multiple access networks. The objective of this thesis is to examine the integration of optical standards, such as RPR and EPON, with the WiMAX standard as a promising solution for access and metro networks. The integration will be applied to the areas of architecture and Medium Access Control (MAC) Protocol.

The first part of the thesis examines the EPON-WiMAX integration as a solution for the access network. Specifically, the proposed solution includes new EPON-WiMAX hybrid network architectures that are suitable for both urban and rural environment requirements, and it also introduces a comprehensive joint MAC protocol for these architectures. The proposed architectures are reliable and provide extended network coverage. The proposed MAC protocol provides a per-stream quality-of-service guarantee and improves the network utilization.

While the first part of the thesis strives to improve the network reliability through protection in the EPON part and extend the network coverage through innovative methods, the second part attempts to maintain and enhance these objectives by adding a reliable technology to the integrated network. Specifically, this section examines the way in which the RPR network can be integrated with the proposed EPON-WiMAX architecture to form an RPR-EPON-WiMAX hybrid network, which can be a solution for both access and metro networks. The proposed joint MAC protocol for the RPR-EPON-WiMAX hybrid network aims to maximize the advantages of the proposed architecture by distributing its functionalities over the parts of the architecture and jointly executing the parts of the MAC protocol.

Keywords – Admission Control, Bandwidth Allocation, EPON, Hybrid Network, IEEE 802.16, IEEE 802.16e, MAC Protocol, Optical, RPR, QoS, Routing, performance analysis, Scheduler, simulation, WiMAX.

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Acronyms

AC	*Admission Control*
ADSL2	*Asymmetric Digital Subscriber Line 2*
AF	*Assured forwarding*
APS	*automatic-protection-switching*
BE	*Best Effort*
BS	*Base Station*
BSBA	*BS Bandwidth Allocation*
CBR	*Constant Bit Rate*
CID	*Connection Identifier*
CIR	*Committed Information Rate*
CO	*Central Office*
DBA	*Dynamic Bandwidth Allocation*
DiffServ	*Differentiation Service*
EDF	*Earliest Deadline First*
EF	*Expedited forwarding*
EIR	*Excess Information Rate*
EPON	*Ethernet Passive Optical Networks*
ertPS	*Extended real-time Polling Service*
FDD	*Frequency Division Duplex*
FE	*Fairness Eligible*
FMC	*Fixed Mobile Convergence*
FR	*Fixed-tuned Receiver*
FT	*Fixed-tuned Transmitter*
FTTH	*Fiber to the home*
GPON	*Gigabit-capable Passive Optical Networks*
HFC	*Hybrid Fiber Coax*
HoL	*Head-of-Line*
IntServ	*Integrated Service*

IOW-AC	*Integrated Optical Wireless Admission Control*
IPTV	*Internet protocol television*
LMDS	*Local Multi-capacity Distributed Service*
LTE	*Long Term Evolution*
MAC	*Medium Access Control*
MAN	*Metropolitan Area Networks*
MLDBA	*Multi-level Dynamic Bandwidth Allocation*
MoF	*microwave-over-fiber*
MPCP	*Multi-Point Control Protocol*
MPEG	*Moving Pictures Experts Group*
nrtPS	*Non-real-time Polling Service*
NS-2	*Network Simulator 2*
OEO	*Optical-Electrical-Optical conversion*
OFDM	*Orthogonal Frequency Division Multiplexing*
OFDMA	*Orthogonal Frequency Division Multiple Access*
OLT	*Optical Line Terminal*
OLTBA	*OLT Bandwidth Allocation*
ONU	*Optical Network Unit*
ONUBA	*ONU Bandwidth Allocation*
OOW	*Optical-Optical-Wireless*
OWW	*Optical-Wireless-Wireless*
PFEBA	*prediction-based fair excessive bandwidth allocation*
PMP	*point-to-multipoint*
PON	*Passive Optical Network*
PTQ	*primary transit queue*
PVN	*Private Virtual Networks*
QDBA	*QoS-based Dynamic Bandwidth Allocation*
QoS	*Quality of Service*
RPR	*Resilient Packet Ring*
rtPS	*Real-time Polling Service*
SLA	*Service Level agreement*
SLE	*Static Light path Establishment*

SONET/SDH's	*Synchronous Optical Network/Synchronous Digital Hierarchy's*
SS	*Subscriber Station*
STQ	*secondary transit queue*
subOLTBA	*subOLT Bandwidth Allocation*
TDD	*Time Division Duplex*
TDM	*Time Division Multiple access*
TDMA	*Time Division Multiple Access*
UGS	*Unsolicited Grant Service*
VBR	*Variable Bit Rate*
VDSL2	*Very high Speed Digital Subscriber Line 2*
VoD	*Video on Demand*
WAN	*Wide Area Networks*
WDM	*wavelength-division multiplexing*
WFQ	*Weight Fair Queue*
WiFi	*Wireless Fidelity*
WiMAX	*Worldwide Interoperability for Microwave Access*
WMN	*Wireless Mesh Network*
WOBAN	*Wireless-Optical Broadband-Access Network*

Chapter 1
Introduction

Many bandwidth-intensive applications, such as Internet protocol television (IPTV), Video on Demand (VoD) and Internet video streaming, have emerged in the last few decades. As a result of its popularity, the broadband access network is becoming increasingly important and needs to provide many benefits besides high bandwidth. For example, the demand for accessing these services from either fixed locations or during motion requires future networks to provide mobility. Consequently, an efficient "last-mile" access network that can address these various challenges needs to be developed. This network should provide bandwidth, network availability, flexibility, mobility, reliability, failure protection, Quality of Service (QoS) support, and cost-effective access.

The last-mile access network currently contains many technologies for connecting subscribers to their service providers, including Asymmetric Digital Subscriber Line 2 (ADSL2) and/or Very High Speed Digital Subscriber Line 2 (VDSL2), Fiber To The Home (FTTH), Hybrid Fiber Coax (HFC), and wireless technologies such as WiMAX and Long-Term Evolution (LTE). Each of these technologies possesses a different level of bandwidth performance and contains its own advantages and disadvantages; hence, no single technology can be considered as the best solution for the access network.

1.1 Optical-WiMAX Hybrid Access Network

Clearly, new and improved network technologies are required to deliver inexpensive yet expandable and resilient network offerings. Despite being initially developed for different communication purposes and scenarios, optical and wireless networks are the ideal candidates for this new and improved access network technology. However, neither optical nor wireless technologies can solve the challenges posed in this access segment. Additionally, while fiber-based techniques, such as the Ethernet Passive Optical Networks (EPONs), offer extremely high bandwidth in addition to possessing reliability and network availability, they are still very costly for deployment to each home, and they provide little flexibility and no mobility.

On the other hand, wireless access technologies such as Worldwide Interoperability for Microwave Access (WiMAX) are continuously expanding their transmission bandwidth, coverage, and quality of service (QoS) support. Also, in contrast to fiber-based technologies, they support mobility and have low deployment costs. Nevertheless, wireless networks generally suffer from a limited wireless spectrum, which results the assignment of low bandwidth to each user when many customers share services offered by these networks.

As a result, it is clear that future access networks should possess characteristics of both optical and wireless technologies. Thus, the integration between optical and wireless technologies to form a hybrid network can provide a superior solution for future access networks. The advantages of a hybrid network have enhanced its attractiveness for both researchers and developers. Hence, the integration between EPON, as a strong optical technology, and WiMAX networks, as one of the best wireless technologies, is a promising solution for access networks.

The Resilient Packet Ring (RPR) standard aims at combining the advantages of the Ethernet and synchronous optical network/synchronous digital hierarchies (SONET/SDHs). The RPR possesses the Ethernet qualities of statistical multiplexing gain, low equipment costs and simplicity, while it inherits the features of availability and reliability from SONET/SDH's. In combination, these advantages support the RPR in building high-performance metro edge and metro core ring networks that interconnect multiple access networks. Hence, the RPR can connect EPON-WiMAX access networks to serve a wide geographical area. Therefore, the integration between RPR, EPON and WiMAX is a promising solution not only for access networks but also for metro networks.

1.2 Thesis Outline

This thesis consists of six chapters; the remaining five chapters are organized in a logical fashion. Chapter 2 presents a review of RPR, EPON, and WiMAX standards and introduces the literature on proposed integrations between EPON and WiMAX as well as between RPR and EPON. Subsequently, Chapter 3 examines the EPON-WiMAX integration as a solution for access networks. Specifically, it proposes a new architecture for the EPON-WiMAX network and introduces a MAC protocol for this architecture; the effectiveness of the proposed solution is demonstrated through the simulations. A new architecture for the RPR-EPON-WiMAX integrated network as well as a routing algorithm and the required scheduler is proposed in Chapter 4. Then, Chapter 5 considers the MAC protocol for the proposed RPR-EPON-WiMAX architecture. In this chapter, bandwidth allocation and admission control for the required MAC protocol is discussed, and the performance of the proposed architecture and MAC protocol are analyzed. Finally, Chapter 6 provides a conclusion along with suggestions for future research work.

1.3 Contributions of this Thesis

Each chapter in this thesis, as well as the thesis itself, contributes to the body of knowledge about the Optical-WiMAX hybrid access network and the provision QoS for these networks. In the following section, the contributions for each chapter of the thesis are presented in detail.

1.3.1 Contributions of Chapter 3

This chapter examines the reliability and coverage extension of the EPON-WIMAX network. It also proposes a MAC protocol for both upstream and downstream directions that ensures and protects the end-to-end QoS of all connections and service types. More specifically, the contributions of this chapter can be summarized as follows:

(1) This chapter proposes the EPON-WiMAX architectures that extend the coverage area of the network in both urban and rural areas. Moreover, the proposed architectures consider protection for improving the reliability of the network against both node and link failures.

(2) This chapter presents a new MAC protocol for EPON-WiMAX that provides QoS and jointly considers admission, scheduling, and bandwidth allocation.

(3) The proposed MAC differs from previous related work, as it enables an end-to-end QoS guarantee for admitted traffic.

(4) The proposed Admission Control (AC) scheme is implemented on a four-stage system. As a decentralized AC, this feature ensures that traffic requirements can be satisfied over the entire network and that the complexity and decision time of the AC scheme are reduced.

(5) The proposed scheduler changes the scheduling in both EPON and WiMAX from a station-based scheme to service-type-based scheduling.

(6) The proposed Bandwidth Allocation (BA) provides one-to-one mapping between WiMAX service types and EPON queues. More importantly, this BA addresses the light-load-penalty phenomena.

1.3.2 Contributions of Chapter 4

(1) This chapter proposes a new architecture for the hybrid RPR-EPON-WiMAX network as a solution for both access and metro networks. Specifically, the architecture is reliable and has a good fault tolerance.

(2) This chapter proposes a routing mechanism for the proposed architecture. The routing mechanism selects routes in a way that minimizes the delay and provides a good load balance.

(3) This chapter proposes a scheduler that is concerned with service types over the proposed architecture from end to end. In both EPON and WiMAX, the

scheduler is service-type-based, and in RPR, the scheduler maps the specified classes to the service types defined in the WiMAX standard.

1.3.3 Contributions of Chapter 5

(1) This chapter proposes an AC for the RPR-EPON-WiMAX network. The AC is concerned with the network state and ensures that newly admitted streams do not affect the running streams. Moreover, the AC can change the WiMAX frame duration and/or the EPON cycle time in order to admit a stream while ensuring that the available bandwidth is sufficient.

(2) This chapter presents the Dynamic Bandwidth Allocation (DBA), which is implemented in all parts of the architecture. The DBA enables the contracted QoS parameters to control the service provided to each connection, thus ensuring the end-to-end per-connection QoS guarantee.

Chapter 2
Literature Review

There is significant controversy regarding which type of network is ideal. Specifically, individuals debate about whether wireless or wired networks are a more effective solution for access networks. While wireless is generally the preferred access medium for the end-user, wired solutions, including fiber, continue to dominate in the backhaul, regional and core networks. In the metro access networks, both wired and wireless continue to be major factors. Accordingly, the Optical-Wireless hybrid network is a solution that combines the advantages of both fields. However, as a type of Fixed-Mobile convergence [1], [2], the Optical-Wireless hybrid network experiences several challenges, especially those relating to technology and cost. In addition to the challenges of Fixed-Mobile convergence, Optical-Wireless networks also experience a plethora of other challenges, such as:

- How to define the limit to which the optical connection should be extended
- How to integrate parts of the two technologies,
- How to define a standard for managing the hybrid network,
- How the protocols of the two domains cooperate to maximize the performance of the hybrid network.

These challenges can be addressed through a careful selection of standards through which integration is performed to achieve the best possible performance from the hybrid network. As a result, this thesis attempts to integrate WiMAX, a candidate from wireless networks, EPON, a promising optical technology in the access network, and RPR, a common selection among optical technologies for metro networks.

This chapter provides a review of WiMAX, EPON, RPR networks as well as the integration among them as proposed in the literature. First, the review presents the WiMAX network and its standards. Subsequently, the networks of EPON and RPR, as well as their standards, are examined. In particular, the review is focused on the architecture and MAC protocols of the EPON-WiMAX and the RPR-EPON hybrid networks.

2.1 WiMAX Standards and Networks

The WiMAX system contains one central Base Station (BS) and multiple Subscriber Stations (SSs) in one architectural cell. Specifically, the BS is responsible for communicating with each SS and regulating its behavior. The WiMAX network can operate in one of two modes: point-to-multipoint (PMP) and mesh mode. In the PMP mode, the transmission between SSs is prohibited, while in the mesh operation mode, each SS can act as a router and forward traffic from its neighbors to the BS.

The WiMAX network can work on different physical layer specifications. The WiMAX PHY layer supports four different modulation schemes: WirelessMAN-SC (single carrier), WirelessMANSCa (single carrier access), Orthogonal Frequency Division Multiplexing (OFDM), and Orthogonal Frequency Division Multiple Access (OFDMA). The WirelessMAN-SC is designed for the frequency band of 10-66 GHz, while the others can be used at the band of 2-11 GHz.

The WiMAX operation is frame-based and supports both Time Division Duplex (TDD) and Frequency Division Duplex (FDD) configurations. In both TDD and FDD, the burst profiling for each SS is set on a frame-by-frame basis. Specifically, the downlink (BS-to-SS) and uplink (SS-to-BS) transmissions occur on the same frequency in TDD, but they occur at different times. The FDD uses different frequencies for downlink and uplink transmissions, but within both types of transmissions, the Time Division Multiple Access (TDMA) is used to multiplex data to and from SSs.

The MAC of WiMAX is connection-oriented, and each connection is associated with a service flow that has predefined QoS parameters. As a result, the QoS parameters defined for the service flow is implicitly provided by the connection's unique

Connection Identifier (CID). The MAC of WiMAX supports the five scheduling services defined in IEEE 802.16e [3]: Unsolicited Grant Service (UGS), extended-real-time Polling Service (ertPS), real-time Polling Service (rtPS), non-real-time Polling Service (nrtPS), and Best Effort (BE). These scheduling services are briefly described below:

- The UGS is designed to support real-time data streams consisting of fixed-size data packets issued at periodic intervals. Examples of these streams include T1/E1 and Voice Over IP without silence suppression.

- The rtPS is designed to support real-time data streams, such as Moving Pictures Experts Group (MPEG) video, consisting of variable-sized data packets that are issued at periodic intervals.

- The ertPS combines the efficiency of both UGS and rtPS, supporting delay-sensitive real-time flows with variable-size data packets on a periodic basis. One example of such a stream is VoIP with activity detection.

- The nrtPS is designed to support delay-tolerant data streams consisting of variable-sized packets for which a minimum data rate is required, such as FTP applications.

- The BE is designed to support data streams for which no minimum service level is required, and therefore, these streams may be managed according to the available space.

Each SS can request bandwidth for one of its connections by sending a special request or a piggy-back request. Consequently, the BS grants bandwidth on a per-connection or per-SS basis.

2.2 EPON Standards and Networks

EPON is a single-channel Time Division Multiplexing (TDM) system that uses separate wavelength channels for downstream and upstream transmissions. Typically, EPON's topology resembles that of a tree, but it can also be implemented in other topologies. EPON, as shown in Figure 2.1, has a root node, which is the Optical Line Terminal (OLT), and a group of leaf nodes that are known as Optical Network Units (ONUs). The OLT is connected to N ONUs through a 1:N optical splitter/combiner. The splitter is an optical coupler that splits the optical signal from OLT fiber into ONUs fibers and reciprocally, combines signals from ONUs fibers into OLT fiber. As a result, the OLT is able to broadcast data to all ONUs in the downstream direction; however, in the upstream direction, the ONUs cannot communicate directly with one another. The OLT dynamically allocates a variable time slot to each ONU based on its bandwidth demands. The Multi-Point Control Protocol (MPCP) controls the operation of EPON, providing mechanisms for discovery, registration, ranging, or Round Trip Time computation, and operations for newly added ONUs. In addition to these mechanisms, the MPCP provides the signaling infrastructure for coordinating the data transmission from the ONUs to the OLT. Specifically, the MPCP uses REPORT and GATE messages to facilitate arbitration.

Each ONU has a set of queues, which may be prioritized, reserving Ethernet frames for upstream transmission to the OLT. The ONU uses the REPORT message to report its bandwidth requirements to the OLT. In the upstream transmission, the scheduling of ONUs is calculated by the Dynamic Bandwidth Allocation module. The OLT transmits GATE messages to issue transmission grants that contain the start times and transmission lengths of ONUs.

2.3 RPR Standards and Networks

The RPR can easily connect to Ethernet networks, such as EPON, and may also span into Metropolitan Area Networks (MANs) and Wide Area Networks (WANs). Hence, RPR is the best candidate for connecting access networks into backbone networks [5].

The RPR is a packet-switched, ring-based architecture consisting of two counter-directional optical fiber ringlets. This network is standardized in the IEEE 802.17 [5], [6] and [7], and accordingly, the features and characteristics of RPR are summarized as follows:

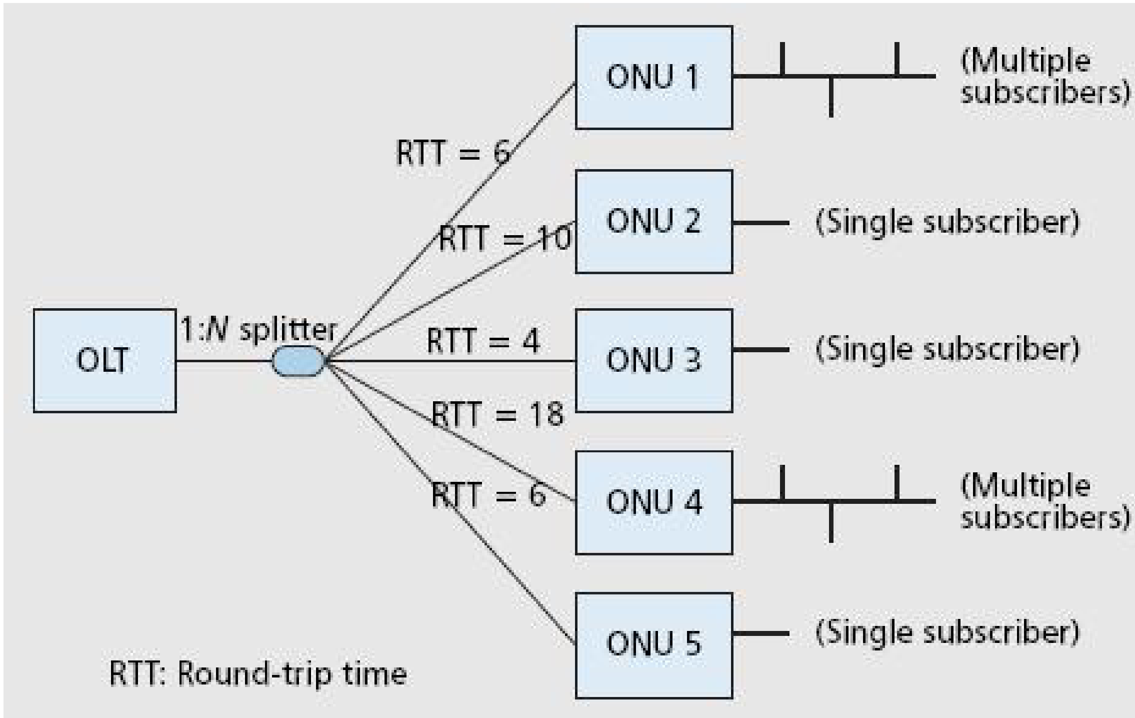


Figure 2.1: Architecture of EPON network (from [4]).

- The RPR works on optical technology and connects networks that are most likely to carry electrical signals, whereby all RPR nodes perform Optical-Electrical-Optical (OEO) conversion.
- The RPR uses destination stripping, where the destination node removes packets from the ring and can deploy spatial reuse over all of the rings, seen in Figure 2.2. Specifically, these features improve the bandwidth efficiency.
- The shortest path mechanism is used to route data on the ringlets.
- The RPR supports three different traffic classes: Class A, Class B, and Class C. Class A provides high-priority service with reduced latency and jittering as well as guaranteed bandwidth. Alternatively, Class B offers medium priority service with predictable latency and jittering, whereas Class C offers low-priority and best-effort service.

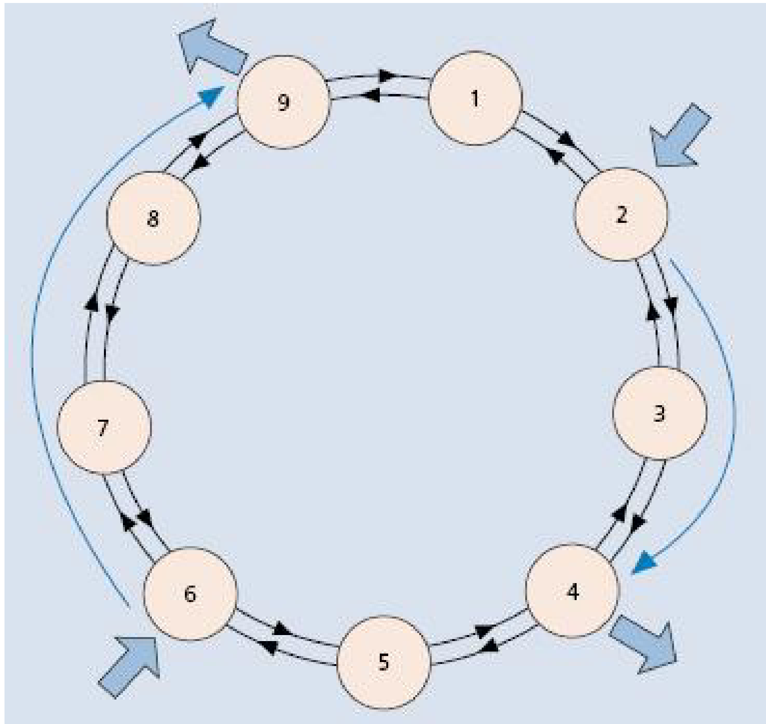


Figure 2.2: serving two streams concurrently over RPR (from [5]).

- Traffic Class A is divided into two subclasses: A0 and A1. Class B is divided into the Committed Information Rate (B-CIR) and Excess Information Rate (B-EIR) subclasses.
- RPR nodes use the topology discovery protocol to broadcast the amount of required bandwidth for each node.
- Bandwidth is pre-allocated for classes A0, A1, and B-CIR. The required bandwidth for A0 is reserved and cannot be recovered by other nodes, even when it is not completely used. The pre-allocated bandwidth for classes A1 and B-CIR is recoverable.
- Unused reclaimable bandwidth and unallocated bandwidth are used to serve Fairness Eligible (FE) traffic, including the B-EIR and C classes.
- The RPR uses the buffer insertion ring [8], [9] as its access method.

- Each RPR node can have one or two transit queues in which to store transiting packets. In the case of two transit queues, the traffic of Class A is buffered in the Primary Transit Queue (PTQ), while Class B and Class C traffic is buffered in the Secondary Transit Queue (STQ).
- The data packets from the node are stored in the stage queue.
- The control packet is buffered in the MAC Control Queue.
- RPR arbitrates ring access among its queues by prioritizing MAC traffic over data traffic.
- RPR ensures that in-transit packets are not dropped by intermediate nodes.
- If a node has a single transit queue, the transit queue is prioritized over the stage queue.
- In dual-transit queue mode, the PTQ traffic is always served first. If only the STQ contains packets, the stage queue is served while the STQ is under a certain queue threshold.

2.4 EPON-WiMAX Hybrid Networks

EPON and WiMAX contain many similar properties that facilitate their integration. In both network types, the controlling station, OLT or BS, polls the controlled stations, ONUs or SSs, for bandwidth requests. Furthermore, the controlling station in each network allocates bandwidth. Lastly, both EPON and WiMAX employ a request/grant mechanism, known as the report/gate in EPON, for bandwidth allocation. As a result of these similarities, EPON and WiMAX can support QoS in a similar way. Thus, the QoS provided by either EPON or WiMAX can be maintained over the integrated EPON-WiMAX network.

Researchers and developers are significantly interested in the integration of EPON and WiMAX technologies to form a hybrid network. Consequently, many literature works propose solutions for an EPON-WiMAX hybrid network. While some of these works focus on the architecture of the hybrid network, other studies examine the bandwidth allocation or scheduler algorithm. However, to the best of our knowledge, no work has concentrated on protecting the EPON-WiMAX hybrid network, possibly because it is similar to the protection of traditional EPON networks.

2.4.1 Network Architectures for EPON-WiMAX

Architectures that exploit the benefits of integration of EPON and WiMAX were proposed in [10]. These architectures include independent architectures, hybrid architectures, unified connection-oriented architectures and Microwave-over-Fiber (MoF) architectures. Moreover, the authors of [10] have discussed many of the design and operational issues like bandwidth allocation and QoS support, network survivability, packet forwarding, handover operation, and network design and planning. All these issues can be accessed in these architectures. Architectures in [10] connect EPON and WiMAX in a straightforward fashion but pay more attention to how WiMAX BSs are integrated with EPON ONUs. Hence they can be considered as integration methods rather than network architectures. These integration methods will be considered in our architecture.

Integration of EPON and WiMAX technologies was first described in [13], [14]. The hybrid networks in [13], [14] consist of a large WiMAX network that transmits its data over a passive optical network to the backbone network. In the WiMAX part of this hybrid network, the functionality of the central controller is divided between the Base Station (BS) and Optical Line Terminal (OLT). This central controller performs all operations for the whole WiMAX network including packet forwarding and bandwidth allocation.

Other types of optical wireless access networks were also proposed in [11], [12]. In these architectures, a wireless Base Station (BS) can be attached directly to gateways/ONUs and data is sent over an Optical Network Unit (ONU). This approach is very similar to the architectures proposed in [10], [14]. Alternatively, they can be connected to gateways over other intermediate wireless BSs by taking advantage of wireless mesh networking. For these optical-wireless networks, the paper mainly dis-

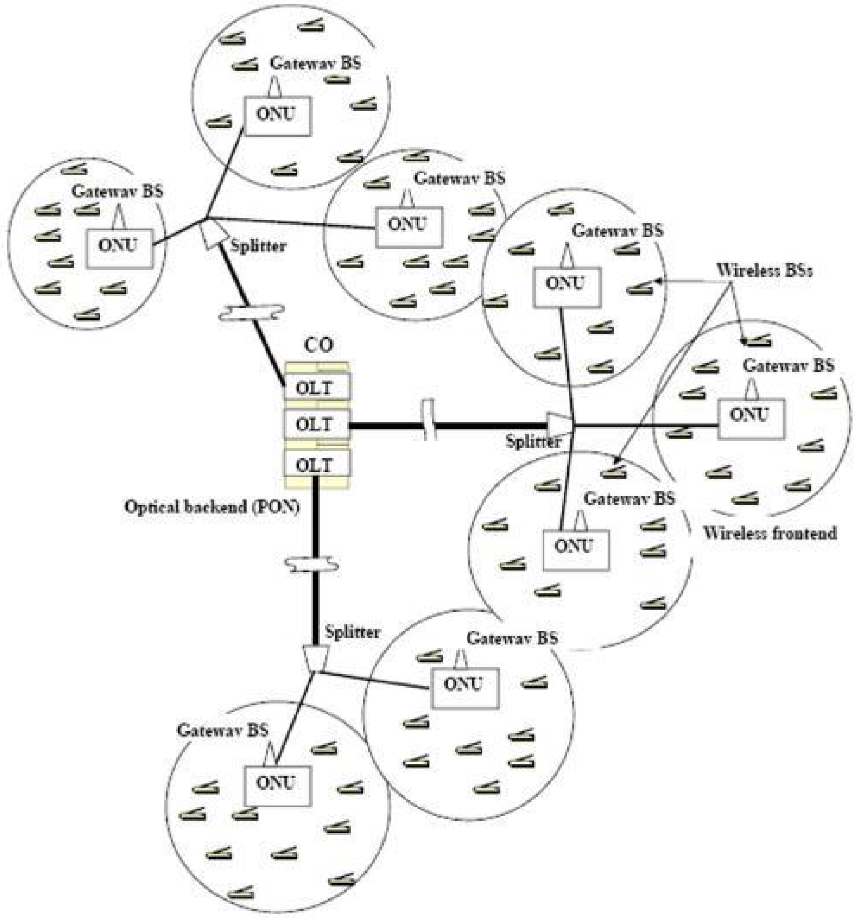


Figure 2.3: Hybrid WOBAN architecture (from [11]).

cussed the issues of routing, load balancing, packet forwarding, and the placement of wireless BSs in wireless mesh networks. Wireless-Optical Broadband Access Network (WOBAN) architecture [11] and optical-wireless-access-network architecture [12], shown in Figures 2.3 and 2.4, are capable of serving many users over a wide area but they do have some drawbacks that we will discuss in Section 3.1. We will also show how our proposed architecture overcomes these problems.

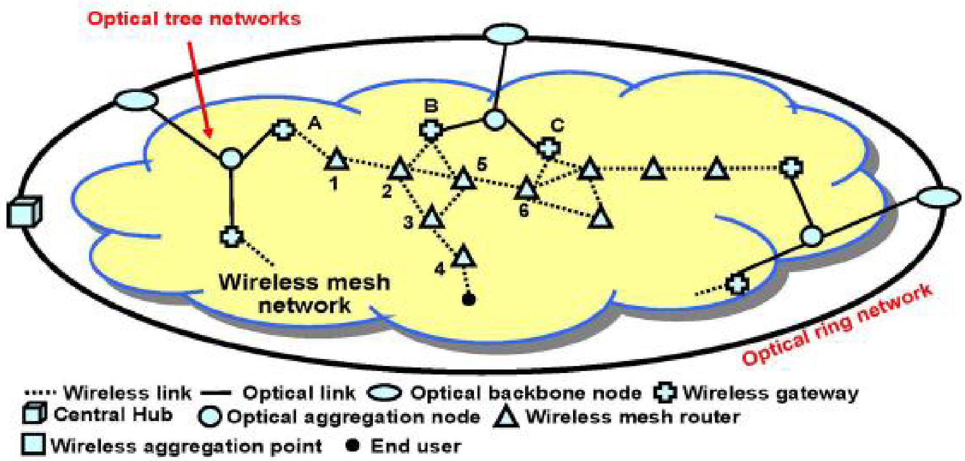


Figure 2.4: Hybrid optical-wireless-access-network architecture (from [12]).

2.4.2 Bandwidth Allocation and Scheduler for EPON-WiMAX

To the best of our knowledge, joint MAC protocols including scheduler, Admission Control (AC), and Dynamic Bandwidth Allocation (DBA) in EPON-WIMAX have not been addressed in a comprehensive way. In [15], the authors propose a joint AC and DBA but only to admit and maintain Private Virtual Networks (PVN) over EPON-WiMAX.

To date, a few scheduling mechanisms have been proposed to support QoS and improve performance for delay sensitive traffic in EPON-WiMAX networks [13], [16], [17]. A QoS-aware scheduling mechanism for hybrid optical and wireless networks is proposed [13] but it does not consider two-level scheduling algorithms and the size of ONU queues. A two-level scheduling scheme for the integrated WiMAX and EPON networks was proposed [16] where link adaption, queue length, and Head-of-Line (HoL) delay were jointly considered. This scheme is characterized by the use of proportional fairness for the transmissions from Subscriber Stations (SSs) over the WiMAX channels and a centralized mechanism at OLT for EPON uplink transmission that connects to multiple WiMAX-ONUs.

Integrated Optical Wireless Admission Control (IOW-AC) [17] proposes to modify the original signaling protocol in the optical domain. IOW-AC modifies GATE message by adding a field carrying the next cycle time, to give ONU-BS the required extra information to know the estimated waiting time for its next poll. As ONU-BS integrates MAC operations for both optical and wireless networks, it uses this information to calculate packet transmission delay in the optical domain.

But these scheduling mechanisms are remote station based mechanisms and consider scheduling in WiMAX and EPON separately.

Additional bandwidth allocation algorithms for EPON-WiMAX networks have been proposed [18], [19], and [20]. QoS-based Dynamic Bandwidth Allocation (QDBA) [19] is incorporated with the Prediction-based Fair Excessive Bandwidth Allocation (PFEBA) scheme in EPON to enhance the system performance. In QDBA, each ONU is in charge of three queues with different priorities. It also classifies WiMAX traffics into three priority levels and maps them to the queues of ONU. In addition to QDBA, the authors in [19] proposed a queue-based scheduling scheme that efficiently satisfies the demand for bandwidth requests and enhances the efficiency of the system. The DBA scheme [18] considers the features of the converged network proposed in the same paper to enable a smooth data transmission across optical and wireless networks, and an end-to-end differentiated service to user traffic of diverse QoS requirements. This QoS-aware DBA scheme supports bandwidth fairness at the ONU-BS level and class-of-service fairness at the WiMAX subscriber station level.

Bandwidth allocation and the support of different service flow [20] modifies the EPON MAC layer mechanism to adopt a connection-oriented MAC layer structure implemented in WiMAX network. This mechanism includes a new convergence sublayer that functions to control and allocate bandwidth in the passive optical network, using the same paradigm as in WiMAX networks. As a result, the whole integrated system can be controlled by a unified set of connection-oriented control protocols extended from WiMAX technology.

None of these BAs have a mechanism to support all service types defined in WiMAX standards over the hybrid access network. Moreover these BAs do not guarantee end-to-end QoS of traffic as they have two-stage bandwidth allocation; one for EPON part and the other for MiMAX part of the network and there is no direct mapping between the two stages.

2.4.3 Protection in EPON-WiMAX

To the best of our knowledge, the issue of protection has not been considered in EPON-WiMAX yet. However, protection has been only considered in EPON networks. A failure in EPON will result in disconnection of a large part of the network whereas a failure in WiMAX may be compensated by user mobility.

Since EPON transmits aggregated high-speed data from a large number of end-users, failure in the network units or links results in serious problems. Hence many studies attempt to provide protection for EPON networks. Some works are concerned about the protection of the most critical components of the network, i.e., OLT and feeder fiber between the OLT and the splitter coupler; while others consider the fault-tolerance in the drop region (optical splitter to ONU).

ITU-T Recommendation G.983.1 [21] discusses four protection architectures of PONs. In the first architecture, protection is provided through a fiber switch and a backup feeder fiber cable. The second architecture employs a cold duplicated OLT module as a protection strategy. The full duplication of all PON elements as a protection is considered in the third architecture. The fourth architecture proposes independent duplication of feeder fiber and branches. However, the drawback of all those architectures is the cost due to the redundancy.

In [22], protection scheme utilizes one cold standby OLT that can protect multiple PONs. This scheme supports only one OLT failure and requires cold standby equipment.

Two configurations to protect feeder portion of EPON networks were discussed in [23]. Fiber duplex architecture that equips a spare feeder fiber is considered in the first configuration. The PON interface is responsible for the failure detection and routing the traffic to the spare fiber. The second configuration provides protection against failure of both feeder fiber and PON interfaces. The splitter is connected to the working OLT and the standby OLT. The standby PON interface is activated when the working PON interface fails.

Protection through redundant fiber connection and an additional device Access Control System (ACS) to detect the failure and route the signal to standby link is proposed in [24]. It focuses on protecting the drop region between splitter and ONUs from the EPON networks.

In [25], an Automatic-Protection-Switching (APS) mechanism copes with a distribution fiber break of ONUs. When branches are down, the transmission of the affected ONU is restored by other interconnected ONUs. But this scheme does not provide any protection for the OLT and feeder fiber.

A resilient fast protection switching scheme [26] protects against feeder fiber breaks or equipment failure that occurs in the CO. This scheme is executed at the CO. The scheme has a redundant feeder. Protection of the most critical components is a key point to ensure the reliability of the access network.

In ring topologies, a protection scheme that protects one point failure in the ring by considering a conventional ring and a backup transceiver and receiver is proposed in [27]. The double feeder fibers with a hybrid small ring proposed in [28] address the problems of the ring topologies, i.e., more fiber usage and higher signal attenuation. The scheme minimizes the fiber usage and assures no packet loss by using hot standby components.

To achieve high reliability and low-cost for deployment, [29] proposes a fault-tolerant Multi-EPON system with cost-effective shared protection that interconnects adjacent EPONs by Bridge ONUs to avoid redundancy. After failures, the Bridge ONU, that controls the faulty EPON, plays the role of OLT and the transmission of faulty EPONs are restored by relaying to other interconnected adjacent EPONs.

For WDM-based PON topology, authors of [30], [31], [32], [33], [34] and [35] have recommended duplicate optical fiber and active components. However, these schemes have a high cost due to their high redundancy. In [36], authors proposed a fault-tolerant architecture for WDM-EPON namely Cost-based Fault-Tolerant WDM-EPON (CFT-WDM-EPON) that lowers the cost of conventional protection architecture. The CFT-WDM-EPON not only protects the optical nodes such as the OLT, but also protects optical fibers such as feeder fibers. It can recover the optical failure by fast wavelength switching between control and data channel, and only equips the backup feeder fiber to connect the adjacent PON system in order to economize the cost of deployment.

2.5 RPR-EPON Hybrid

The integration between two known standards, RPR and EPON, can provide good reliability for the optical hybrid network. Works [4] and [37] have employed this integration as an optical backhaul network in core and edge metro networks. Furthermore, the integration between Wavelength-Division Multiplexing (WDM), EPON and RPR is supported with a single-hop, star sub-network architecture called STARGATE in [4] and a very similar architecture called SuperMAN in [37].

2.5.1 Network Architecture for RPR-EPON

The STARGATE architecture [4] integrates Ethernet-based access and metro networks. Specifically, this architecture consists of an RPR metro edge ring that interconnects multiple WDM EPON tree networks to each other as well as to the Internet and server farms. For STARGATE, the authors explore the merits of deploying an additional P2P or P2MP fiber link in EPON tree networks for connecting the OLT with a subset of ONUs in the downstream direction. In particular, the RPR network in STARGATE consists of Central Offices (COs), which are interconnected via a single-hop WDM star sub-network, and RPR ring nodes.

In [37], the authors employ the same architecture proposed in [4]; however, they also examine the way in which WiMAX can be integrated with the RPR ring. Specifically, they extend the ring part of the architecture by an optical-wireless interface that connects with the WiMAX networks, and they detail the node located at the optical-wireless RPR-WiMAX interface.

2.5.2 MAC Protocol for RPR-EPON

In [4], the authors proposed to alter the discovery and registration operations in WDM EPON according to the modification described in [38]. Specifically, the authors suggested that ONUs use the first queue set for the report messages, so that these messages can carry one or more queue sets to report the bandwidth requirements of the standard EPON connection for sending data to the OLT. Also, the ONU can report bandwidth requirements on any of the star network connections for sending data to an ONU located in a different EPON. In order to accomplish this process, the given ONU uses an additional queue set and writes the MAC address of the destination ONU in the reserved field of the REPORT MPCP message, and then it sends this message to the OLT.

Although the authors do not propose any DBA algorithm for STARGATE, they specify that the DBA algorithm for STARGATE should dynamically establish transparent all-optical circuits across the network at the wavelength and sub-wavelength levels. Also, the DBA should provide predictable QoSs for bounded delay and guaranteed bandwidth between ONUs in different WDM EPONs.

In [37], the authors are not concerned about the MAC protocol of the RPR-EPON. Instead, they focus on the MAC of the PRP-WiMAX integration, elaborating on the importance of various scheduling algorithms used by downlink, uplink, and RPR schedulers. Specifically, they have proposed an integrated hierarchical scheduler that maps RPR traffic classes to WiMAX scheduling services. Moreover, this scheduler provides end-to-end QoS connectivity and satisfies the QoS requirements of different traffic classes and scheduling services in integrated RPR-WiMAX networks.

2.6 Summary

Since this thesis examines the integration among RPR, EPON, and WiMAX networks, it was first necessary to explain the various factors that should be considered for this integration. Subsequently, the features and characteristics of each of these standards were reviewed. As the RPR-EPON-WiMAX integration has not yet been examined, we reviewed literature for the existing EPON-WiMAX and RPR-EPON combinations. EPON-WiMAX networks have been considered in many works, and architectures, bandwidth allocations, and schedulers have been proposed for these networks. However, only two legitimate architectures have been proposed for EPON-WiMAX networks, and these architectures have several drawbacks. Also, the MAC protocol for EPON-WiMAX networks has not yet been considered in a comprehensive way, and the Admission Control has not even been mentioned for these networks. Lastly, the bandwidth allocation and schedulers have been discussed individually, so that both of them manage EPON and WiMAX separately. RPR-EPON has been studied as a proposed integration between metro and access networks. Nearly all of the works that considered RPR-EPON suggested the same architecture for this network. Within this architecture, the messages that manage the EPON operation are modified and extended to work with the RPR-EPON integration. However, no single author has proposed a protocol for integrating the MACs of RPR and EPON to manage and maximize the performance of its hybrid network.

Chapter 3
Proposed Solution for EPON-WiMAX

Implementation of wired and wireless access networks into one single network architecture which is controlled by a single control system, known as fixed mobile convergence (FMC) [39], results in significant cost reduction. FMC is envisioned as a future architecture for broadband access networks. This work focuses on the integration of EPON and WiMAX technologies as the representatives of optical and wireless technologies respectively.

The complementary features of EPON and WiMAX make the integration of these technologies a superior solution for access networks [10], [18]. This integration combines advantages of both technologies; i.e, the high bandwidth and reliability of EPON networks and the mobility and flexibility of WiMAX networks. Specifically, there are several important factors that motivate such integration.

- First, EPON and WiMAX show a good match in capacity hierarchies. EPON bandwidth can be shared by a group of remote Optical Network Units (ONUs), in a way that gives each ONU a capacity in the range of the bandwidth offered by a WiMAX Base Station (BS).

- Second, integration can improve the overall network performance and QoS support by using integrated packet scheduling and bandwidth allocation.

- Third, since the integration realizes the FMC, it reduces design and operational costs of the network significantly. Moreover, it supports mobility in the access network.

- Fourth, both EPON and WiMAX employ a generic poll/request/grant mechanism. A central station (Optical Line Terminal (OLT) or WiMAX Base Station

(WiMAX BS)) polls a remote station (ONU or SS) for bandwidth requests. The remote station responds with requests for bandwidth and the central station then grants bandwidth. This poll/request/grant mechanism makes EPON and WiMAX very similar in bandwidth allocation and QoS support.

The integration between EPON and WiMAX technologies in hybrid network architecture has advantages over the traditional optical and wireless networks. The advantages of EPON-WiMAX hybrid access networks are summarized as follows:

a. In hybrid access networks, there is no need to lay fiber all the way to every customer's premises. This significantly reduces the cost of network deployment and incurred maintenance as compared to that of pure fiber based access networks in built-up neighborhoods.

b. Hybrid networks are more flexible than pure optical access networks. The "anytime-anywhere" approach is also applicable to the hybrid network because users are served through the wireless frontend of the hybrid network. This allows users inside the network to seamlessly connect with one another.

c. Hybrid networks are more robust than the traditional wired networks. In case of a fiber failure, all users served by a particular fiber/wireless access point pair can immediately move to another serving access point close by.

d. Hybrid networks do not suffer from the problem of congestion and information loss. This is due to the inherent reliability of the network. Moreover, hybrid networks can have a better load-balancing capability due to users' mobility.

e. Fault tolerance, robustness with respect to network connectivity, and load balancing characteristics of the hybrid networks make them "self-organizing".

The complete solution for EPON-WiMAX hybrid network should include architecture and a joint MAC protocol for this architecture in order to improve the performance of hybrid access network. Architectures proposed for EPON-WiMAX in literature either concern on the ways of integrations [10] or have some drawbacks [11]- [12].

Components of MAC protocol; admission control, bandwidth allocation and scheduler; for EPON-WIMAX have been considered in individual manner. But MAC protocol has not been considered jointly to measure effect of all these components on the network performance. Although one work consider joint Admission Control and Bandwidth Allocation, but it did this to implement virtual private networks on EPON-WIMAX.

In this chapter, we propose a new architecture for the integrated WiMAX and EPON networks that overcomes drawbacks of earlier architectures by providing a protection in the EPON part of the network and extends the converge range of the access network. A MAC protocol that includes joint bandwidth allocation algorithm, scheduler, and Admission Control is proposed. This MAC protocol supports QoS for different services types that are incorporated in the proposed architecture.

This chapter is organized as follows: First, the new architectures for EPON-WiMAX networks are presented in Section 3.1. Section 3.2 outlines the general setting of the suggested MAC protocol for the EPON-WiMAX networks. Then in Section 3.3, Distributed Admission Control for one of the proposed architectures is presented. The Multilevel Dynamic Bandwidth Allocation is provided in Section 3.4. Then in Section 3.5, Hybrid Scheduler is presented. The performance of the proposed solution is evaluated and compared with other solutions proposed in the literature in Section 3.6. Finally, Section 3.7 summarizes the chapter.

3.1 New Network Architecture

3.1.1 Motivation

Hybrid access network architecture should be scalable, resilient, support packet routing and forwarding, enable smooth protocol adaption, and allow QoS support with efficient bandwidth sharing. The authors of [10] and [40] explore the benefits of four proposed architectures for EPON and WiMAX integration, but they focused on the possible methods of integration rather than a particular architecture. It would be more suitable to refer to [10], [40] as "methods of EPON-WiMAX integration."

The hybrid network architecture in [13], [14] consists of a large WiMAX network that transmit its data over a passive optical network as a backhaul. This architecture can be considered straightforward since its architectures are typical when comparing them to [10] and [40].

Among EPON-WiMAX architectures proposed in the literature, architectures in [11] and [12] are the most interesting ones. Hence we consider these architectures and their drawbacks as a motivation for our proposed architecture. The Wireless-Optical Broadband-Access Network (WOBAN) architecture [11] consists of a wireless network at the front end, and it is supported by an optical network at the back end. This architecture has many PON segments supported by a telecom Central Office (CO). Each PON segment connects an OLT located at the CO, with a number of ONUs, which are connected to wireless BSs from the wireless portion of WOBAN. The front end of a WOBAN is a multi-hop Wireless Mesh Network (WMN). This WMN consists of wireless "gateway routers" and wireless routers/BSs. Gateway routers are the connecting points between the optical and the wireless parts and work as the gateways for both sides.

In the network architecture proposed in [12], the optical backhaul consists of a ring and multiple tree networks. Each tree network connects one OLT with multiple ONUs. OLTs of all tree networks are connected to the ring network. Each ONU of every tree network is connected to a gateway router of a Wireless Mesh Network (WMN). WMNs form the wireless portion of the architecture. A central hub connecting the ring to the metro network maintains a central management system responsible for bandwidth allocation, integrated routing, flow control, traffic engineering, and network management.

Both architectures have many advantages, but here we focus on the drawbacks as a source of motivation for our architecture. The drawbacks of the architecture in [11] are as follows. First, in the case of OLT or fiber failure the optical-wireless loses full or a large portion of network connectivity, where users' traffic will need to be re-routed. Second, as all OLTs are located at the same CO, the central office may become the system bottleneck and any physical failure of CO may result in the failure of the entire system. The architecture proposed in [12] offers fault tolerance against a single link failure but does not do so in the case of two or more link failures. The system offers fault tolerance against a single OLT failure only if the wireless part is mesh network but does not do so if the wireless network is in point-to-multipoint mode. The other drawbacks of the architecture are that the entire network is under the same management system and that the bandwidth that each OLT can get over the ring decreases as the number of OLTs in the system increases.

3.1.2 Proposed Architecture

Our proposed architecture addresses these drawbacks and combines the advantages of architectures in [11] and [12] resulting in the following characteristics:

1) It offers superior protection against failures.

2) The bandwidth of OLT is independent of the number of OLTs in the system.

3) The management system is distributed over all OLTs.

4) OLTs do not need to be located together at the same CO.

The reliability of the system can be achieved by implementing a protection mechanism in the optical part of the network.

The protection in the EPON part of the architecture is implemented through two mechanisms; by duplicating the functionality of OLT and making the splitter dual connected to the OLT. The OLT with double functionality protects the system against OLT failure. As the splitter is connected to the OLT through two fiber cables, this protects the system against the fiber break.

In addition to the mentioned advantages that give proposed architecture the ability to overcome drawbacks of architectures proposed in [11][12], the proposed architecture extends the network converge distance of optical network beyond 25 km. This makes the proposed architecture serve more end-users who share an optical line terminal link. Extension of coverage distance of the architecture can be done by inserting an intermediate network between the backhaul and front end networks. This can be done in two different ways: one is suitable for urban areas and another for rural areas.

Optical-Optical-Wireless (OOW) architecture

In urban areas where fiber is deeply deployed, an Intermediate Network can be an additional optical network using the two stages optical network design proposed in [41]. This will form the Optical-Optical-Wireless (OOW) architecture Figure 3.1. OOW architecture consists from two EPON network stages. In the first stage, the OLT is connected through the splitter to a group of nodes (called SubOLT) instead of traditional ONUs. Each subOLT performs the functions of OLT in the EPON segment for the second stage of the architecture. In the second stage of the architecture, ONUs are replaced with units that implement functionalities of both EPON ONU and WiMAX BS. Namely, each subOLT is connected to a group of ONUs and each ONU is connected to a WiMAX BS. The connection between ONU and BS can be implemented in different ways as seen later. The splitter in the first stage is dual connected to the OLT and each splitter in the second stage is connected to two subOLTs to improve the reliability of the architecture.

Optical-Wireless-Wireless (OWW) architecture

In rural areas, providing wired broadband connectivity may be prohibitively expensive, time consuming, and difficult to maintain. In such situations, an Intermediate Network can be a high-capacity wireless backhaul such as P2P WiMAX, Local Multi-capacity Distributed Service (LMDS) and so on. This will form the Optical-Wireless-Wireless (OWW) architecture Figure 3.2. In OWW architecture, OLT is connected with a group of nodes that work as subOLTs for the optical network and as BSs for the wireless network (subOLT/BS). Moreover, each BS has a long range wireless connectivity with a group of BSs in the front end of the network. SubOLT/BS is a unit that performs the functionality of both the subOLT and WiMAX BS in a way similar to that of ONU/BS of integration architectures in [10].

3.1.3 Elements structure in EPON-WiMAX

The SS in the architecture is a standard WiMAX SS with the exception of mechanisms that grantee that each connection will not exceed its rate limit as in Section 3.4.

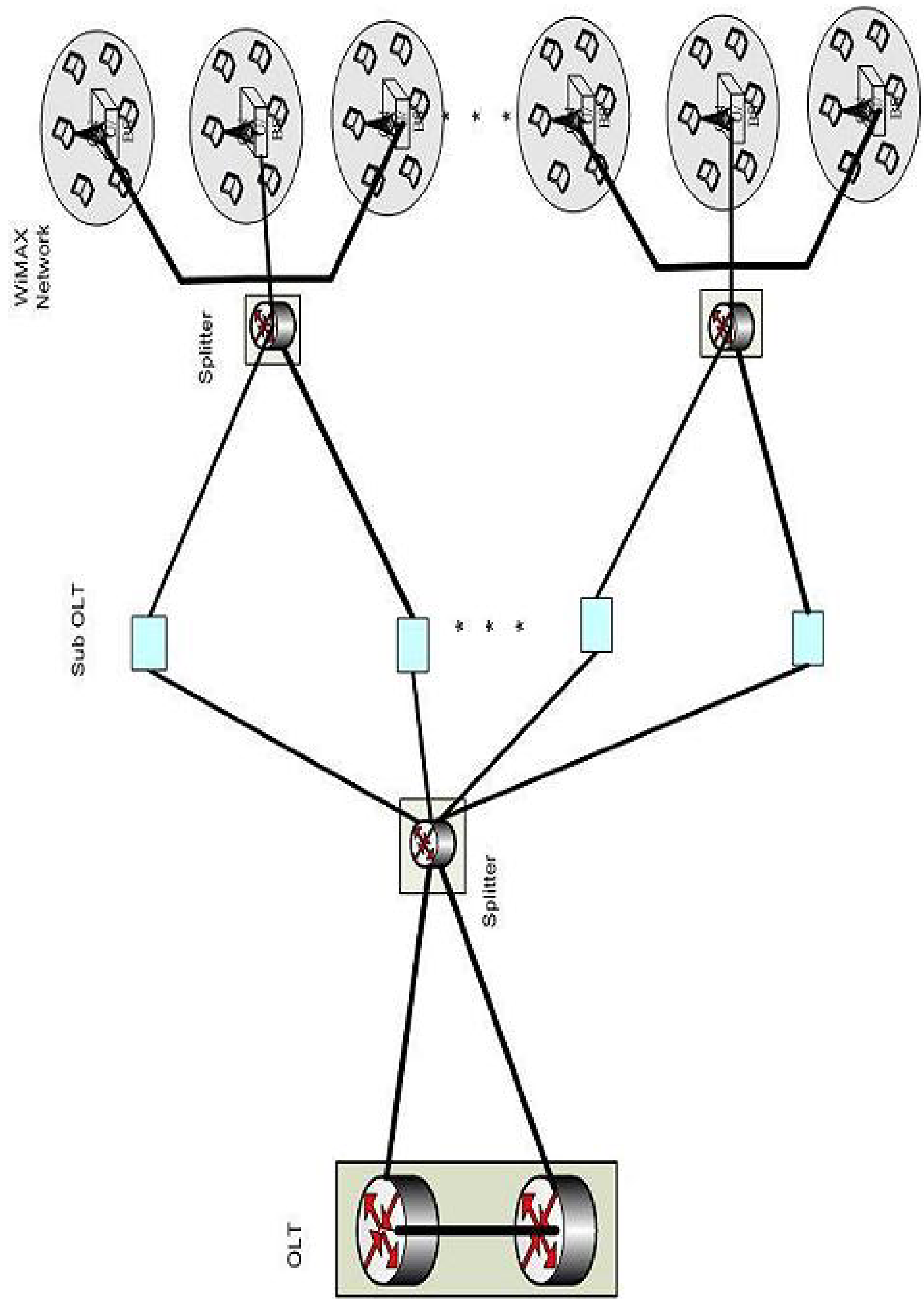


Figure 3.1: Optical-Optical-Wireless architecture

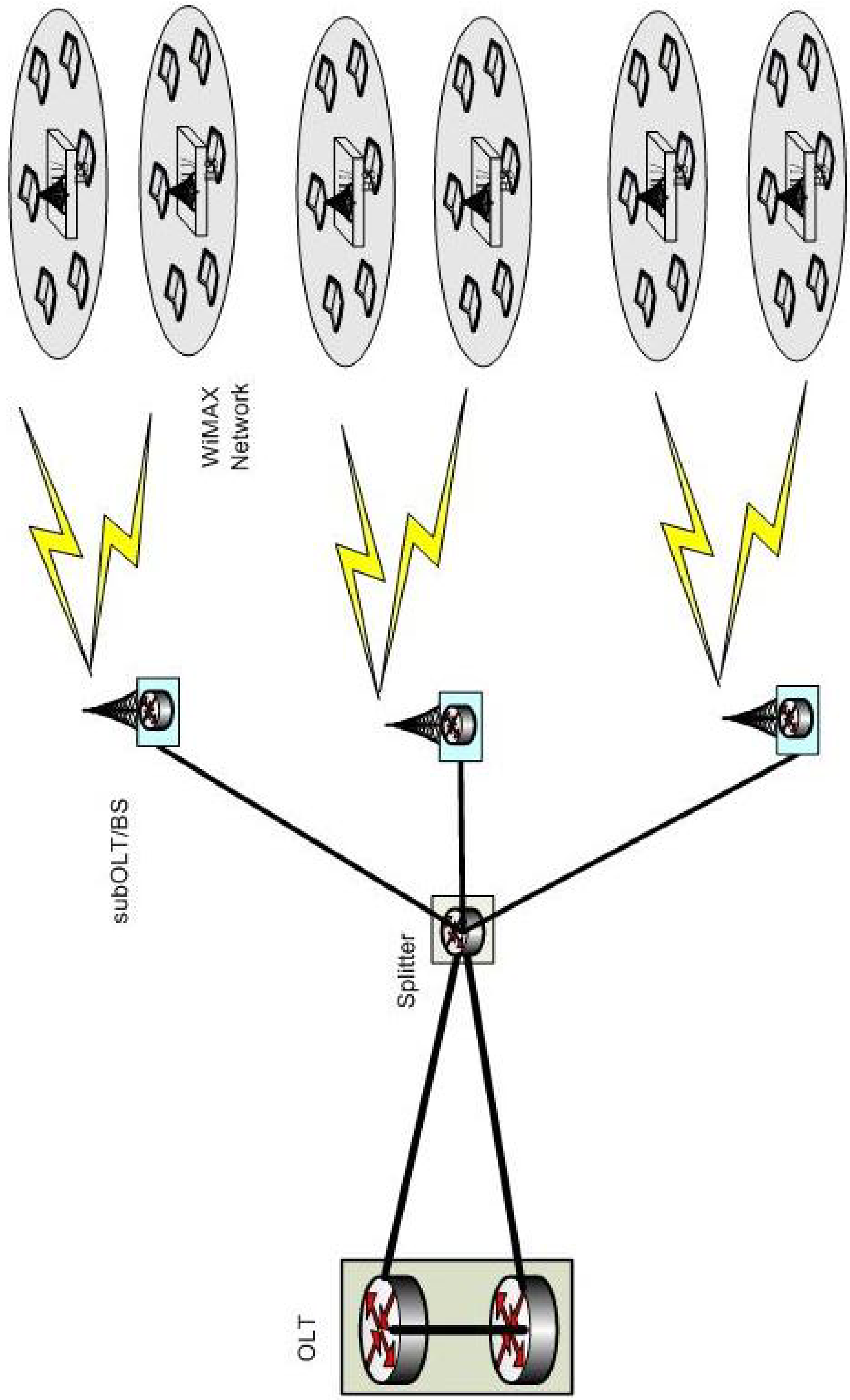


Figure 3.2: Optical-Wireless-Wireless architecture

Structure of BS in the front end of Figure 3.2, is a standard WiMAX BS. Structure of the BS connecting to EPON (in front end in Figure 3.1 and in intermediate in Figure 3.2) is dependent on the way WiMAX integrates with EPON. The connection between WiMAX and EPON can be done according to one of the proposed integration architectures in [10]: independent architecture, hybrid architecture, unified connection-oriented architecture, or microwave-over-fiber (MoF) architecture. In case of independent integration, BS is a standard WiMAX BS. If a hybrid or unified connection-oriented architecture is used as integration method, the architecture has no dedicated BS but the functionalities of BS are implemented as a part of the ONU/BS unit. In MoF integration architecture the BS is replaced with a dumb antenna installed on ONU and the functionalities of BS are carried out by both the ONU and OLT (see [10] for details).

In the EPON domain, the ONU structure differs according to WiMAX and EPON integration. It is a standard EPON ONU for independent integration. For both hybrid and unified connection-oriented integrations, the ONU is implemented as a part of an ONU/BS unit. But for unified connection-oriented integration, the ONU replaces the Ethernet frames in EPON packet with WiMAX MAC PDUs, and then encapsulates the Ethernet frames as client data in the WiMAX MAC PDUs. If WiMAX is integrated with EPON according to the MoF technique, the ONU, in addition to standard EPON ONU functions, receives WiMAX signals from SSs and modulates them on a special carrier frequency and then multiplexes them with EPON signals. The ONU then modulates multiplexed signals onto a common optical frequency and transmits them to the OLT.

The OLT is a standard EPON OLT, but if WiMAX is integrated with EPON according to MoF architecture, then OLT consists of two modules, standard EPON OLT and a central WiMAX BS [10].
The subOLT in Figure 3.1, is a unit that proposed in [41]. It is implementing both ONU and OLT modules. In the case of MoF integration, the subOLTs have a central WiMAX BS for their ONUs and consider WiMAX signals modulation and multiplexing toward the OLT.

Generally MAC functionalities of OLT, ONU, BS, and SS are differing from that of standard ones seen in Sections 3.3 - Section 3.5.

All splitters in proposed architectures are 2Xn where n is the number of subOLTs in the first stage and the number of ONUs in the second stage of the architecture.

The EPON part of the proposed architecture can be TDM or WDM EPON. The splitter in the architecture can be a WDM splitter, TDM splitter, or hybrid WDM/TDM implementation. Although this chapter is considering the TDM splitter in order to simulate the architecture and measure its performance, it recommends the WDM/TDM implementation to give the network the capability to be upgraded to a WDM extension.

3.1.4 Routing in the proposed architecture

The splitter in Figure 3.2 and the first splitter in Figure 3.1 are connected to the two access points at OLT; one of these access points is the primary gateway of the splitter and the second access point works as the secondary gateway. The OLT monitors connection statuses of both the primary and the secondary gateways. When an OLT receives a packet for a subOLT, the packet is received by the primary gateway. To forward the packet, the primary gateway checks the connection with the splitter. If it is up and has a reasonable transmission time, it sends the packet; otherwise the packet is sent through the secondary gateway. In the uplink direction, the splitter simply broadcasts the data from subOLTs over the two connections to both the primary and the secondary gateways. In the normal operation condition where both connections and both gateways are working, only the primary gateway gets and processes the data packets. In the case of failure of the primary gateway or its connection, the secondary gateway handles the packets.

A routing procedure is also needed for splitters in the second stage of OOW architecture in Figure 3.1, as each splitter is connected to both the primary and the secondary subOLT. In the downlink direction, data is routed through the primary subOLT unless this subOLT or its connection is failed. In the downlink direction, data is broadcast to the both subOLTs. Only the primary subOLT extracts packets and forward them to the splitter, unless the primary subOLT or its connection is failed. In uplink direction, the splitter sends packets to both subOLTs at the same time. The secondary subOLT receives and processes the packet only when the primary subOLT or its connection fails. It is clear that this procedure needs subOLTs intercommunication. This subOLTs intercommunication can be made according to the mechanism described in [10] for ONUs intercommunication.

3.1.5 Protection and Costs Reduction

We strive to make the architecture more reliable in case of failures in the first stage (from OLT to the splitter in both Figures 3.1, 3.2 and between subOLTs and splitter in Figure 3.1). Firstly and more importantly, the first part of the network is critical because failure in this part results in a disconnection of a large part of the network; whereas the second stage (from splitter to ONU/BS in Figure 3.1) failure can affect only a small portion of the network. Secondly, failure in the second part of the architecture can be compensated to some limit by user mobility and/or handover in the wireless part. Moreover, failure in the wireless part of the network can occur only at the Base Station location; therefore, it is relatively uncomplicated to locate and fix the failed components.

The costs reduction of the proposed architecture can be achieved through the minimum use of redundant fiber cables used in EPON protection. Fiber redundancy can be minimized by using one spare feeder fiber as a standby connection for two adjacent EPON networks as shown in Figure 3.3 where the connections of the two OLTs are combined to the shared fiber through 2X1 optical switch and the shared fiber is connected to the two splitters through 1X2 optical switch. The same mechanism can be applied between subOLTs and splitters as shown in Figure 3.1. As each EPON network operates on its own wavelengths, optical switches should have wavelength multiplexing/de-multiplexing and/or wave length filter to prevent interference between EPON networks.

In addition to reduction of the architecture cost, configuration in Figure 3.3 can be used for further protection. This configuration can protect against a failure

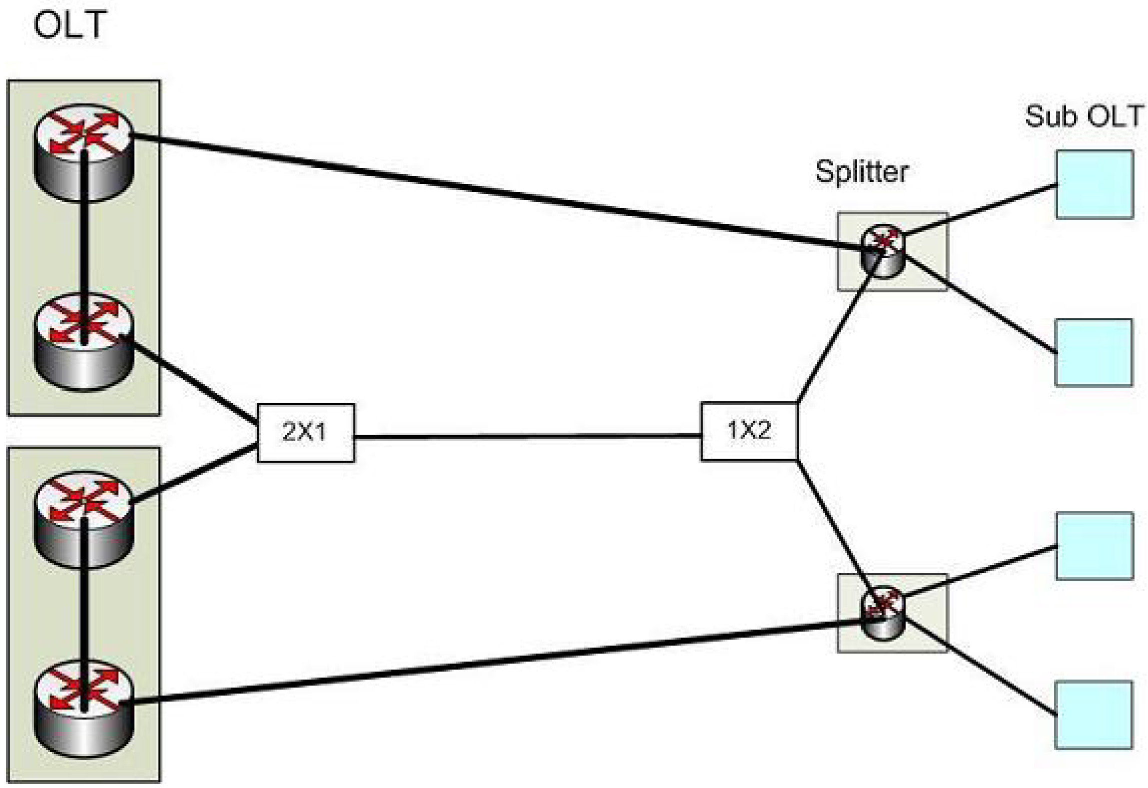


Figure 3.3: Protection of EPON in OOW architecture.

of the primary OLT and/or main feeder fiber of both EPON at the same time by serving them through the spare feeder connection and secondary OLTs. Also, it can protect from a complete failure of both OLTs and main feeder connection of EPON network because user traffic served by this EPON can be routed through the spare connection to the secondary OLT of the neighboring EPON.

3.2 Joint MAC Protocol for EPON-WiMAX

The MAC Protocol is designed for the proposed Optical-Optical-Wireless hybrid network architecture shown in Figure 3.1. This MAC protocol considers that the ONU and WiMAX BS are integrated in a single system box (ONU-BS) according to the hybrid architecture in [10].

As users are mostly served through the WiMAX part of the network, this MAC protocol should support all service types defined in the WiMAX standard namely Unsolicited Grant Service (UGS), real-time Polling Service (rtPS), extended real-time Polling Service (ertPS, defined in 802.16e), non-real time Polling Service (nrtPS) and best-effort (BE).

The WiMAX part of the hybrid network works in a similar fashion as the traditional WiMAX network in the sense that the BS manages the bandwidth allocation and scheduling. Bandwidth allocation is done according to the total data rate (in bps) that can be used at BS (C_{BS}). C_{BS} depends on both the data rate available in the wireless interface of the BS (C_{BS_wl}) and the data rate of backhaul connection (C_{BS_bh}) that connects BS to the rest of the network. In hybrid network, C_{BS} is different from that in the traditional WiMAX network. In the traditional WiMAX network, C_{BS_bh} is constant, hence C_{BS} varies dependent on C_{BS_wl} only. In the hybrid network, C_{BS_bh} varies from cycle to cycle dependent on the bandwidth allocated to the ONU (by the OLT or Sub-OLT) to which the BS is attached to. Therefore,

$$C_{BS} = min(C_{BS\_wl}, C_{BS\_bh}). \tag{3.1}$$

The proposed joint MAC protocol consists of Distributed Admission Control, Hybrid Scheduler, and Multi-level Dynamic Bandwidth allocation modules. The details of these modules are given in the following three sections.

3.3 Distributed Admission Control

Admission control is essential to ensure that the admitted traffic gets the promised resources and their service qualities are not deteriorated while accepting new. To the best of our knowledge, Admission Control has not been considered in EPON-WiMAX networks. Although Admission Control has been considered extensively in WiMAX networks, it did not get this consideration in EPON networks. Few works such as [42] addressed Admission Control in EPON networks.

We proposed a distributed admission control for the designed architecture in the previous Section. The proposed Admission control runs in different parts of the architecture: WiMAX Base Station, Sub-Optical Line Terminal (sub-OLT), and OLT.

To decide whether a new connection can be established or not, the following three-level admission process is adopted. First stage of admission is completed locally at the BS. Next it may need to go through second stage at the subOLT to which BS/ONU is attached. Some connections may further need to go through the third stage at OLT to be admitted.

Admission Control that runs at BS in the proposed MAC protocol differs from the one in a stand alone WiMAX network in two aspects. First, in the stand alone WiMAX network, AC in BS (such as the one in [43]) serves connection admission requests on a first-come-first-serve basis; whereas in the proposed protocol, connection admission requests are served on priority basis by giving each service type a priority level and serving the highest priority class requests first and then moving to the next level.

Second, in the stand alone WiMAX, BS sets frame duration at the start and on receiving a connection request. If both bandwidth and delay requirements of the connection can be satisfied according to the frame duration, the connection is accepted. Otherwise, if either bandwidth or delay requirements cannot be satisfied, the connection is rejected. In our proposed protocol, we propose dynamic frame duration to meet the delay requirements of a connection. Therefore, on receiving a new request, if the delay requirement of the connection cannot be satisfied according to the current frame duration, the frame duration is changed by choosing another frame size from the frame sizes defined in WiMAX Standard to meet the delay requirement of the connection. If the frame size cannot be changed without affecting any of the active connections, the new connection is rejected.

In general, to maintain QoS parameters of the active connections and satisfy QoS requirements of the new connection, a connection is admitted if:

1. The available bandwidth can accommodate the new connection request.

2. The new connection will receive QoS guarantees.

3. QoS for the existing connections are maintained.

The admission control (Figure 3.4) shows that these conditions are verified at the BS for both C_{BS_wl} and C_{BS_bh}. In the proposed AC, there are three main functionalities: admit new connection (Figure 3.4(a)), manage waiting connections (Figure 3.4(b)), and monitor under-test connections (Figure 3.4(c)).

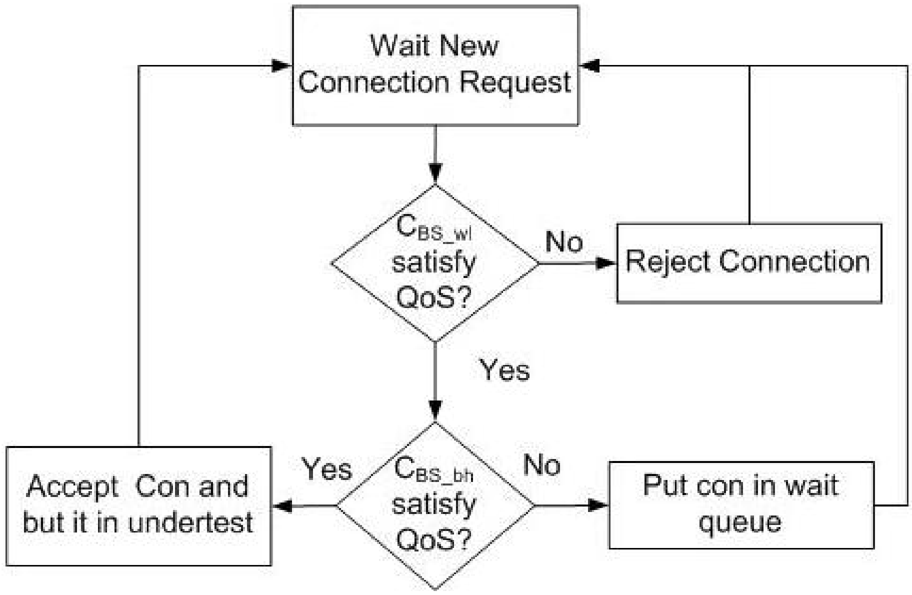
3.3.1 Admit new connection

1. If admission conditions fail against C_{BS_wl} , the connection request is rejected.
2. If conditions are satisfied by C_{BS_wl}, they are verified for C_{BS_bh}:
   (a) If all conditions are satisfied by C_{BS_bh} , the connection request is accepted; the connection's status change to under-test connection. In the hybrid EPON-WiMAX network C_{BS_bh} is not constant but varies according to the bandwidth allocation scheme at the subOLT. The BS sends the requirements of the connection with those of admitted connections for bandwidth allocation.
   (b) If any of these conditions fails against C_{BS_bh} , the connection is scheduled for the second stage admission by putting connection in the wait queue and sending its QoS and delay requirements to the subOLT. The QoS requirements of waiting connections are considered in C_{BS_bh} whereas bandwidth allocation to the BS is considered in the subsequent cycle. Moreover the delay requirement of this connection can change the cycle length if it is required.

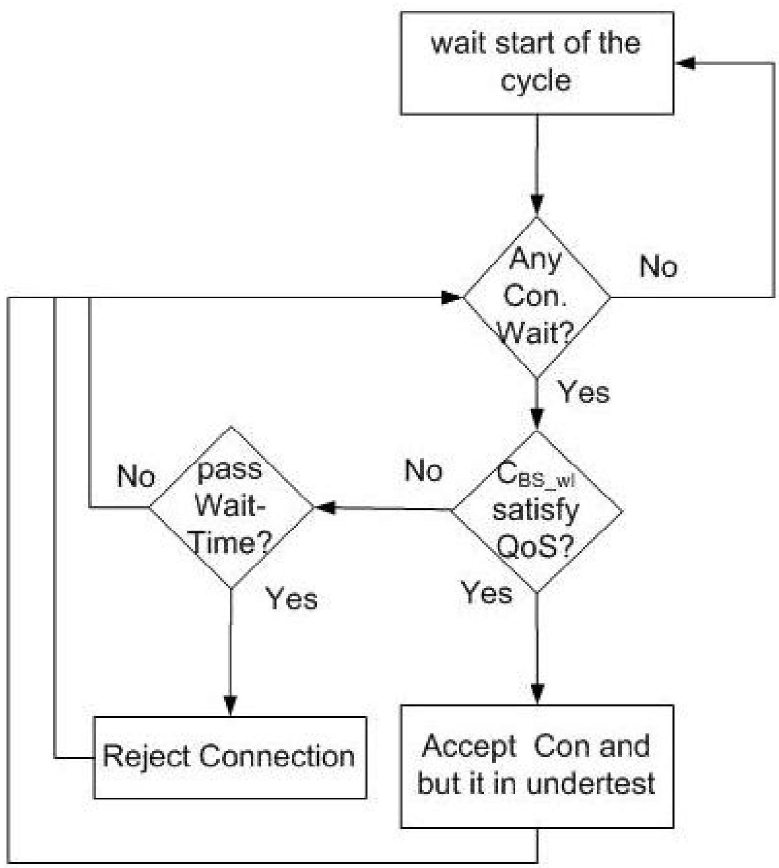
3.3.2 Managing Waiting Connections

At the start of each cycle, for every waiting connection, the BS examines the connection requirements against the new C_{BS_bh}.

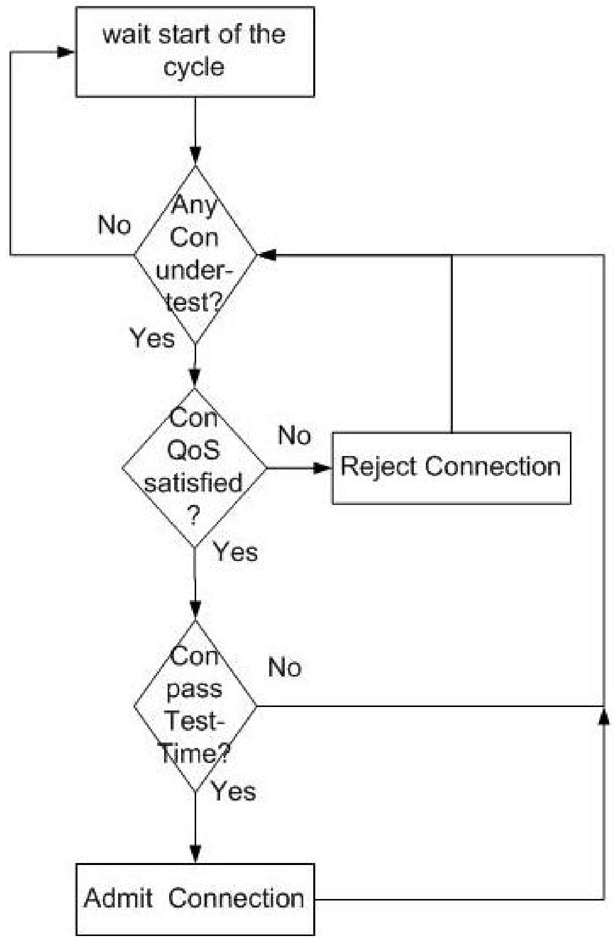
1. If the connection QoS requirements are satisfied, the connection is accepted and its status is changed to under-test as in (3.3.1 2-a).



(a) admit new connection.



(b) manage waiting connections.



(c) monitor under-test connections.

Figure 3.4: Admission Control

2. If any of the required conditions fail or if the connection has spent the maximum waiting time in the queue, the connection is rejected. The maximum waiting time should be long enough to ensure that bandwidth and delay requirements of the connection are checked at the subOLT and OLT levels. At maximum, the waiting time is three-cycle time and in the worst case where we use maximum cycle time of 20 ms, the connection may wait for 120 ms before it is rejected or finally admitted in the network. This interval is chosen to ensure that the connection QoS requests are being considered at the OLT.

3.3.3 Monitoring Under-test Connections

At the start of each cycle, for each under-test connection, the BS examines if the QoS requirements of the connection can be satisfied.

1. If the connection QoS requirements are satisfied for a Test-Time period, the connection is admitted to the network. Test-Time is at least three-cycle period to ensure that the allocated resources to the connection are being granted by the OLT for 2 cycles. According to Bandwidth Allocation Algorithm (Section 3.4), resources allocated to connections by OLT are reserved until connection terminate.

2. If any of the required conditions fails, the connection is rejected.

3.3.4 How AC admitting Connections

The bandwidth and delay requirements of the connection of each service are verified as follows. Let C_i^B and C_i^d be the be the bandwidth requirement and the delay bound for the connection i, respectively. The connection request can be accepted if the following condition is satisfied:

$$C_i^B + \sum_k C_k^B \leq \beta. \tag{3.2}$$

Where β is the bandwidth allocated to the BS, C_{BS_wl} or C_{BS_bh} depending on whether the condition is verified against C_{BS_wl} or C_{BS_bh}, respectively. $\sum_k C_k^B$ is the total bandwidth requirements of all current connections served by BS.

AC admits the connection based on the delay requirement if the following condition is satisfied:

$$C_i^d \geq MPF_l. \tag{3.3}$$

$$MPF_l = \min(PRF, F_l). \tag{3.4}$$

$$PRF = \lfloor 2C_i^d \rfloor. \tag{3.5}$$

Where F_l is the current frame length used by the BS. It is related to the cycle time of the whole. PRF is the frame size defined in the WiMAX standard and satisfies the following two conditions at the same time. The first condition is that the frame size is less than or equal to the delay requirement of the connection. The second condition is that the bandwidth of the network corresponding to this frame size should accommodate current and new connections. Hence the selected frame size satisfies the bandwidth requirements of all connections (current and new). Moreover, as it can only be less than the current frame size (Eq. 3.4), it satisfies the delay requirements of all connections too.

Satisfying both conditions depends on the type of the connection request. BE traffic is bursty and does not require delay requirements or bandwidth guarantees. Thus, for a BE connection request, these conditions are always satisfied and BE is thereby directly admitted. UGS is a Constant Bit Rate (CBR) traffic. It requires constant bandwidth over a fixed period. It is non-bursty and can be simply characterized by its mean data rate in bits per seconds (bps). For CBR traffic, a flow may be admitted in case its mean data rate can be supported by the current system. UGS connection then needs to satisfy the bandwidth condition but it should not violate the delay requirements of the active connections.

The rtPS, ertPS and nrtPS are types of Variable Bit Rate (VBR) traffics. They are bursty and are characterized by the following parameters: Peak Arrival Data Rate, Maximum Burst Size, Maximum Delay Bound, and maximum and minimum packet sizes. For VBR traffic, the AC may admit a VBR stream according to either its peak rate or its mean data rate. We chose to admit these traffics according to mean data rate to save network bandwidth. nrtPS connection has no delay requirements, so only the bandwidth condition needs to be satisfied. rtPS and ertPS connections need both bandwidth and delay requirements and should not violate QoS requirements of other connections.

3.4 Multi-level Dynamic Bandwidth Allocation (MLDBA)

Bandwidth Allocation is a four-level algorithm: the first level of Bandwidth allocation runs at the BS; the second level runs at the ONU; the third level runs at the subOLT, and the fourth level runs at the OLT of the OOW architecture. Note that the subOLT and OLT use almost the same algorithm.

3.4.1 BS Bandwidth Allocation (BSBA)

First step in BSBA is to set frame size (F_l) of the BS according to

$$F_l = min(2C_i^d) \;\; \forall i \in N. \tag{3.6}$$

Where N is the group of active connections at the BS. F_l depends on the minimum delay requirement of all connections.

After setting the frame size, bandwidth allocation for different types of connections is computed as follows:

- BSBA assigns bandwidth according to strict priority. This is because traffics are admitted only if their bandwidth demands are guaranteed. Hence using strict priority ensures that the admitted connections get their required bandwidth and meet their delay constraints. Service types priorities from highest to lowest are UGS, ertPS, rtPS, nrtPS and BE. To stop higher priority connections from monopolizing the network, traffic policing is included in each SS. This policing forces the connection's bandwidth demand to honor its traffic's Service Level Agreement (SLA). SS can implement a token bucket for each service type that ensures that the admitted traffic of this service type does not exceed the specified average rate; moreover token bucket reduces fluctuation.

- To provide per-stream QoS guarantee, BSBA allocates each stream a bandwidth that meets its QoS requirements.

- To avoid BE connection starvation, BSBA reserves a portion of network's bandwidth that serves BE traffic. Other types of service are protected against the starvation as they only admitted into the network if their bandwidth can be provided.

- UGS traffic: Each UGS connection is assigned a constant bandwidth (fixed time duration) based on its fixed bandwidth requirement. This policy is determined by the IEEE 802.16 standard.

- ertPS traffic: BSBA allocates the requested bandwidth (fixed time duration) based on their fixed period requirement.

- rtPS traffic: To ensure that no packet misses its transmission deadline, we apply the Earliest Deadline First (EDF) service discipline to this service flow. Bandwidth needed to transmit packets with earliest deadline is assigned to each SS first. Then the bandwidth for other packets is divided among SSs. The packets' deadlines are determined by the packet's arrival time and delay requirement of the connection. Hence, the bandwidth allocated to rtPS connection is calculated as follows:

$$B_{i,rtPS} = B^{fdl}_{i,rtPS} + B^{nfdl}_{i,rtPS} \tag{3.7}$$

$$B^{fdl}_{i,rtPS} = \frac{C^{fdl\_sz}_{i,rtPS} \times B^{fdl}_{rtPS}}{\sum_k C^{fdl\_sz}_{k,rtPS}} \tag{3.8}$$

$$B^{nfdl}_{i,rtPS} = \frac{C^{nfdl\_sz}_{i,rtPS} \times B^{nfdl}_{rtPS}}{\sum_k C^{nfdl\_sz}_{k,rtPS}} \tag{3.9}$$

$$B^{nfdl}_{rtPS} = B_{rtPS} - B^{fdl}_{rtPS} \tag{3.10}$$

$$B_{rtPS} = min(B_{av}, B^{req}_{rtPS}) \tag{3.11}$$

Where B_{av} is the available bandwidth. B^{req}_{rtPS} is the bandwidth required to send all packets of all rtPS connections. B^{fdl}_{rtPS} is the bandwidth needed to send the earliest deadline packets and B^{nfdl}_{rtPS} is the bandwidth to send packets with deadline after the next cycle (non-earliest deadline). $B_{i,rtPS}$, $B^{fdl}_{i,rtPS}$ and $B^{nfdl}_{i,rtPS}$ are the total bandwidth, earliest deadline, and non-earliest deadline bandwidths assigned to rtPS connection i, respectively. $C^{fdl\_sz}_{i,rtPS}$, $C^{nfdl\_sz}_{i,rtPS}$ are the sizes of earliest deadline and non-earliest deadline packets of the rtPS connection i, respectively.

- nrtPS traffic: here only bandwidth requirements need to be satisfied, BSBA apply Weight Fair Queue (WFQ) service discipline to this service type. Each nrtPS connection gets bandwidth based on the weight of the connection (the ratio between the connection's nrtPS average data rate and total nrtPS average data rate).

- BE traffic: The reserved quota for BE and the remaining bandwidth from other service types if any, is equally allocated to each BE connection.

3.4.2 Bandwidth allocation at ONU (ONUBA)

Bandwidth allocation for the optical part of hybrid network starts at the ONU. The ONU receives data from the BSs and from users connected directly to the ONU. It classifies data based on their QoS requirements to suitable queues and then sends a bandwidth request to the subOLT. Each ONU has eight Priorities Queues (PQ). These PQs have different priority levels and are described as follows:

a. UGS queue: holds queuing data of UGS connections and has the highest priority.

b. ertPS queue: holds data of ertPS connections and has the second level of priority. The size of this queue is the actual required bandwidth for ertPS connections and it differs from the minimum amount reserved for ertPS.

c. rtPS-s-dead queue: has the third level of priority and holds packets of rtPS connections whose deadline time is within the next cycle.

d. rtPS-l-dead queue: holds packets of rtPS connections with deadline time later than the next cycle and comes in fourth level of priority. This queue is scanned periodically to move packets with deadline in the next cycle to rtPS-s-dead queue.

e. nrtPS queue: is used for data of nrtPS connections and comes in the fifth level of priority.

f. Under-test queue: holds data of connections that are accepted by BS and monitored for Test-Period. This queue holds data for all types of connections and sorts them according to their priorities, e.g. UGS, ertPS, rtPS and nrtPS. It comes in the sixth level of priority.

g. New-connections queue: holds bandwidth requirements of waiting connections that cannot be admitted by BS. This queue contains two elements for each connection; one element for bandwidth requirement and another for frame size required to satisfy delay requirement of the connection. Data of connections in this queue are sorted in ascending order according to the required frame size. This queue has seventh level of priority.

h. BE queue: holds data of BE connections and comes in the last level of priority.

In addition to these queues, ONU stores information about BS; total data rates of all UGS connections, total of minimum data rates of all ertPS connections (ertPS-min), and total of mean data rates of all rtPS connections (rtPS-mean). This information is updated when a new connection is finally admitted by the BS and when one of the running connections completes service.

When ONU requests bandwidth from subOLT, it sends a report message with ten fields; one report message can carry up to thirteen fields. The report message shown in Figure 3.5, indicates that only one set of queues is reported. Fields f4 and f7-f10 are self-explanatory. The other fields are explained as follows:

- f1: The essential bandwidth. It is equal to the sum of UGS queue size , ertPS-min, and rtPS-mean.

- f2: The difference between the size of the ertPS queue and ertPS-min.

- f3: The difference between the size of the rtPS-s-dead queue and rtPS-mean.
- f5, f6 : The expected rates for the ertPS and rtPS queues; here the ONU does not request bandwidth for existing data of ertPS and rtPS only, but also requests additional bandwidth for predicted upcoming data between sending the report message and receiving the grant message. message.

The subOLT grants bandwidth to the ONU; the ONU divides this bandwidth among PQs by the scheduler.

To predict the incoming traffic of a service type, ONU first calculates the interval T_{prd} during which the predicted traffic arrives. This interval is the time between sending report message and the starting time of ONU's slot in the next cycle. This interval has been calculated in [42] as:

$$T_{prd} = t_{start} + T_S - t_{rep} \tag{3.12}$$

Where t_{start} is the start time of ONU's transmission, t_{rep} is the time when last ONU's report message is sent, and T_S is the slot duration of ONU. The expected traffic R_s (in packets) of rtPS or ertPS service types is:

$$R_s = T_{prd} \times \lambda_{s\_avg} \tag{3.13}$$

Where λ_{s_avg} is the average arrival rate of the service type and it is calculated in each cycle as:

$$\lambda_{s\_avg} = (1 - \delta)\lambda_{s\_avg} + \delta \frac{N_q}{T_{cycle}} \tag{3.14}$$

Where N_q is the current queue size of the service type, T_{cycle} is the cycle time of EPON, and δ is a real number $(0 \leq \delta \leq 1)$.

3.4.3 Bandwidth Allocation at subOLT (subOLTBA)

First the subOLT sets its cycle time as:

$$T_{s\_cycle} = \eta * \min(F_l) \ \ \forall (BSs\ served\ by\ subOLT) \tag{3.15}$$

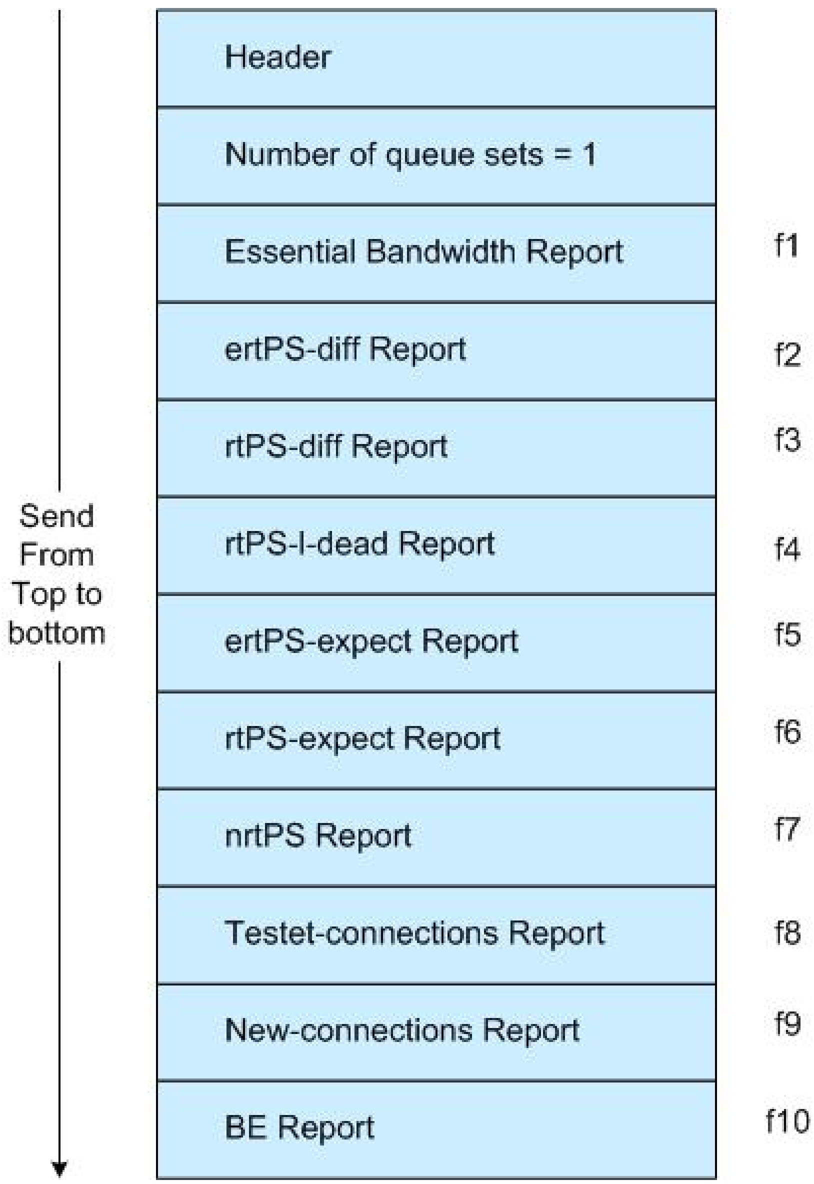


Figure 3.5: Report message of ONU.

The cycle time of the subOLT (T_{s_cycle}) is related to the minimum frame size of all BSs where η is a constant dependant on the ratio between the data rate of the BS and that of the fiber connection of the subOLT.

The subOLT allocates bandwidth among ONUs based on total data rate ($C_{s\_OLT\_total}$) that it assigned by OLT. The subOLT allocates Bandwidth as follows:

a) First the subOLT assigns the fundamental part of bandwidth B_{min} for each ONU, where

$$B_{min} = B_{UGS} + B_{ertPS}^{min} + B_{rtPS}^{sdl}. \tag{3.16}$$

where B_{UGS} , B_{ertPS}^{min} , and B_{rtPS}^{sdl} and are the bandwidth requested for UGS, ertPS-min, and rtPS-s-dead queues, respectively. SubOLT stores these quantities for each ONU and updates them when a report message of the ONU comes with new values. The total of B_{min} over all ONUs is the reserved part of the subOLT's bandwidth.

b) Then, the subOLT tries to satisfy the bandwidth requests for the rest of the queues as follows:

   i. Calculate the remainder capacity after the bandwidth assigned in previous step as

$$C_{rem} = C_{s\_OLT\_total} - \sum_{\forall ONU} B_{min} \tag{3.17}$$

   To satisfy the remainder requirements of ertPS, each ONU i is granted $B_{i,ertPS}^{rem}$ depending on its remainder of ertPS request $C_{i,ertPS}^{rem}$ and C_{rem} hence,

$$B_{i,ertPS}^{rem} = min(C_{i,ertPS}^{rem}, \frac{C_{i,ertPS}^{rem} \times C_{rem}}{\sum_k C_{k,ertPS}^{rem}}). \tag{3.18}$$

   ii. Step (i) will repeat, in sequence, for the rtPS, predicted ertPS, predicted rtPS, nrtPS, under-test, new-connections, and BE requests.

c) After assigning all requests of all queues, if $C_{rem} > 0$, C_{rem} is divided among ONUs according to the weight of the total requests of the ONU,i.e. $\frac{C_i^{req}}{\sum_k C_k^{req}}$, where C_i^{req} is the total requested bandwidth of ONU i.

d) Each ONU is granted bandwidth B_{ONU}^{total} that is the sum of all components granted in the previous steps.

e) If new connection requests can be satisfied based on bandwidth of subOLT, $C_{s\_OLT\_total}$, these connections requests are allocated to its ONU and connections are set under-test. Any connection that can be accepted is removed from the queue. If it requires frame size that cannot be satisfied by current cycle time, the cycle time is changed according to new frame size. Conversely, any connection that cannot be admitted based on $C_{s\_OLT\_total}$, will be forward to OLT.

3.4.4 Bandwidth Allocation at OLT (OLTBA)

Bandwidth allocation among subOLTs at the last stage of the network, i.e. OLT, is almost identical to subOLT's bandwidth allocation, where subOLTs play the roles of ONUs and the subOLT's action is carried out by the OLT. Also OLT keeps the reserved bandwidth for each subOLT and the sum of all theses bandwidths is the reserved part of OLT's bandwidth. However, there are three dissimilarities:

a) The maximum limit of the cycle time is set to the minimum cycle time of all subOLTs.

b) OLT data rate is constant and does not change from cycle to cycle.

c) Any new connection that cannot be accepted based on the bandwidth of OLT will be rejected.

3.5 Hybrid Scheduler

Similar to the bandwidth allocation, the scheduler is multi-level in OOW network. Here we discuss BS, ONU, and subOLT schedulers. Though similar to that of subOLT, the scheduler at the OLT is not discussed, as we focus on the architecture performance. OLT scheduler affects the down stream performance in the architecture.

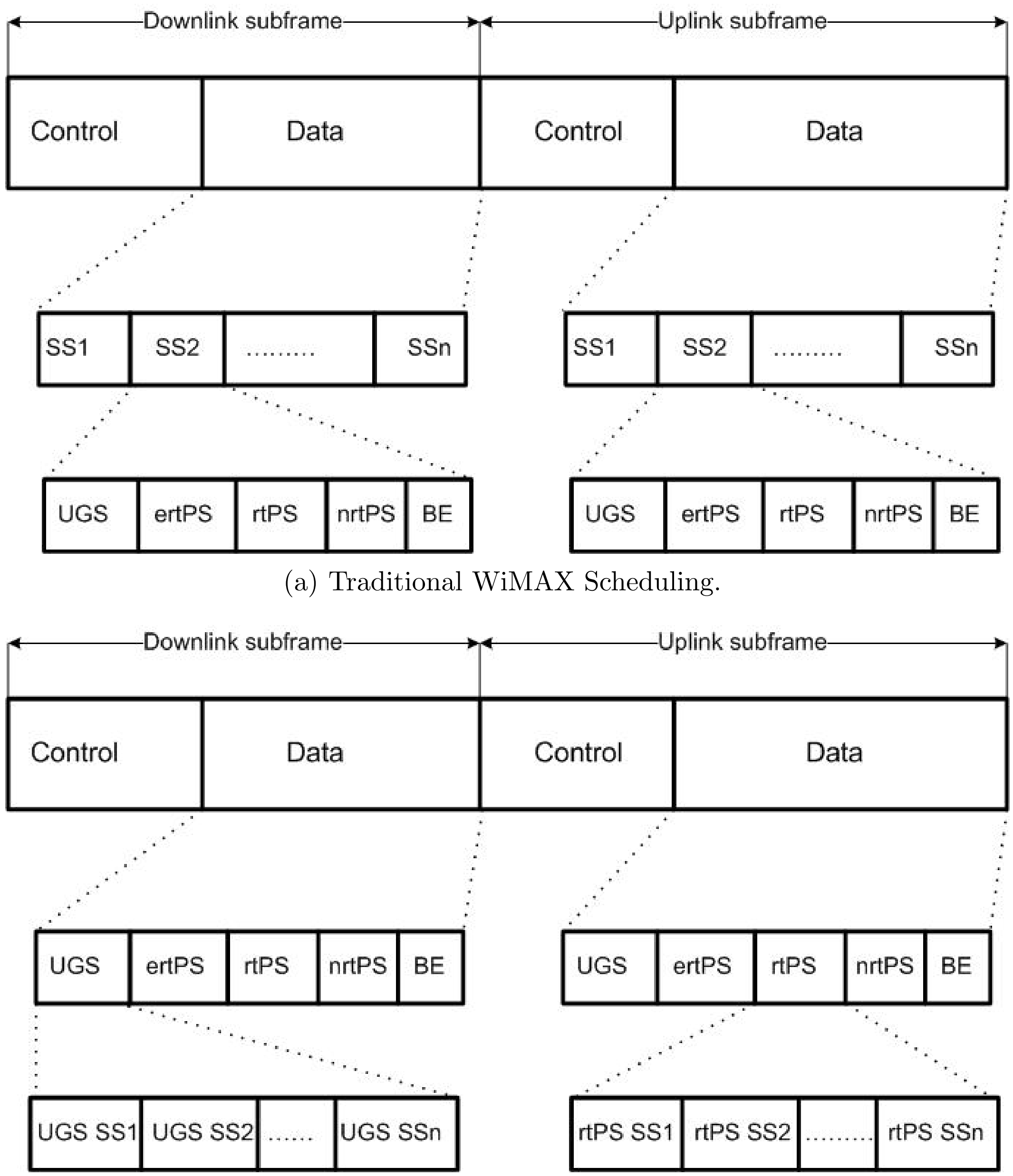
3.5.1 BS Scheduler

According to WiMAX standard, Time Division Duplex (TDD) frame is divided into downlink sub-frame and uplink sub-frame; each sub-frame has a control part and a data part. The proposed scheduler is service-type based; it differs from traditional WiMAX's scheduler which is station-based schedule. In traditional WiMAX networks, the scheduler manages connections traffic as stated in the literature [13], [16] and [17], by scheduling all possible packets of all connections of first SS in the time slot assigned to this SS. Then the scheduler moves to the next SS until it schedules all traffics or reaches the end of available bandwidth. In our proposed protocol, the scheduler transmits highest priority type's packets from all SSs first. Then it moves to the next level until it schedules all traffics or reach the end of available bandwidth.

In the traditional WiMAX, data part in any sub-frame has slot for each SS to transmit its data packets. Unlike traditional WiMAX scheduler, the proposed BS scheduler divides data portions of downlink and uplink sub-frames into five sub-data frames, one for each service type: UGS, ertPS, rtPS, nrtPS, and BE. Each sub-data frame has a slot for each SS. Frame structure in the proposed BS scheduler compared with frame structure in the traditional WiMAX is shown in Figure 3.6. Only an overall pictorial view of data scheduling is shown in Figure 3.6. There are many details about gaps between downlink and uplink and between data from different SSs. These details are explained in WiMAX standard [44].

3.5.2 ONU and subOLT Scheduler

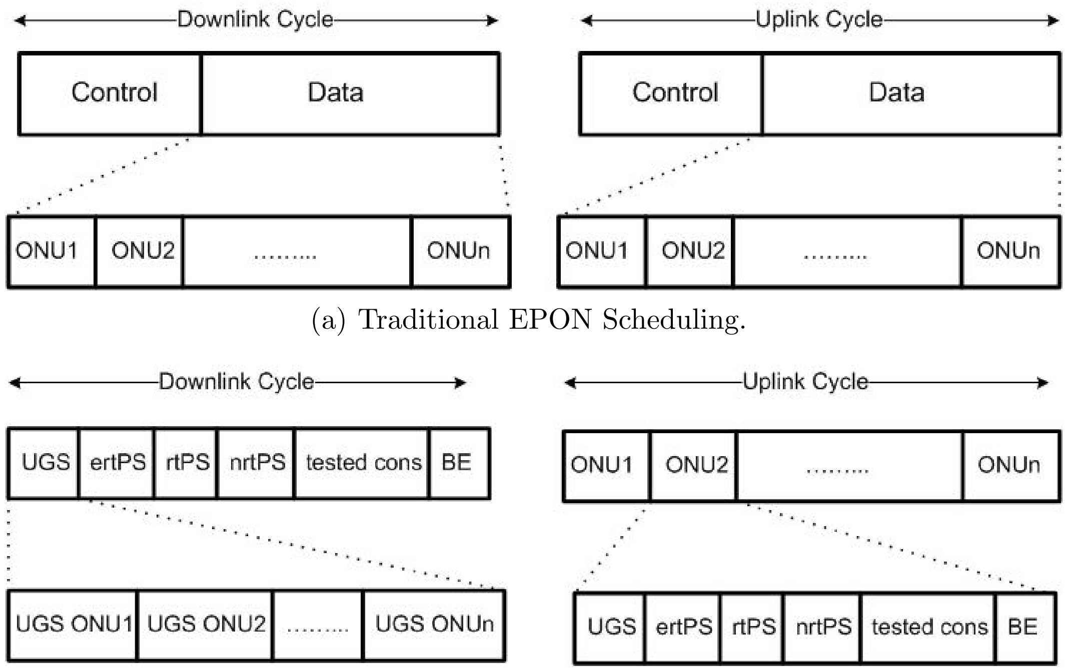
ONU and subOLT perform scheduling in the same cycle, so we discuss ONU and subOLT schedulers together. The subOLT sends data to all ONUs in the downlink cycle and ONUs send their data to the subOLT in the uplink cycle. According to the EPON standard, the subOLT should assign every ONU a time slot in the uplink and the downlink cycles. However, in the proposed scheduler, the subOLT assigns every ONU a time slot in the uplink cycle and up to six time slots in the downlink cycle. Every ONU is responsible for scheduling its data in its own time slot in the uplink cycle, while the subOLT is responsible for scheduling all ONU's data in the



(a) Traditional WiMAX Scheduling.

(b) Proposed WiMAX scheduling.

Figure 3.6: Scheduling in WiMAX.



(a) Traditional EPON Scheduling.

(b) Proposed EPON scheduling.

Figure 3.7: Scheduling in EPON.

downlink cycle. In the traditional EPON network, according to the EPON standard, both the ONU and OLT do not classify packets based on the services types mentioned here. Therefore, they schedule packets according their arrival time in both the uplink and downlink cycles. In the proposed scheduler, the ONU schedules packets from its queues in this order: UGS, ertPS, rtPS, nrtPs, connection under test, BE. When a subOLT schedules data packets in the downlink cycle, it first transmits UGS packets to all ONUs, then it transmits ertPS traffic. It continues to do so until it reaches the end of sub-cycle or no more data packets are left in queue. The cycle structure in the first segment of the EPON part of OOW architecture compared with the corresponding one in traditional EPON network is shown in Figure 3.7. Again, only data scheduling is shown in the figure, with no details about gaps.

3.6 Performance Analysis of Proposed Solution

To simulate the proposed OOW architecture and MAC protocol, we use NS-2 simulation software [45] and our developed WiMAX module for NS-2 (Appendix A.2) which is based on WiMAX module for NS-2 developed by *The National Institute of Standards and Technology* [46]. We also developed an EPON module for NS-2. The network was simulated similar to that in Figure 3.1. It consists of an OLT and 6 subOLTs, where each subOLT services 6 ONU/BS. The subOLTs are located 20 km away from the OLT and connected to the OLT through 10 Gb/s fiber optic cable. ONUs are located 20 km away from the subOLTs and also connected to them through 10 Gb/s fiber optic cable. Each ONU is attached to a WiMAX BS. In this network, each BS serves 4 SSs which are located 2.5 km away from the BS. Each SS has 7 UGS, 8 ertPS, 7 rtPS, 9 nrtPS, and 5 BE connections.

In the simulation WiMAX PHY is OFDM-TDMA and we use packets with a fixed size of 320 bytes. For UGS traffic we use Constant Bit Rate (CBR) traffic with data rate 25 packet/s. The QoS parameter settings of ertPS, rtPs, nrtPS, and BE connections are listed in Table 3.1.

Table 3.1: QoS Parameter Settings for the EPON-WIMAX Simulation

	ertPS	**rtPS**	**nrtPS**	**BE**
Offered rate (Mbps)	1.4	2.3	1.5	2.3
Max sustained rate (Mbps)	1.0	1.0	1.0	1.0
Min reserved rate (Mbps)	0.5	0.5	0.5	N/A
Max latency (ms)	5	5	N/A	N/A

At the beginning of the simulation, the frame duration of the WiMAX and the cycle time of EPON are set to 5ms and 20ms, respectively. In the OOW system, the ratio between the frame duration and the cycle length is maintained if the frame duration is changed to meet the delay requirement.

The NS-2 built-in exponential traffic model with parameters in Table 3.1 is applied to simulate the traffic flow offered to all connections, except for UGS ones, which are simulated as CBR models. The run time for each simulation experiment is 25 seconds, and each experiment runs 10 times. Thus, the results are observed as the average outcome of these runs.

In this work we measure the performance of the system based on error-free channel condition in WiMAX. The effect of channel condition on system performance can be considered in future work.

Our objective is to evaluate the performance of the proposed OOW setup and compare it with non-integrated EPON-WiMAX network. We call this EPON-WiMAX network EPMAX. In EPMAX there is no integration between EPON and WiMAX meaning EPON serves traffics from WiMAX as well as data from a user connected to EPON. In EPMAX, connection is admitted only by WiMAX BS; it is dependent on its current data rate and the frame size cannot be changed to meet delay requirements of connection. The scheduler in EPMAX is station-based in both EPON and WiMAX. Lastly, in EPMAX, bandwidth allocation for EPON and WiMAX are disjoint.

Average rtPS traffic throughput and system throughput are shown in Figure 3.8. It shows that the rtPS' throughput in OOW outperforms that in EPMAX by 30% to 44%, and that the average throughput of rtPS in OOW is constant whereas the average throughput of rtPS in EPMAX decreases slightly as the number of connections per SS increases. Moreover, Figure 3.8 shows that the whole system throughput in OOW is generally greater than that in EPMAX (47% to 69% higher). Furthermore, the system throughput in EPMAX decreases slightly as the number of connections per SS increase. Meanwhile, the system throughput in OOW increases as the number of connections per SS increase. This shows better OOW bandwidth utilization.

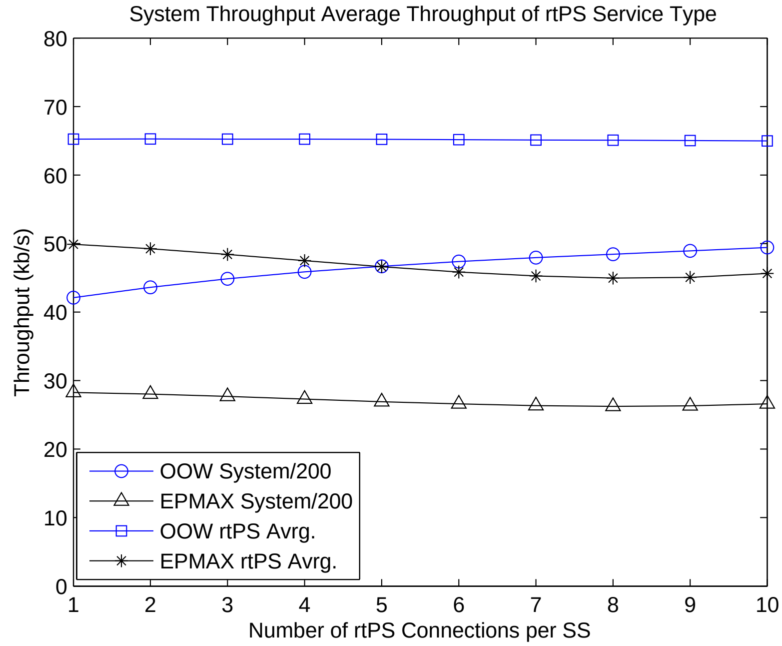


Figure 3.8: Average Throughput of rtPS service type & System Throughput

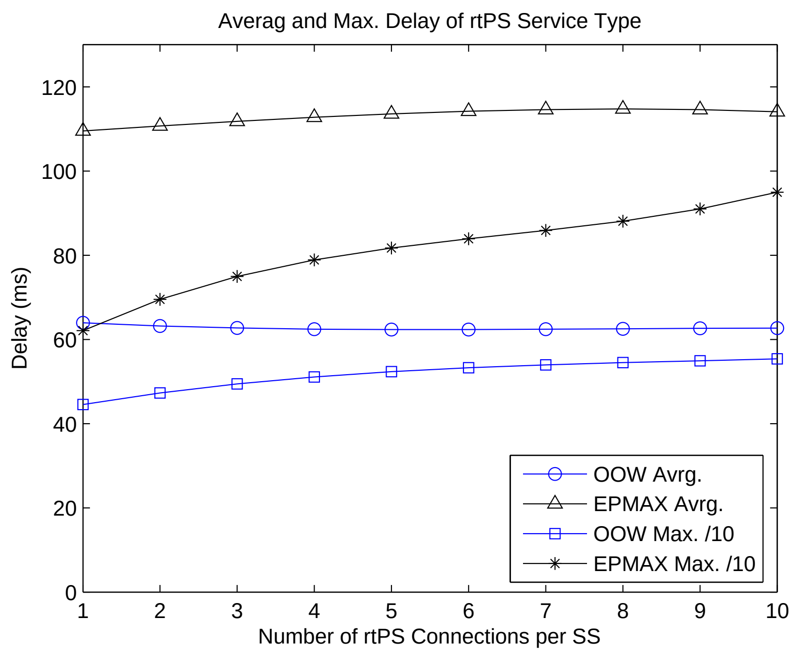


Figure 3.9: Average and Max. Delay of rtPS type

Average and max delays of rtPS traffic are shown in Figure 3.9. Delay distribution of some randomly selected connections is measured when each SS has 4 and 8 rtPS connections. Delay distribution of connection 4 in SS10 is presented in Figure 3.10 and delay distribution of connection 4 in SS17 is shown in Figure 3.11. From Figure 3.9 both the average and the maximum delays of rtPS in OOW are less than the average and the maximum delays of rtPS in EPMAX, respectively. Figure 3.9 shows that the average delay in EPMAX is almost twice the average delay in OOW. The average delay in OOW decreases slightly as the number of connections per SS increase; then it settles down when 4 connections run per SS; whereas in EPMAX, average delay increases as the number of connections increase. But at 7 connections per SS delay starts to decrease. The decrease in the average delay is due to the fact that as the number of connections increase, more packets are queued for each service type. This makes many packets transmit together in the same frame and minimizes delay of these packets. But the number of packets from the same service type's queue that can be transmitted in the same frame is dependent on both the frame size and the service type's traffic rate. Hence, the average delay in OOW first decreases as the number of connections increase. When the system reaches the limit of packets that can be transmitted from the same queue in one frame, the delay settles down.

The delay behavior can be seen clearly from the delay distribution in Figures 3.10 and 3.11. In Figure 3.10, the OOW delay is distributed over the same range; either 4 or 8 connections run per SS. In Figure 3.11, for OOW with 4 connections per SS, delay is distributed up to 250 ms and with 8 connections per SS, delay is distributed only up to 120 ms. Hence delay is decreasing or at least has the same value. In EPMAX, the delay is affected by the decreasing factor as in OOW. But unlike what happens in OOW, the delay in EPMAX is subject to the increasing factor. The delay increase is due to the fact that with more connections many packets need to be transmitted from each SS with more connections.

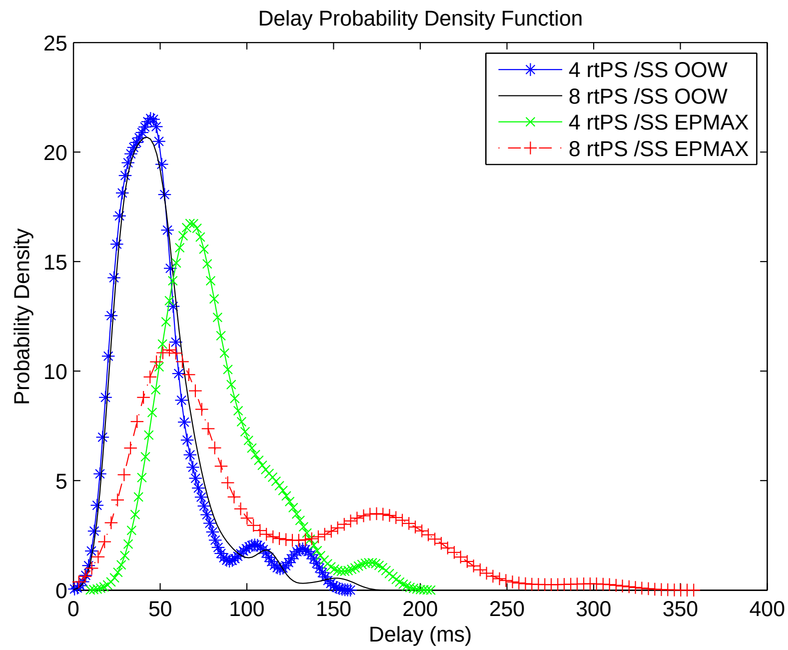


Figure 3.10: pdf of Delay of con. 4 in SS10

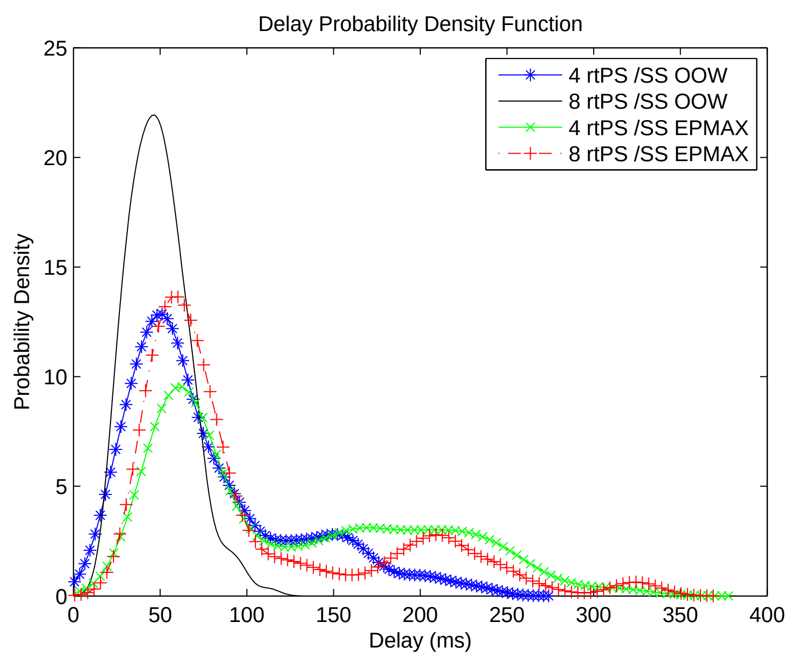


Figure 3.11: pdf of Delay of con. 4 in SS17

The scheduler in EPMAX transmits all packets from one SS and then moves to the next SS. This means that the packets of all SSs except the first one will wait for a long time. But after a certain network load, the decreasing factor can balance or even exceed the increasing factor. Firstly increasing factor has the dominant effect so delay is increasing. When the decreasing factor becomes equal or greater than the increasing factor, i.e. when 7 connections run per SS, delay starts decreasing. From delay distribution Figure 3.10 and 3.11, we notice that for EPMAX, delay distribution shows increases in the delay in Figure 3.10 and decreases in the delay in Figure 3.11. Hence delay can increase or can decrease depending on how many connections have increasing or decreasing trends.

UGS connections are granted fixed bandwidth amounts in both EPMAX and our proposed OOW. Thus, UGS connections should not suffer from delay; it was still measured for this type of connections in order to find the queuing delay. As network congestion affects the number of UGS connections that are admitted in the network, it is reasonable to compare the number of rejections in UGS and all connections in OOW to that in EPMAX. The number of rejections is measured as the number of UGS connection per SS varies from 1 to 12. Rejected UGS and all type of connections are shown in Figure 3.12. Figure 3.12 shows that OOW admits more UGS connections than EPMAX does. It is normally that number of rejected connections increase as number of connections per SS increase as the bandwidth of the system can accommodate a limited number of connections. But the number of UGS rejected connections in EPMAX increases rapidly over the OOW case. OOW does not reject connections of other types in order to accept UGS connections. Figure 3.12 shows that rejected connections of all services types in EPMAX is more than rejected connection in OOW.

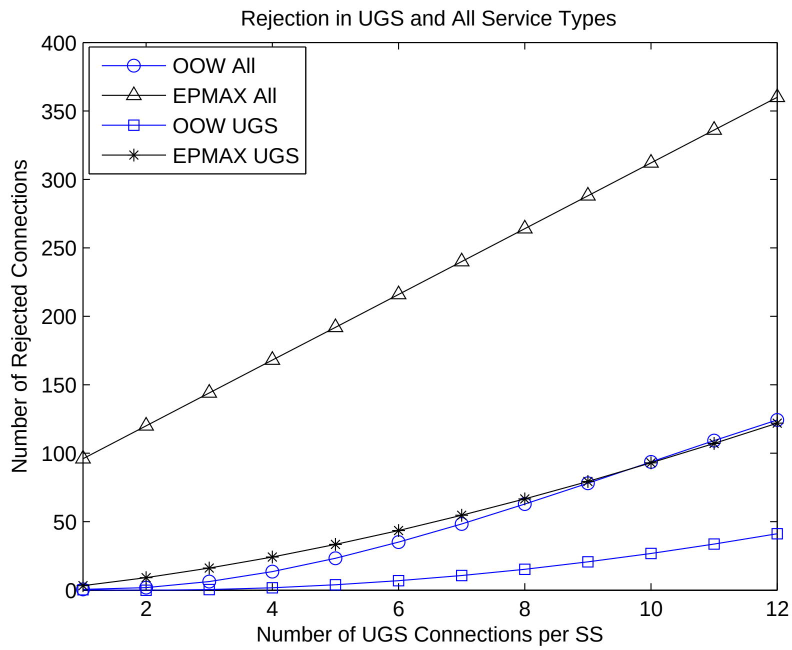


Figure 3.12: Rejection in UGS and all service types

Also we can measure delay jitter and average throughput of UGS connections. Jitter distribution of randomly selected connection is massacred. Jitter distributed of connection 3 in SS1 in OOW system is shown in Figure 3.13 which shows that the jitter is 40 ms when 3, 6, and 9 UGS connections runs on each SS. When 12 UGS connections run on each SS the jitter distribution extends over the range from 37 to 43 ms.

Jitter distributed from connection 3 in the SS1 in EPMAX system is shown in Figure 3.14. These distributions are taken when each SS has 3, 6, 9, and 12 UGS connections. From this figure we see that jitter is distributed from a few milliseconds up to 300 ms and it changes as the number of UGS connections per SS increases.

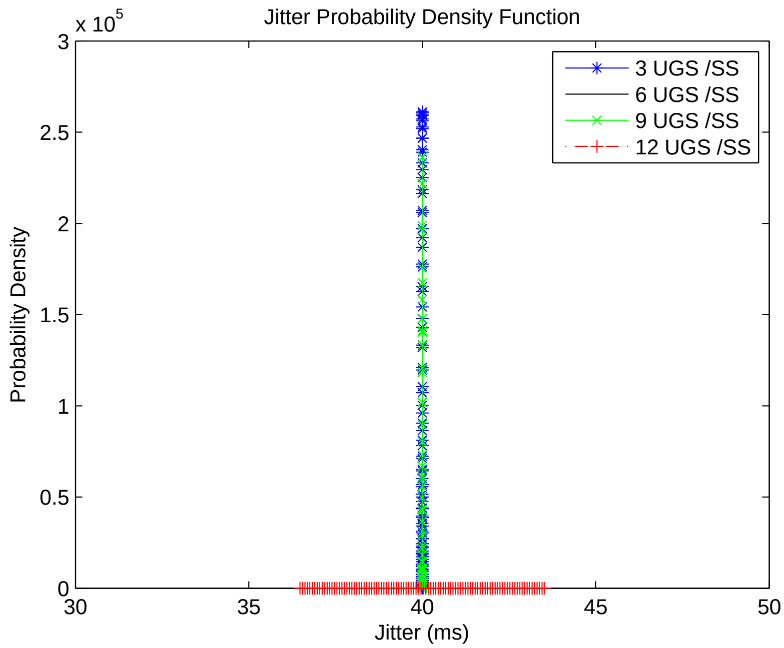


Figure 3.13: Jitter pdf of con 3 SS1 in OOW

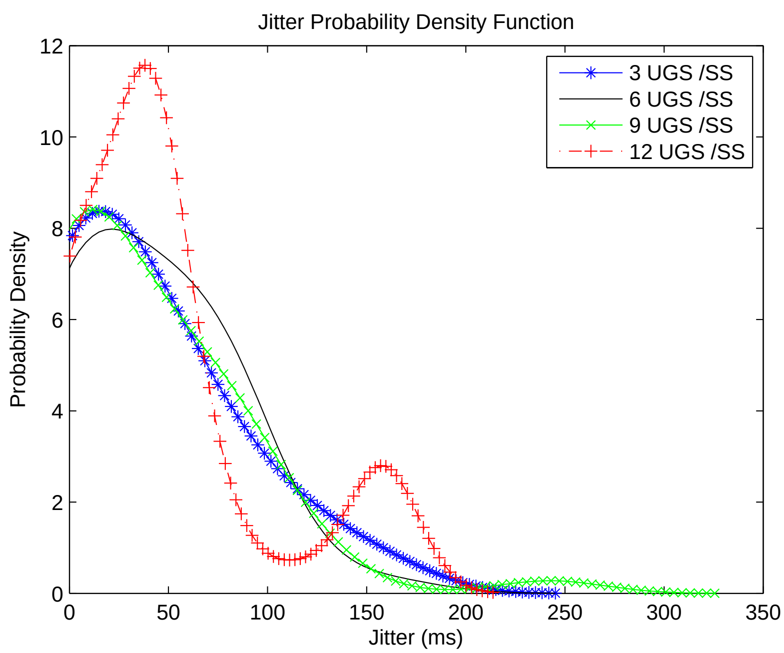


Figure 3.14: Jitter pdf of con 3 SS1 in EPMAX

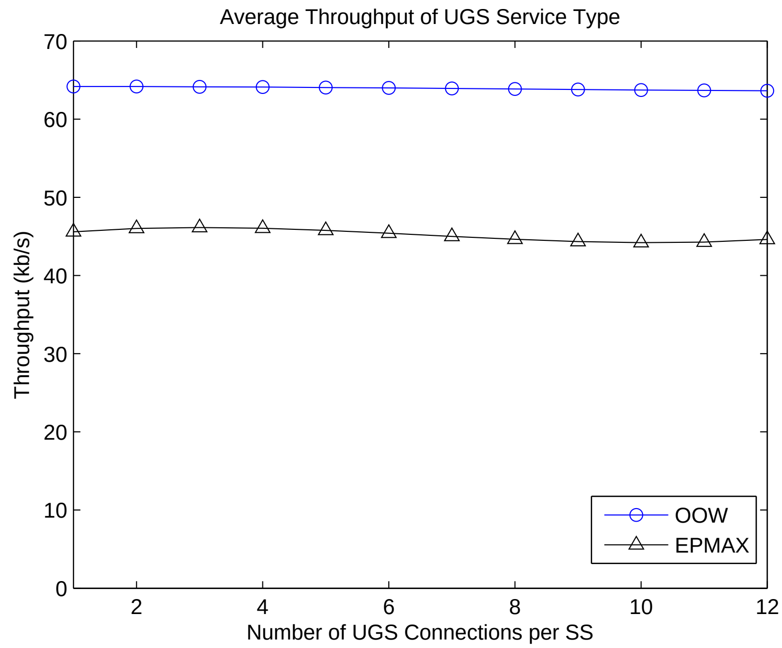


Figure 3.15: Average Throughput of UGS Service Type

Average throughput of UGS connections is shown in Figure 3.15. As it is expected, throughput in both OOW and EPMAX almost do not change with the number of connections, but OOW has a higher throughput than EPMAX. The delay of UGS connections is shown in Figure 3.16 and it ensures that the UGS has almost a fixed delay in both OOW and EPMAX but delay in OOW is about one third of delay in EPMAX. This shows the effectiveness of the proposed scheduler.

Furthermore, it is a good measure to compute the number of connection rejections as a function of the delay requirement for connections. A number of connections of all types will be kept fixed and their data rates will be guaranteed to be satisfied by bandwidth of the network. Minimum delay requirements of connections will vary and the number of connection rejections is measured with each value of minimum delay. The delay requirement of each connection is generated by a uniform random variable between the Min-Delay and 10 ms. To measure rejection due to the delay requirement, we set UGS, ertPS, and BE connections as 3, 5, and 4 respectively. The rtPS and nrtPS connections are set in ranges 2-11 and 3-12 respectively. For each

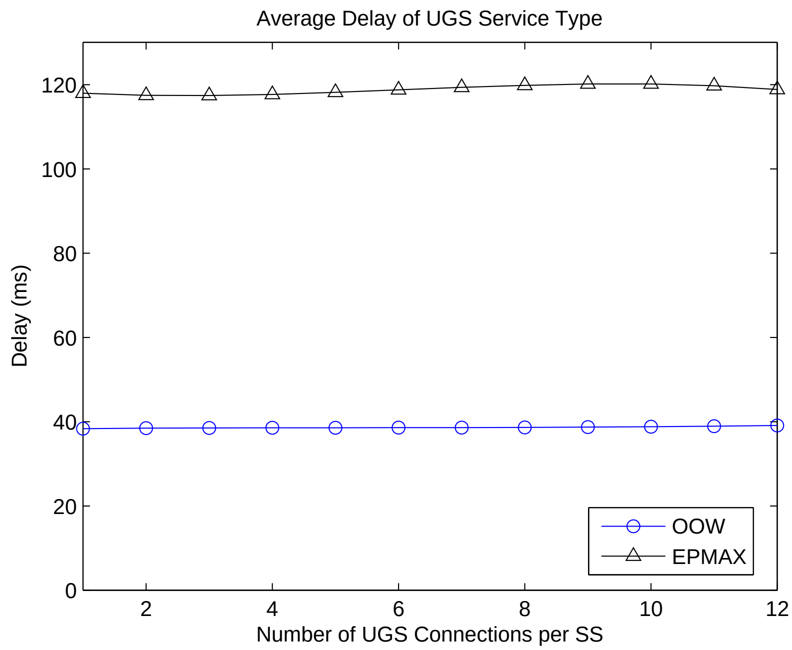


Figure 3.16: Average Delay of UGS Service Type

value, Min-Delay is changed from 0.9 to 1.8 ms and the number of rejected connections is measured. Finally, we find the average number of rejected connections for each value of Min-Delay over all runs shown in Figure 3.17. The Number of rejected connections in EPMAX is higher than the number of rejected connections in OOW. This is because OOW can change the frame size to meet the delay requirements of a connection, but EPMAX does not. Furthermore, the figure shows that when the delay requirement is 1.5 ms or more, the OOW system chooses a frame duration that satisfies both the bandwidth and delay requirements for all connections. Due to this action, OOW admits all requests while EPMAX still rejects connections.

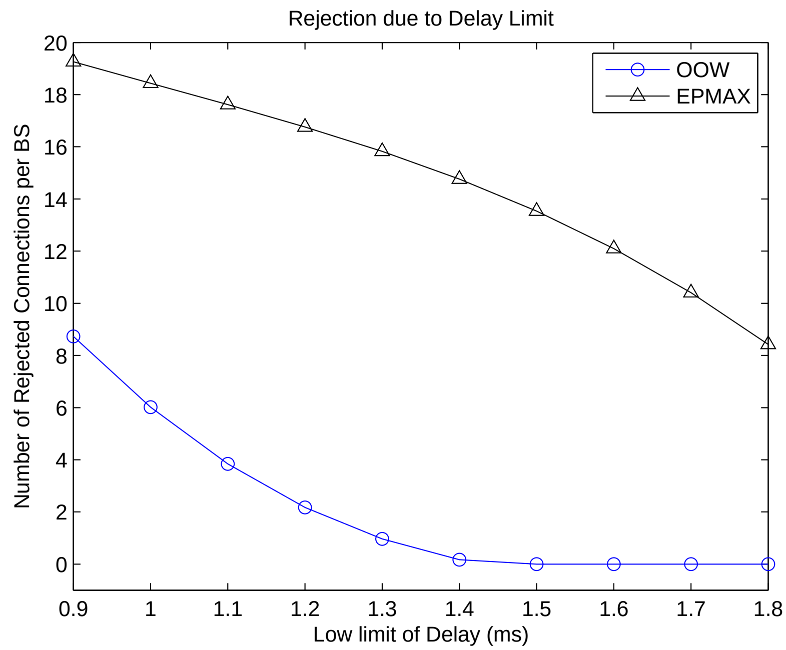


Figure 3.17: Rejection due to Delay Limit

Figures 3.18 and 3.19 show that in our system, queuing delay for low priority traffic classes does not increases when the network load is very light. In other words, our system does not suffer a light-load penalty phenomenon that was discovered and discussed in [42]. The figures prove that average and maximum delays of both nrtPS and BE traffics increase as network load increases. Also figures show that delay of nrtPS connection is going higher than that of BE beyond a certain network load. This is due to the fact that the system reserves a small percentage of system bandwidth for BE traffic, meaning the delay of BE connection is not completely due to priority scheduling.

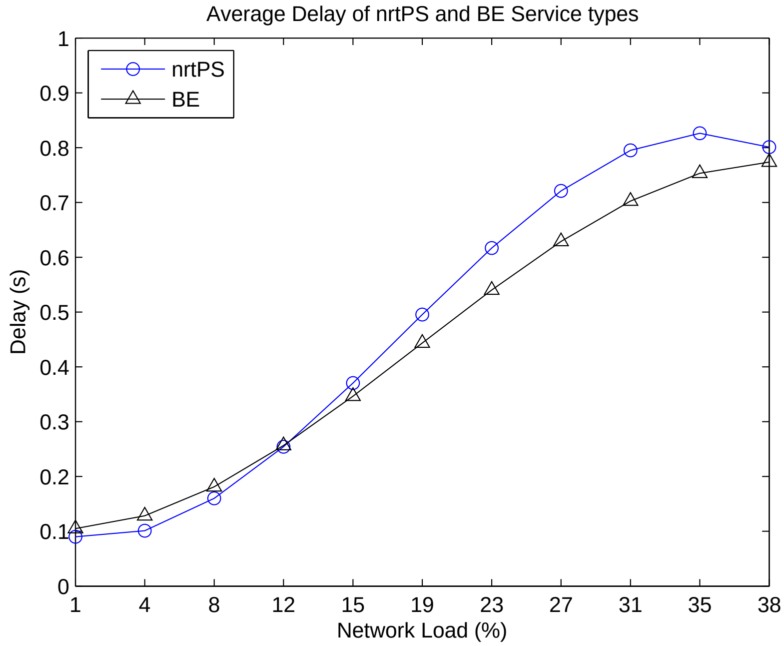


Figure 3.18: Average Delay of nrtPS and BE Service Types

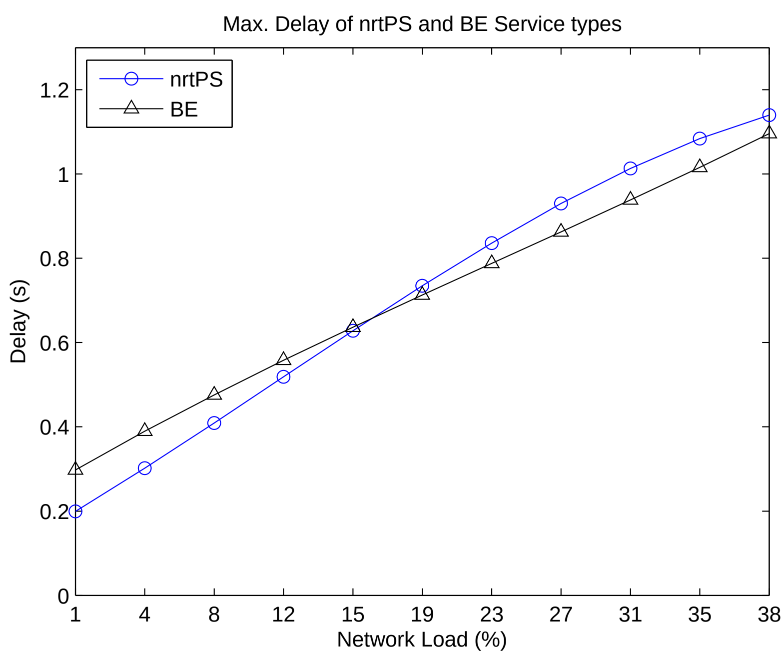


Figure 3.19: Max. Delay of nrtPS and BE Service Types

3.7 Summary

This chapter proposes a new architecture for EPON-WiMAX hybrid network that is suitable for both urban (OOW architecture) and rural (OWW architecture) regions. These architectures are more reliable and have a good fault tolerance against nodes and connection failure in EPON part. Also, this chapter proposes a MAC protocol including Admission Control, Scheduler, and Bandwidth Allocator for OOW architecture. The proposed architecture and MAC protocol are verified by simulating them in a NS-2 network simulator. The performance of the proposed solution is compared with another solution that does not implement the proposed enhancements. It was found that the proposed solution provides improvement over the other solution based on delay, throughput, and number of rejected connections. Also through the simulation, it was proved that the proposed solution does not suffer from the light-load penalty phenomenon.

Chapter 4
RPR-EPON-WiMAX Solution for Metro-Access Networks

The Resilient Packet Ring (RPR) standard aims at combining the advantages of the Ethernet and the synchronous optical network/synchronous digital hierarchy (SONET/SDH). Hence, RPR possesses statistical multiplexing gain, low equipment cost, and the simplicity features of Ethernet in addition to the SONET/SDH advantages of high availability and reliability. These features make RPR a promising candidate that builds high-performance metro edge and metro core ring networks interconnecting multiple access networks [5]. The integration between the Ethernet Passive Optical Network (EPON) and the Worldwide Interoperability for Microwave Access (WiMAX) networks is considered as a promising solution for the access network [10], [18]. Hence the combination of RPR with EPON and WiMAX can be a promising solution not only for access networks but also for connecting the access network to metro networks. In previous chapter, we considered the Optical-Wireless hybrid network as the integration between the EPON and WiMAX networks. Specifically, we proposed the architecture for the EPON-WiMAX hybrid network, which is reliable and immune to failures. Moreover, we proposed a MAC protocol for the proposed architecture.

In the previous chapter, we made the network architecture reliable in the optical part by duplicating the functionality of root nodes - Optical Line Terminal (OLT) of EPON. The leaf nodes in each segment of the architecture, the subOLT or the Optical Network Unit (ONU), are dually connected to root nodes, the OLT or the subOLT respectively. In this chapter, we attempt to make the optical part of the hybrid network reliable in different way. In particular, the integration between the two known standards, RPR and EPON, can provide the desired reliability for the optical part in the hybrid network. In this chapter, we consider the optical-wireless hybrid network that employed the integrated RPR-EPON as an optical backhaul network and WiMAX as a front end network. This configuration will form the RPR-EPON-WiMAX hybrid network. Accordingly, we propose both the architecture and the MAC Protocol for the RPR-EPON-WiMAX hybrid network. Specifically, this chapter presents the proposed architecture for the RPR-EPON-WiMAX network, a routing mechanism for the architecture and a scheduling scheme. However, the proposed MAC protocol for our suggested architecture will be discussed in the next chapter. Our proposed architecture for the RPR-EPON-WiMAX network attempts to combine the features of the three standards. In doing so, this architecture strives to improve the reliability of the network by providing dual-entry for each EPON segment on the ring network.

The rest of this chapter is organized in the following way: first, the new RPR-EPON-WiMAX hybrid network architecture is presented in Section 4.1. In Section 4.2, a routing mechanism for the new architecture is described. The scheduling technique for the proposed scheme is discussed in Section 4.3. Finally, Section 4.4 summarizes this chapter.

4.1 The Proposed Architecture

4.1.1 Motivation

To the best of our knowledge, the integration of RPR, EPON, and WiMAX has not yet been considered as a solution for the metro and access networks. However, the integration between RPR and EPON has been studied for core and edge metro networks. In [4], the authors proposed the combination of WDM EPON and RPR, which was supported with a single-hop star sub-network in architecture called STARGATE. In particular, they demonstrated that STARGATE provides transparent connections at the wavelength and sub-wavelength levels between ONUs residing in different WDM EPONs. Furthermore, as a solution for the access network, the EPON-WiMAX integration has been proposed in many works, such as [10]- [14], [18], and [47]. Nevertheless, the reliability of the EPON-WiMAX hybrid network is insufficient, especially for node and connection failure in the EPON part. Moreover, it may be desirable to extend the coverage area of the EPON-WiMAX hybrid network. Unlike our proposal in the previous chapter, the factors of reliability and extended coverage can be achieved by integrating EPON and RPR standards in the optical part of the hybrid network. In addition, the reliability of the EPON part of the network needs to be improved in order to attain the desirable reliability of the entire network. In fact, all of the desired features are achieved in the proposed architecture, which is explained in the following subsections.

4.1.2 Proposed Architecture

Our proposed architecture for the RPR-EPON-WiMAX hybrid network is shown in Figure 4.1. The front end of the architecture includes a group of WiMAX networks that are served by the backhaul Optical Network, and the optical part of the architecture consists of many EPON segments that are rooted at the RPR ring network. In fact, the optical part of our architecture is similar to the STARGATE network architecture proposed in [4]; however, our architecture does not include the Star Sub-network, as it aims to measure the performance of the network based on the RPR standard reliability. Moreover, the Star Sub-network in STARGATE aims to minimize the delay in the ring network, while in the proposed architecture, the delay results from the WiMAX part. Thus, network performance is not improved by decreasing the delay of the ring network.

4.1.3 Architecture Reliability

The proposed architecture is composed of RPR, EPON, and WiMAX parts. RPR is reliable against any one node or two connector failures. WiMAX has no channel disconnection, as its channel can experience service degradation for certain periods of time. Moreover, the node failure in WiMAX can be partially compensated by user mobility, especially when the BS fails. However, if a traditional EPON segment is used in the architecture, as shown in Figure 4.2, a large portion of the architecture

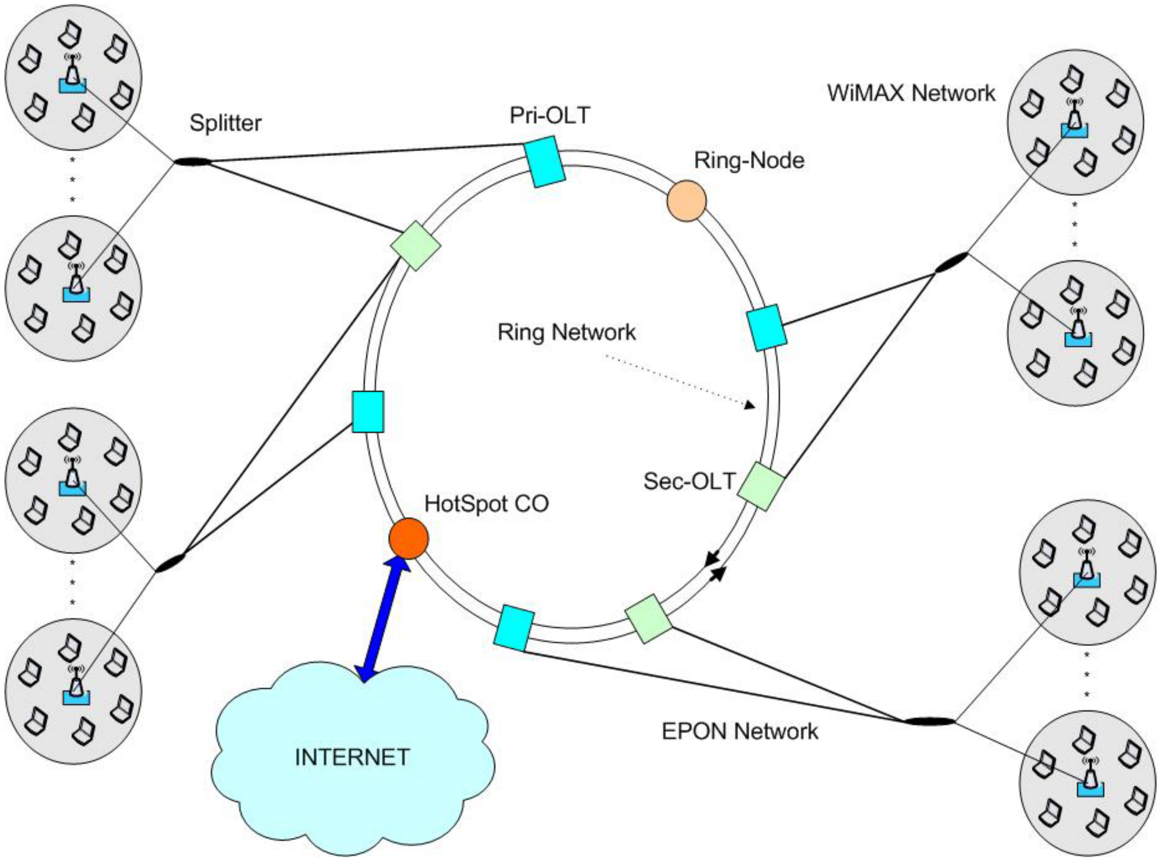


Figure 4.1: RPR-EPON-WiMAX Network Architecture.

will be disconnected in the case of OLT or feeder fiber failure, especially as the feeder fiber connects the OLT to the splitter. Due to presence of the EPON part, the entire architecture is not immune against one node or connection failure. Hence, we need to make the EPON part reliable against OLT or feeder fiber failure in order to improve the reliability of the architecture.

The reliability of the EPON part can be improved by connecting the splitter of each EPON segment to two OLT-nodes on the ring. This solution can be easily achieved by connecting the splitter of each EPON segment through a second feeder fiber to the OLT of one of the two adjacent segments, as shown in Figure 4.3. However, there are two possible drawbacks to this solution. Firstly, the process of installing fiber connections across EPON segments can be costly, as the distance between EPON segments is normally significant. Secondly, when users of two segments are served

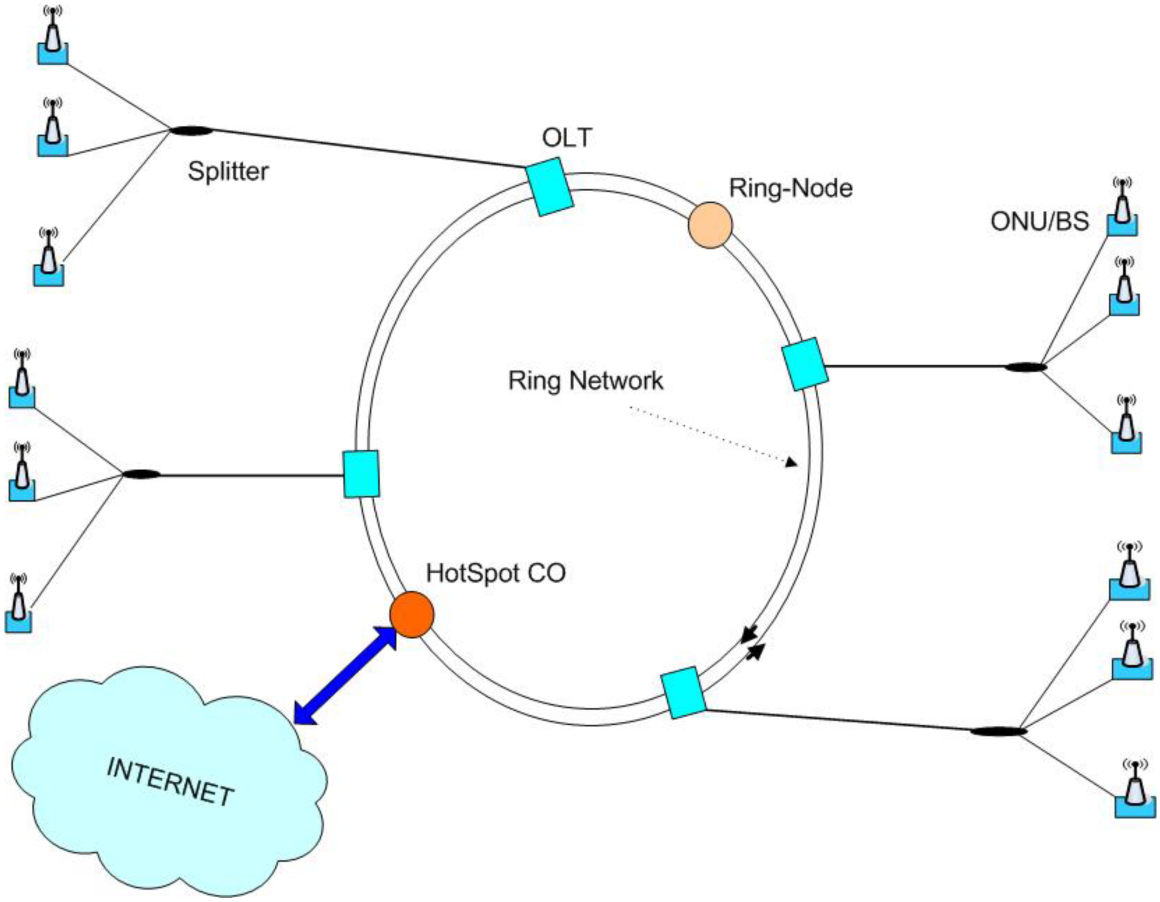


Figure 4.2: RPR-EPON-WiMAX Architecture with traditional EPON.

through one OLT in the case of failure, the QoS granted to theses users is adversely affected. Hence, we will have to accept QoS degradation in the case of failure or we should keep the segments lightly loaded during normal operation.

In order to reduce the cost of fiber installation and prevent QoS degradation, redundant OLT-nodes, known as Sec-OLTs, are employed on the ring, as demonstrated in Figure 4.1. One Sec-OLT can be employed for each EPON segment, or, if the distance is reasonable, a single sec-OLT can serve two segments. As discussed in subsequent sections, redundant nodes can be used for large distances between OLTs on the ring; Sec-OLTs can replace these nodes while also performing their original job.

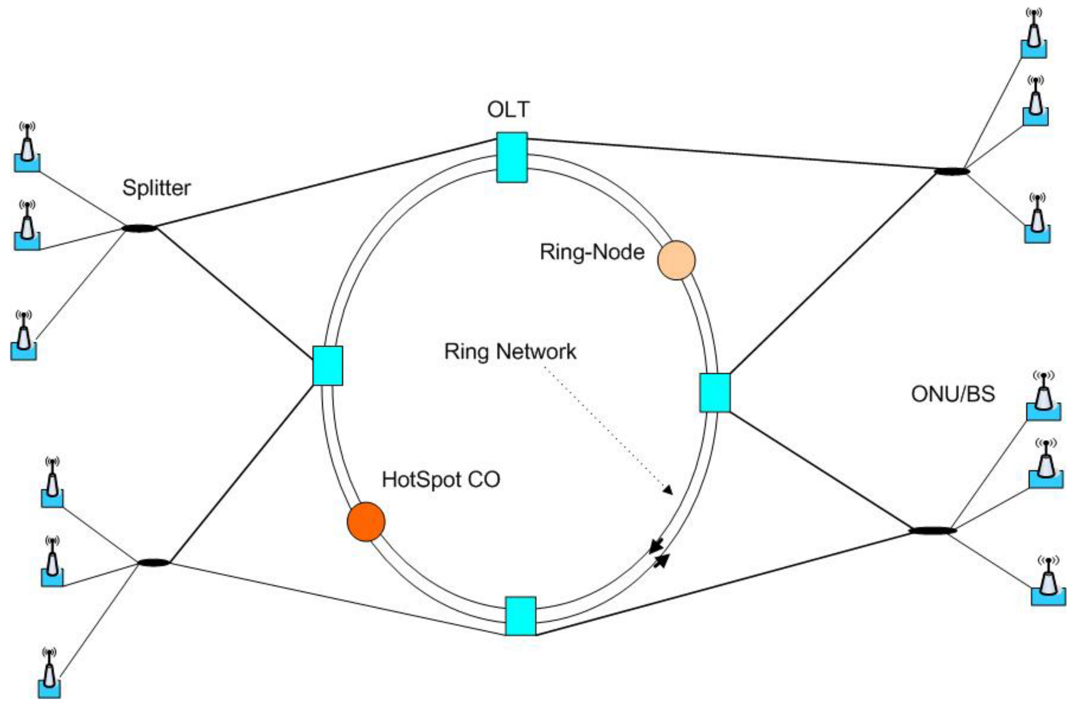


Figure 4.3: RPR-EPON-WiMAX Architecture with dual feeder fiber in EPON.

4.1.4 Architecture Elements structure in RPR-EPON-WiMAX

In the proposed architecture, the structures of the BS, SS, ONU and splitter correspond to those in the EPON-WiMAX network of Chapter 3, as explained in Section 3.1.3. Hence, the SS in this proposed architecture is a standard WiMAX SS. The structure of both the WiMAX BS and the EPON ONU differ according to the integration method between WiMAX and EPON, as explained in Section 3.1.3. In the proposed architecture, all splitters are 2Xn, where n is number of ONU/BS nodes in the EPON segment. However, the OLT structure in the EPON network is different from that in the WiMAX network, as will be explained later.

The RPR-ring network in the architecture has three types of nodes: the ring-node, the Hotspot Central Office (HCO) node, and the OLT-node; the structures of these nodes are discussed in the following section.

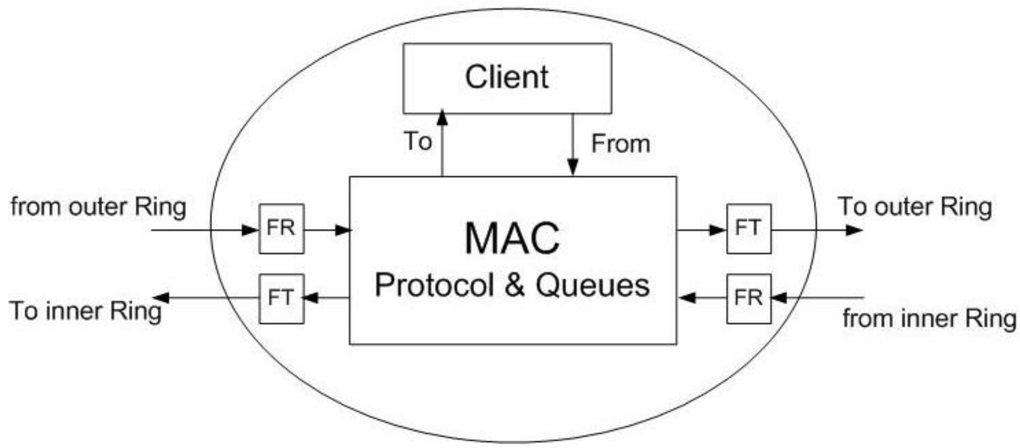
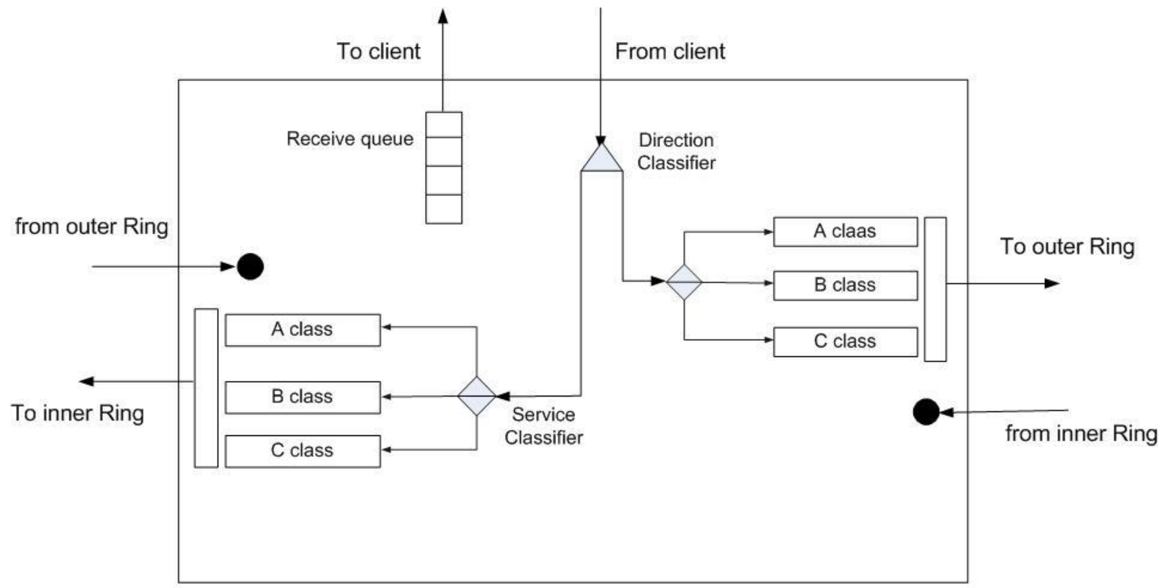


Figure 4.4: Ring-node structure.

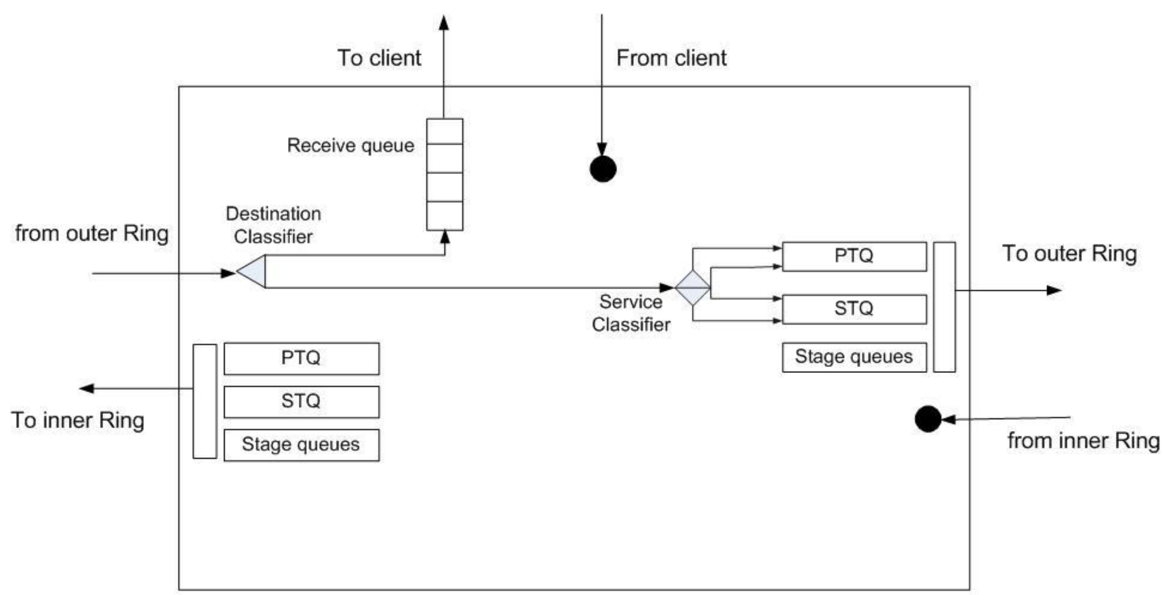
Ring-Node Structure

The ring-node is the standard RPR node. Every ring-node is equipped with two Fixed-tuned Transmitters (FTs) and two Fixed-tuned Receivers (FRs), one for each ring, as shown in Figure 4.4. Both FT and FR operate at the single wavelength channel of the corresponding ring. Each ring-node has separate transit and station queues for either ring. For each direction, a ring-node has four types of queues [5]; first, there is one or two transit queues for storing data packets received from other nodes before they are injected into the ring. Secondly, one set of transmit queues hold data packets from the node itself until it has the opportunity to transmit these packets over the ring. Specifically, this set of queues includes a stage queue and three class queues, one of which is for each service class defined in the RPR standard: A, B, and C. Furthermore, a receive queue holds received data packets for the node before sending them to the client. Lastly, there is one queue for the MAC control packets from the node itself as well as from other nodes.

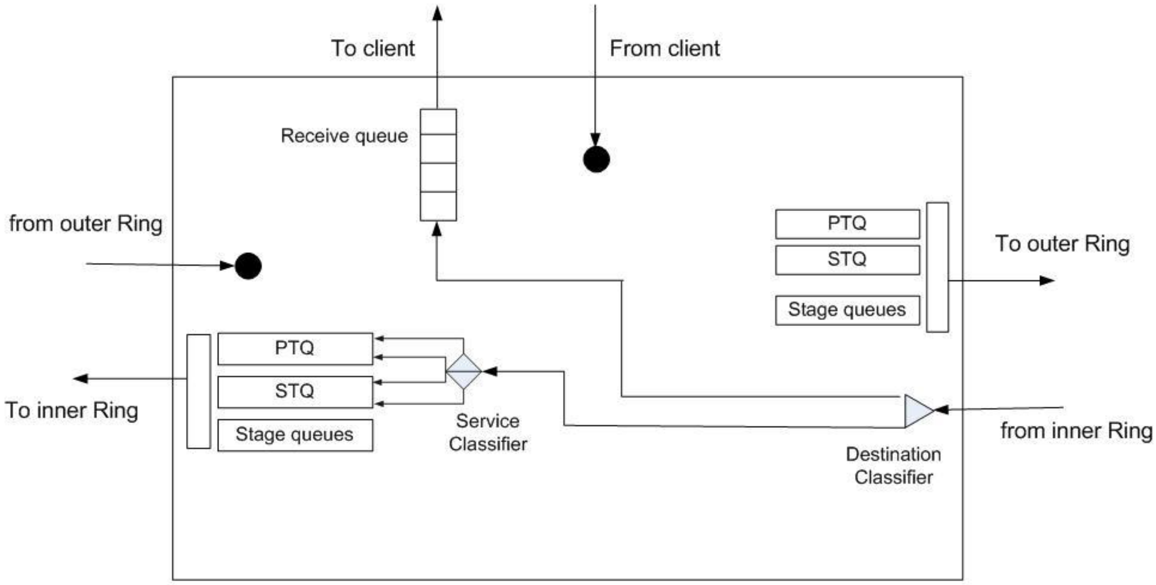
Figure 4.5 depicts the path and queue selection of ring-node data queues where the node has two transit queues: the Primary Transit Queue (PTQ) and the Secondary Transit Queue (STQ). This figure only shows the queues that are necessary for this particular process. For instance, if packets are stored in the transmit queues, the classes' queues are shown; otherwise, only the stage queue is illustrated. When



(a) Packet arriving from the client.



(b) Packet arriving from the outer ring.



(c) Packet arriving from the inner ring

Figure 4.5: Path and queue selection of ring-node

the ring-node receives a packet from its client, it first selects the appropriate ring direction for the packet according to the routing mechanism, as discussed in Section 4.2. Subsequently, the packet is stored in the selected ring transmit queues.

For transmit queues, the packet is classified into one of service classes' queues according to its service class. The rest of this chapter will describe this process as the packet's insertion in the transmit queues. A packet arriving from the ring and destined to the node is extracted from the ring and put in the receive queue. Alternatively, the packet that is received from the ring and destined to another node is stored in one of the two transit queues according to its service class until it gets opportunity to be forwarded to the ring.

The arbitrating service selects the next packet from transmit or transit queues to send on the ring; this decision is made according to the scheduling algorithms, as explained in Section 4.3.

Ring nodes are optional in the architecture; they are only employed to extend the coverage area of the network. Generally, they are used when a significant distance exists between two OLTs and a repeater is needed. However, the replacement of repeaters with ring nodes provides the architecture with sufficient scalability.

Hotspot Central Office

The Hotspot Central Office (HCO) has the same structure as a ring-node. In addition, HCO has an additional functionality to connect the ring network to the Internet through a router; however, this process is not shown in Figure 4.1.

OLT Node Structure

The OLT-node functions similarly to both the ring-node and the OLT in EPON networks. Each OLT-node is equipped with the same transceivers and queues as a ring-node. In addition, each OLT has at least one transceiver and one queue set that is needed to communicate with the ONUs of the EPON segment. Hence, the OLT is equipped with an array of fixed-tuned transmitter and fixed-tuned receiver, respectively operating at the downstream and upstream wavelength channels of EPON. The OLT can have one tunable/TDM receiver and one tunable/TDM transmitter to communicate with all ONUs over the feeder fiber connection. Accordingly, Figure 4.6 shows the structure of an OLT-node with a TDM receiver and transmitter.

The queue structure is depicted in Figure 4.7. In particular, this figure shows the selection of both path and queue for the OLT-node with two transit queues. In addition to the queues of the ring-node, the OLT-node has a set of queues corresponding to ONUs, which are similar to those described in Section 3.3 and will be explained in the subsequent chapter. Depending on the routing mechanism, the packet received from the client can be directed to transmit queues of one ring direction, especially if it is destined to another OLT/ring-node. If the packet received from the client is destined to an ONU, it is put in one of ONUs queues on the basis of its destination and priority type. Any packet received from the ring can be put in the receive queue, ONUs queues, or one of the transit queues, depending on whether its destination is the node itself, an ONU, or another OLT/ring-node, respectively. Also, packet arriving from an ONU is put into the receive queue or directed to the transmit queues

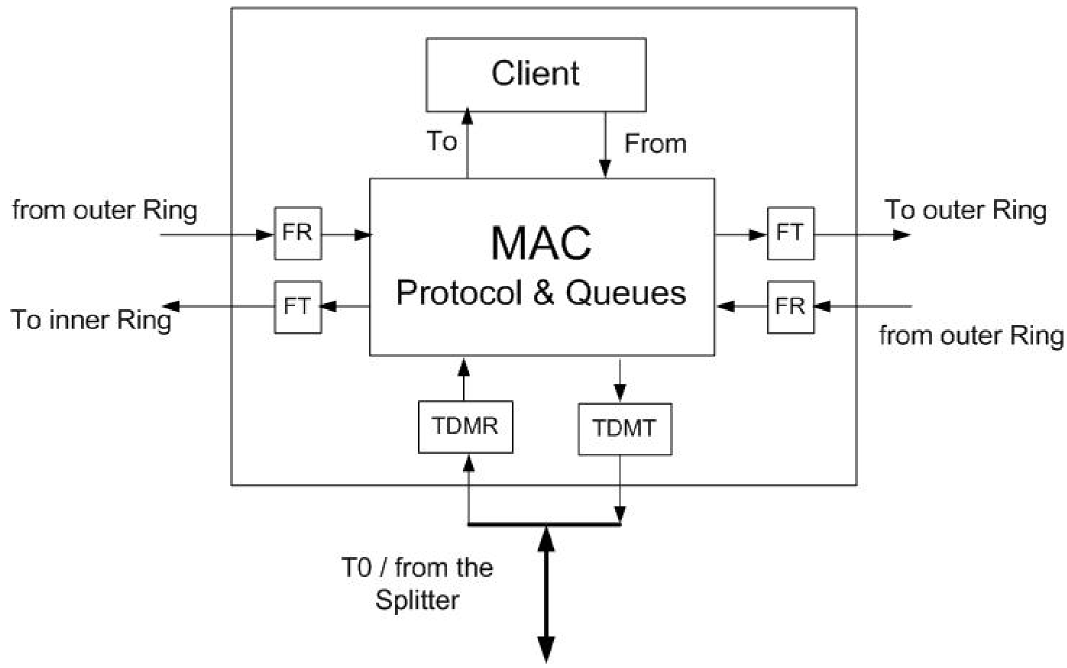


Figure 4.6: OLT-node structure.

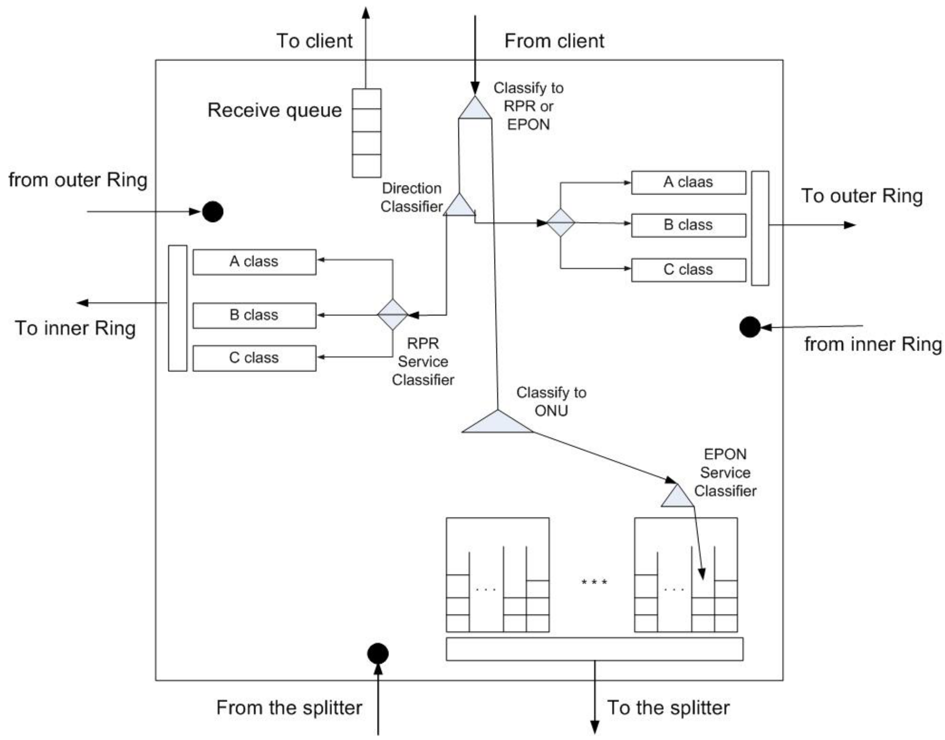
depending on whether the packet's destination is the node itself or another OLT/ring-node. If this packet is not destined to the node, it is inserted in the transmit queues of one ring direction, according to routing mechanism.

4.1.5 Architecture Discovery

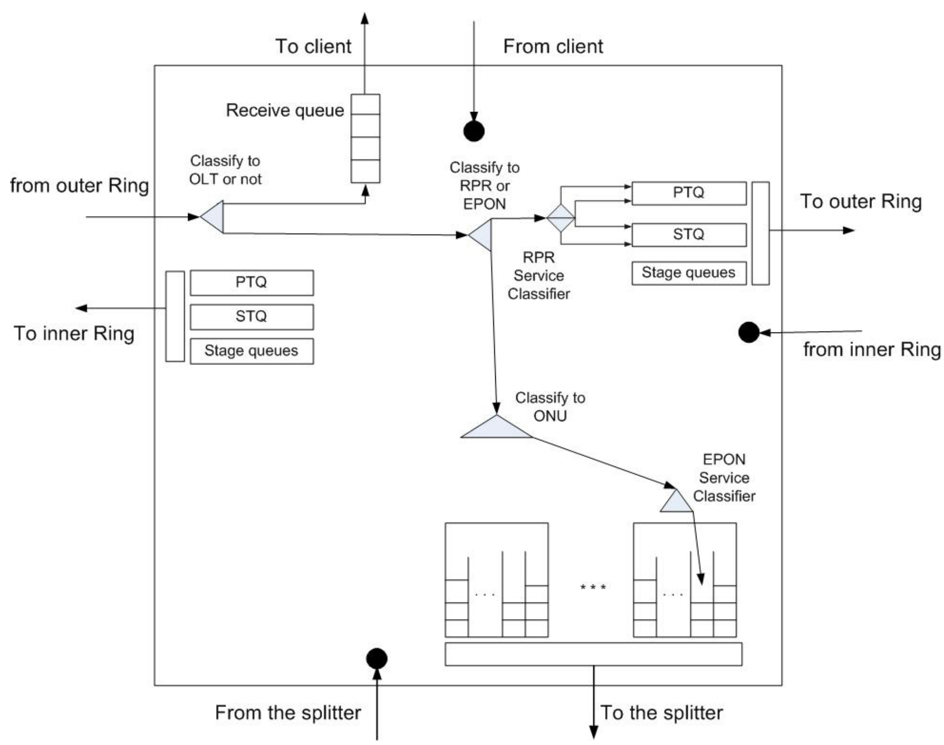
As in the case of the RPR standard, we need a protocol that provides nodes on the RPR ring with the ability to build and maintain an image of the network topology.

The architecture discovery protocol is based on the topology discovery message that is periodically broadcasted by all nodes on the ring according to the RPR standard. The discovery message in the RPR standard includes the following information:

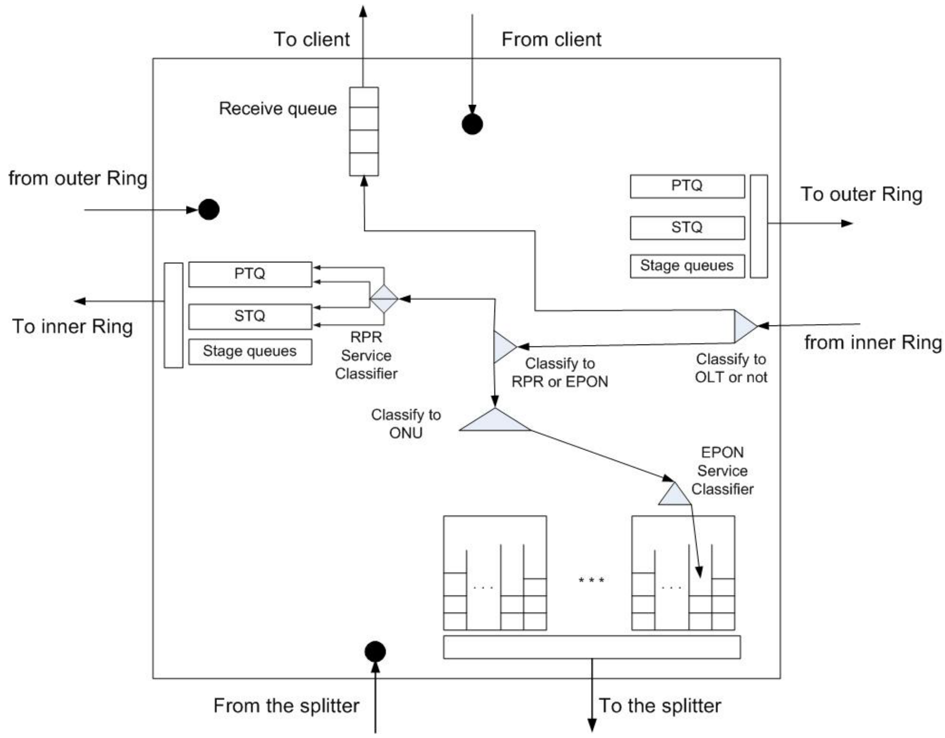
- Information that enables each node receiving a topology message to determine the relative ring position of the node that issued the message
- Status information about the node that sent the message; this information would indicate whether the node is working or failing



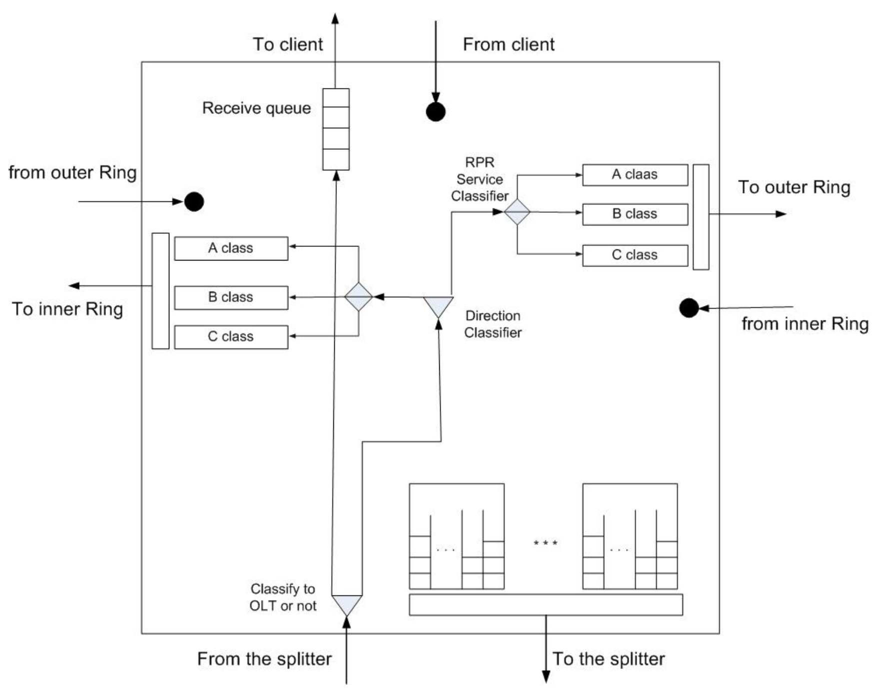
(a) Packet arriving from the client.



(b) Packet arriving from the outer ring.



(c) Packet arriving from the inner ring.



(d) Packet arriving from the EPON.

Figure 4.7: Path and queue selection of OLT-node.

- Information about the node bandwidth allocation that enables the other nodes to calculate the bandwidth remaining on each link to serve best-effort traffic

- Information about any link or node failure detected by the source node of the message.

The topology discovery message is sent immediately when a new node is inserted to the ring, or when a node detects a failure at its links or neighboring nodes. Otherwise, this message is sent periodically. Additionally, a node sends a topology discovery message if it receives another such message that is inconsistent with the information in its database.

In our architecture, the topology message issued by a node also contains the following information:

- Whether the node is a ring-only or a ring-OLT node

- If the node is an OLT, the message should indicate:

  - The EPON segment in which the OLT is connected
  - Whether the OLT is primary or secondary
  - The status of the feeder fiber that connects the OLT to the splitter
  - Information about new nodes that have joined the segment of the OLT or nodes that were disconnected from the segment.

In the proposed architecture, the OLT requires knowledge of all nodes in its EPON segment in order to send information about new nodes joining the segment or existing nodes that leave the segment. The OLT collects information about nodes in the segment through the registration protocol in the segment. According to the WiMAX standard, each SS joint in the network sends a registry request to the BS. Also, the BS can discover the disconnection of any of its SSs. A working BS sends messages about SS registration or deregistration to the OLT through ONU, to which it is attached. Consequently, the OLT is informed about BSs joining or leaving the segment through the ONU registration or deregistration.

4.1.6 Network Operation and Management

Not unlike ring nodes, OLT nodes store information about the shortest path and direction for each ring-node in its database. Additionally, for each EPON, the OLT maintains a record of the Pri-OLT and Sec-OLT and indicates which OLT has the shortest path. Subsequently, the OLT that has shortest path is determined according to the routing mechanism and is changed according to the ring status.

In contrast to the standard RPR network, not all packets passing the ring within our architecture are destined to nodes on the ring. Specifically, the nodes on the ring should:

- Differentiate between the packets that are sent to the ring-nodes and the packets that are sent outside the ring
- For packets sent outside of the ring, the ring-node that functions as the best gateway for the destination should be chosen.

The first task, differentiating between the packets, can be easily achieved if the packets contain a field in their header that indicates the EPON destination of the packet. Specifically, packets that are intended to go inside the ring can be marked by setting this field to a special value. Although this is a relatively simple solution, it is not practical, as it requires the source of packet to adhere to the network's architecture. Moreover, this solution requires a change in the upper layers of the network stack to include the EPON destination in the header of each packet.

Consequently, an alternative solution involves creating OLT stores in the database for each non-ring node destination, indicating to which EPON it belongs. This solution is practical, since it only requires OLT nodes to focus on the situation. However, this method is costly and requires the OLT nodes to concentrate on the size of the architecture, which makes the solution non-scalable.

When the destination EPON is specified, the second task, sending the packet to the best gateway, can be easily performed by sending the packet to the OLT of the EPON that has the shortest path from the sending OLT.

The following steps are performed to manage redundant OLT-nodes and support the routing mechanism in the decision to send data to any EPON segment through its Sec-OLT or Pri-OLT:

1. In its database, each Pri-OLT stores the MAC address of the Sec-OLT that is associated with it.

2. The Sec-OLT can be associated with one or more Pri-OLTs, and it stores MAC addresses and ring directions for these Pri-OLTs in its database.

3. For each of the other EPON segments, the OLT keeps two records of information for the Pri-OLT and Sec-OLT. These records include MAC addresses, path distances, ring directions, and the connection status of the OLT.

4. Each OLT stores sufficient information about its corresponding OLT, including reserved data rate, unreserved data rate, available data rate, and served streams.

5. The Sec-OLT sends a discover message when one of its Pri-OLTs fails.

6. The ring-node may or may not be a source or destination of data. When it is not a data source or destination, it only forwards packets to OLT nodes.

7. Both Pri-OLTs and Sec-OLTs behave like ring nodes when they are neither a source nor destination of any data or a gateway to its EPON segment.

In the EPON segments, the splitter is connected to the Pri-OLT and Sec-OLT on the ring. In the downlink, the splitter combines the traffic from the Pri-OLT and the Sec-OLT. Conversely, in the uplink, the splitter routes the traffic from ONUs to either the Pri-OLT or Sec-OLT, which, for each destination, requires the EPON segment to record whether it can be reached through the Pri-OLT or the Sec-OLT. Since a stream has a fixed source-destination pair, its route is specified at setup time of the stream and is stored in the ONU. As a result, the stream route can only be changed in the case of failure, at which time the routes of all EPON segment streams will most likely be re-calculated. The process of routing to one of the two OLTs is performed in one of two following ways:

1. For a TDM splitter, a mono-wavelength channel EPON, in uplink, the ONU indicates the MAC address of the desired OLT as the next-hop address of the packet and broadcasts it to both OLTs. However, only the desired OLT will extract the packet and forward it. In downlink, Time-Multiplexing is used by the splitter to combine the traffic of both OLTs, which requires the time between these OLTs to be managed efficiently.

2. For the dual or multi wavelength EPON, in uplink, each ONU sends stream packets on wavelength channels of the desired OLT. In downlink, the splitter is equivalent to two splitters, each of which works on a set of wavelength channels.

4.2 Routing Protocol for RPR-EPON-WiMAX

4.2.1 Routing in the WiMAX part

In the WiMAX part, the routing task involves finding a route from the packet's source router to a gateway, a wireless node attached to the ONU, or vice versa. There is no routing protocol needed if a Point-to-Multi-Point (PMP) WiMAX network is employed in the front end. In case of the WiMAX mesh network, the routing algorithm similar to DWRA in [48] can be used; however, in this case, there are two modifications:

- Rather than finding a route for every packet, the routing algorithm finds a route for streaming. Hence, the routing algorithm is executed at stream setup or the route has to be changed due to unforeseen circumstances such as failure.
- In addition to the link delay in the route selection, link congestion is also considered.

To route a stream in the mesh WiMAX:

1. Each link in the mesh network is assigned a weight W_{ld} according to the transfer delay of this link, as performed in [48]. In particular, a greater the link delay causes a more substantial delay-weight.

2. All possible routes that have a total delay less than or equal to the delay requirements of the stream should be indicated. The total delay is the sum of the delay of all links in the route.

3. Each route has delay weight W_{rd}, where

$$W_{rd} = \sum_{\forall \; route \; links} W_{ld}. \tag{4.1}$$

4. Each route is assigned a congestion weight W_{rc}, which is related to the maximum traffic rate served by any link in the route. Accordingly, each link has a traffic rate R_t, which is the average data rate of all streams served by the link. The congestion weight W_{lc} of the link is

$$W_{lc} = R_t/C. \tag{4.2}$$

   where C is the capacity of the link. Hence, a greater R_t indicates a higher congestion weight W_{lc}. The route congestion weight is

$$W_{rc} = \max(W_{lc} \;\; \forall \; route \; links). \tag{4.3}$$

5. The route with the lowest weight $W = W_{rd} + W_{rc}$ is selected to route the stream. in order to give delay and congestion balanced roles in the route selection, the delay weight should be calculated in a way that gives values in the same rang of the congestion weight values.

Since route selection is dependent on the streams served by each link, when streams finish their work, any router in the route that discovers a more efficient modification of the route can send a notification to the source. In this case, the source re-executes the routing algorithm for the indicated stream.

4.2.2 Routing in the Optical part

In the optical part, the EPON and the RPR ring, the routing task involves selecting the route between the ONU in the source EPON and that in the destination EPON. Specifically, this task entails choosing one OLT in both of the source and destination EPONs as well as the path on the ring between these two OLTs.

Since the set of connections in the architecture is predetermined, the routing should work in a similar way to Static Light path Establishment (SLE) in optical wavelength division multiplexing (WDM) networks [49]. Also, as the traffic load for each source and destination pair is depends upon the traffic rates of streams, the routing selects the route for a stream instead of finding the route for a packet.

Each link in the architecture is assigned a cost, and the route with the lowest cost is selected. Assuming that all links are free of failure and have infinite queues, the cost of the link corresponds to its delay. Also, the cost of the link is assigned in such a manner that the links with more delays are given more weight.

In addition to finding the route with the lowest delay, the routing algorithm is concerned with load balancing. Specifically, the routing algorithm aims to find a route with the least congestion among the light paths. Hence, the cost metric of the links is estimated on the basis of the links' delay and congestion. Consequently, the traffic is routed over the lightly loaded links that have minimal delay.

In each EPON segment, we need to select between two paths; however, this choice cannot be made separately from the selection of the path on the ring. The selection of an OLT that has minimum cost to the OUN in each EPON segment can result in a more expensive cost path on the ring, thus indicating that this route choice is not ideal.

As a result, all possible routes from the source ONU to the destination ONU are considered, and then the route with the lowest cost is selected. Since there are two paths in each EPON and there are two paths over the ring for each OLT source-destination pair, there are eight possible routes. Each route has an EPON cost and a ring cost. The EPON cost depends on the distance between the OLT and the splitter as well as the traffic rate of the OLT in the EPON direction. Alternatively, the cost of the ring is dependent on the number of hops between the selected OLTs and the congestion of each path segment.

The routing algorithm similar to that in [50] is used to select the best possible route as follows:

1. For each link, i, calculate the link delay, D_i, and the congestion index of the link, C_i. C_i is calculated as

$$C_i = R_{ser}/R_i. \tag{4.4}$$

where R_i is the data rate of the link and R_{ser} represents the total data rates of all streams served by the source node of the link. The source nodes are OLT for EPON links and OLT or the initial ring-node for ring links.

2. The link cost function, $Cost(i)$, is then defined as

$$Cost(i) = D_i + Fc(i). \tag{4.5}$$

where $Fc(i)$ is a function that has a value in the range of network delays corresponding to C_i. Thus, if D_{max} and D_{min} are the maximum and minimum link delays in the network, respectively, and, as $0 \leq C_i \leq 1$, then

$$Fc(i) = D_{min} + C_i * (D_{max} - D_{min}). \tag{4.6}$$

3. After each link is assigned a cost, Dijkstra's shortest path algorithm [51] is subsequently used to compute the lowest-cost path as the selected route.

A route for each stream is selected at stream setup time. In the case of OLT or its EPON connection failure, all traffic in the segment will be routed through the other OLT. This rerouting may result in the recalculation of routes for all streams served by the malfunctioning OLT. If the OLT functions as a Sec-OLT for more than one EPON segment, all of these segments will be affected due to the failure in the Sec-OLT or in one of Pri-OLTs.

In case of a faulty OLT ring connection, the paths over the ring are recalculated and all traffic in the segments may be rerouted.

4.3 Scheduling in RPR-EPON-WiMAX

The proposed architecture in Section 4.1 supports the same service types as those supported by the EPON-WiMAX architecture in Chapter 3 and as those that will be discussed in Chapter 5. Hence, the architecture supports UGS, ertPS, rtPS, nrtPS, and BE service types.

The proposed scheduler for the architecture is a three level process, as various parts of the scheduler run at WiMAX BS, ONU, and OLT.

The scheduler for the WiMAX BS is the same as the BS scheduler in the EPON-WiMAX architecture in Section 3.5.1. The schedulers of ONU and OLT are discussed in the following subsections.

4.3.1 ONU Scheduler

The ONU is responsible for scheduling its data in the uplink direction to the OLT during the uplink cycle. Unlike the EPON-WiMAX architecture, in the architecture of Figure 4.1, the ONU is connected to two OLTs. Hence, part of its data is sent to Pri-OLT and the other part is sent to the Sec-OLT. Based on this situation, the UNO scheduler in this architecture is different from the ONU scheduler in the EPON-WiMAX architecture. Moreover, the ONU scheduler in the proposed architecture is dependent on the type of EPON employed in the architecture.

In case of WDM EPON, ONU routs to each OLT on a different set of wavelength channels. For each wavelength channel, the ONU schedules various types of data over this channel in a similar method to that in Figure 3.6(b), which depicts the ONU scheduler in the EPON-WiMAX architecture. However, in that case, all cycles do not necessarily contain all service types.

In case of TDM EPON, the uplink cycle is divided to two sub-cycles: one for Pri-OLT and other for Sec-OLT. Each ONU is assigned a time slot in one or both of sub-cycles, depending on which OLT serves the streams of ONU. Within the time slot of any sub-cycle, the ONU schedules service types in the same order as that for EPON-WiMAX. For the proposed scheduler, the uplink cycle structure in TDM EPON is shown in Figure 4.8.

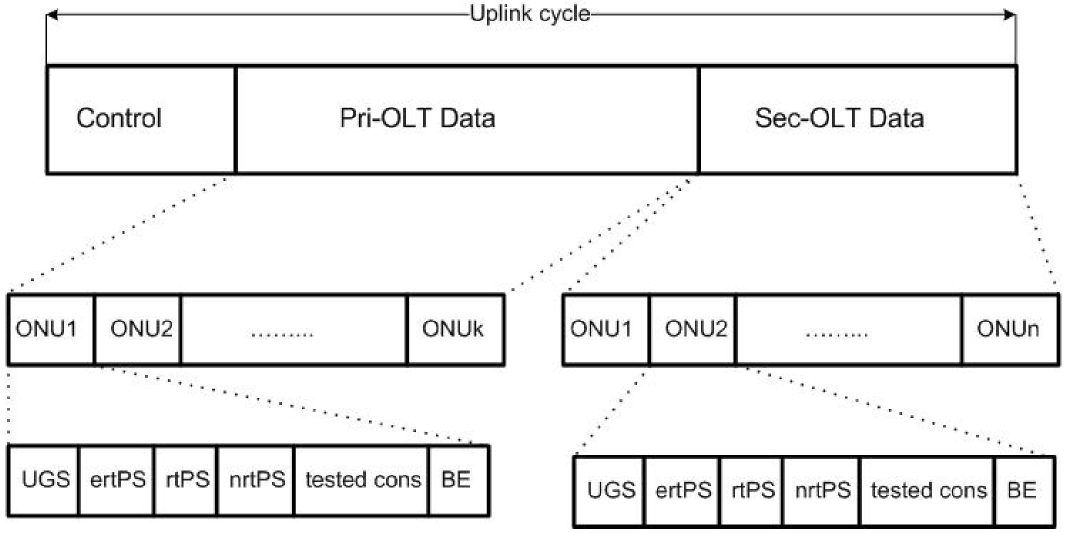


Figure 4.8: Uplink cycle structure for TDM EOPN in RPR-EPON-WiMAX.

4.3.2 OLT Scheduler

The OLT scheduler has two tasks; first, it schedules data to the ONUs in the downlink direction for EPON. Secondly, it schedules data received from the ONUs, which is not destined to OLT, to its destination within the ring.

4.3.2.1 OLT Scheduler in EPON

In the downlink direction, data to the ONUs in the EPON segment is dependent upon the EPON type. For WDM EPON, if multiple wavelength channels are employed, the OLT has a separate downlink cycle for each wavelength channel, which serves a group of ONUs. The downlink cycle of wavelength channels is identical to that in Figure 3.6(b) of EPON-WiMAX architecture in Chapter 3.

For TDM EPON, the cycle time is divided to two sub-cycles: one sub-cycle for each Pri-OLT and Sec-OLT. Each OLT schedules traffic in its sub-cycle in the same manner as the subOLT in EPON-WiMAX. Figure 4.9 shows the structure of a downlink cycle in the EPON part of the architecture depicted in Figure 4.1.

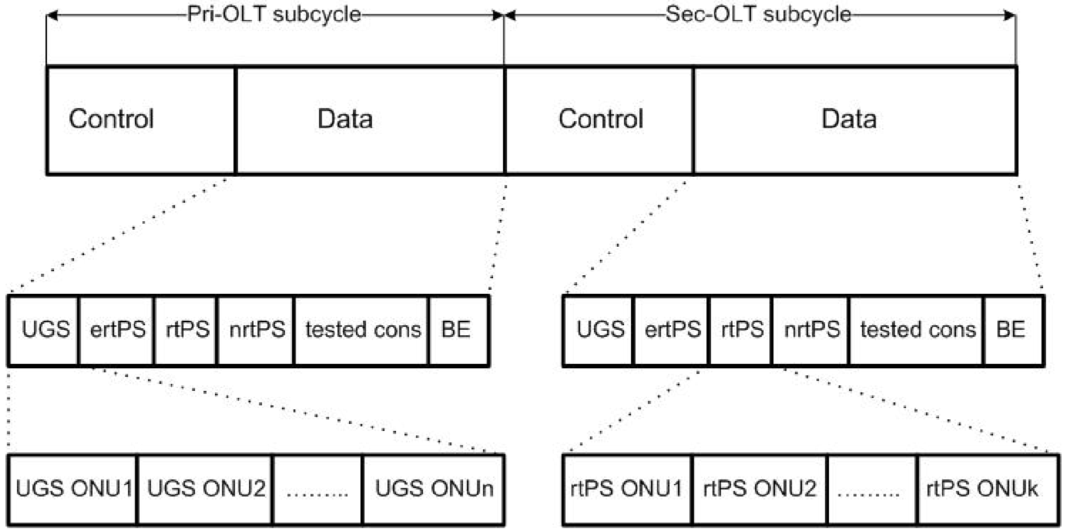


Figure 4.9: Structure of downlink EPON cycle in RPR-EPON-WiMAX.

4.3.2.2 OLT Scheduler over the Ring

Over the ring, the OLT schedules data after classifying it according to the service classes defined in the RPR standard. Hence, the OLT's scheduling of ONU data over the ring is dependent on how the OLT maps the data of service types from the EPON to the RPR classes. In order to maintain consistency with the way in which traffic is treated in the WiMAX and EPON parts, the OLT can consider under-test connections traffic as FE traffic. One possible, straightforward configuration involves mapping the WiMAX service types and RPR classes according to Table 4.1. As in the RPR standard, Class A traffic has priority over Class B traffic, which has priority over Class C traffic. Therefore, the OLT schedules these traffic classes in the order of A0, A1, B-CIR, B-EIR, and C. Traffic that is under test connections is treated as the B-EIR class. Hence, the OLT schedules packets of service types from ONUs over the ring in a way that the ONU schedules data in its own time slot. However, in this case, there is no ordering relationship between nrtPS packets and under-test connection packets.

There are several differences between ONU scheduling and OLT scheduling. First, the OLT does not receive a time slot to schedule these data over the ring as in

Table 4.1: Mapping of RPR Classes and WiMAX Services types

RPR class	**WiMAX service**	**Chrematistics**	**Application**
A0	UGS	Real-time, fixed-size on a periodic basis	VoIP, T1, and E1 voice service
A1	ertPS	Real-time, Delay-sensitive, variable-size on a periodic basis	VoIP with activity detection
B-CIR	rtPS	Real-time, variable-size on a periodic basis	MPEG video
B-EIR	nrtPS	Delay-tolerant, minimum data rate	FTP
C	BE	Delay- and jitter-tolerant	web browsing, e-mail

the case of the ONU. Rather, the OLT schedules over the ring by prioritizing MAC traffic over data traffic. Specifically, if the OLT has a single-transit queue, priority is given to the in-transit ring traffic over the station traffic. In the dual-transit queue mode, the PTQ traffic is always served first. If only the STQ has packets, the transmission queues are served while STQ is under a certain queue threshold. Hence, the OLT schedules packets of ONU data when it does not have to serve transit traffic. Consequently, this may result in unequal gaps between periods when these packets served. Secondly, the ONU is allocated a time slot every cycle, whereas there is no periodic scheduling for OLT.

The effectiveness of the proposed scheduler and routing algorithm in Section 4.2 can be measured by calculating the average delay of both UGS and rtPS in the proposed solution, which is termed IRPEW in the figures. These delays are measured through simulation in the NS-2 Simulator and compared with the delays of another system, referred to as UN-IRPEW. This alternative system is similar to the proposed solution but contains differences that will be discussed in the next chapter. Figure 4.10 shows the average delay of the UGS and that of the rtPS is shown in Figure 4.11.

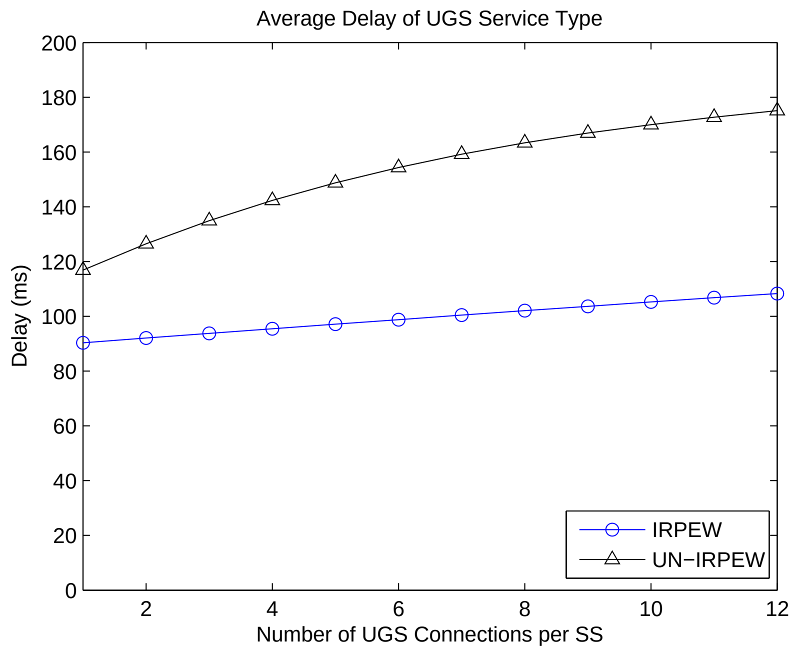


Figure 4.10: Average Delay of UGS type

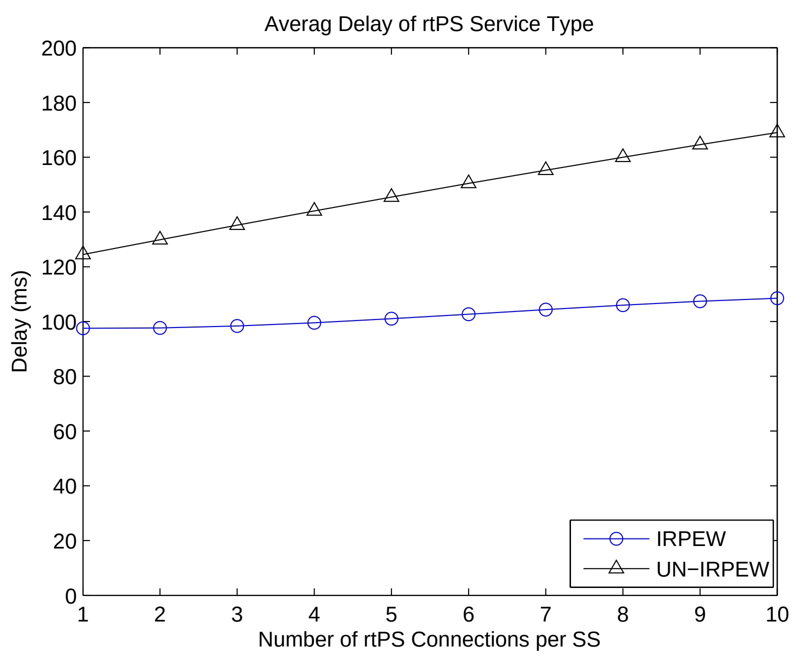


Figure 4.11: Average Delay of rtPS type

4.4 Summary

This chapter proposes a new architecture for the RPR-EPON-WiMAX hybrid network as a solution for both access and metro networks. Specifically, the architecture is reliable and contains a high fault tolerance against node and connection failure. The reliability of the architecture results from the dependability of the RPR standard and the protection mechanism employed in the EPON network. In order to apply the solution for practical use, this chapter proposes a routing mechanism for the proposed architecture. This routing mechanism selects a route for each stream in both the WiMAX and optical parts in a way that minimizes the delay and provides a balanced load. Subsequently, the chapter proposes a scheduler that is concerned with service types over the entire architecture. The delay measure for certain service types shows the effectiveness of the scheduler and routing mechanism in the proposed architecture.

Chapter 5
MAC Protocol for RPR-EPON-WiMAX Networks

This chapter presents a new MAC protocol for the RPR-EPON-WiMAX hybrid network architecture demonstrated in Figure 4.1. The proposed MAC protocol includes a multi-level, dynamic bandwidth allocation algorithm and distributed admission control; it aims to maximize the advantages of the suggested architecture. In order to achieve the desired target, the MAC protocol distributes its functionalities over the parts of the architecture. Specifically, as each part performs its role in the MAC protocol, it cooperates with other parts to ensure maximum performance for the network. Moreover, parts of the MAC protocol are executed jointly with the scheduler and the routing algorithm proposed in Chapter 4. For example:

- The routing algorithm is used in admission control to assign each stream to the OLT that provides the best available route for this stream
- The allocated bandwidth for both the BS and OLT are divided among service types by the scheduler
- The admission control, while admitting streams, may change the frame duration of the WiMAX and/or the cycle time of the EPON in a way that provides a required bandwidth for all streams while satisfying the delay limitations.

In summary, the proposed MAC protocol tries to accomplish these goals:

1. Utilizes the network resources efficiently.
2. Provides end-to-end QoS for streams over the network.

3. Guarantees that a stream admitted into the network will not suffer degradation in its required QoS while it is working

This chapter is organized as follows; first, it presents reasons for the necessity of the proposed MAC Protocol in Section 5.1. Subsequently, the general specifications of the proposed MAC protocol are explained in Section 5.2. Then, in Section 5.3, the proposed Distributed Admission Control is presented, and the Multilevel Dynamic Bandwidth Allocation is provided in Section 5.4. Section 5.5 evaluates the performance of the proposed MAC protocol with the proposed architecture from Section 4.1. Moreover, in this section, the performance of the proposed solution is compared with the performance of a system that merely implements standards of RPR, EPON, and WiMAX and without any integration among them. Finally, Section 5.6 summarizes the chapter.

5.1 Motivation

As stated in Chapter 4, the integration of PRP, EPON and WiMAX has not, to the best of our knowledge, been considered as a solution for metro and access networks. Hence, the MAC protocol for this hybrid RPR-EPON-WiMAX network has not yet been proposed. As the integrations between RPR and EPON and between EPON and WiMAX, have been separately considered, the MAC protocols for these integrations have also been examined separately. In [4], the authors proposed an architecture called STARGATE, which consists of the integration between WDM EPON and RPR and is supported with a single-hop star sub-network. They also proposed a partial MAC protocol for this architecture, which only focuses on minimizing the delay over the ring and does not consider the combined MAC protocols of RPR and EPON.

Furthermore, as a solution for the access network, the EPON-WiMAX integration has been proposed in many works, such as [10]- [14], [18], and [47]. Each of these studies focuses on one or more parts of the MAC protocol based on the EPON-WiMAX integration, which leads us to propose a joint MAC protocol for EPON-WiMAX in Chapter 3.

Hence, the MAC protocol for RPR-EPON-WiMAX has not yet been proposed, and the MAC protocols suggested for its discrete parts, RPR-EPON and EPON-WiMAX, do not work jointly. In fact, the lack of a comprehensive MAC protocol is the primary motivation behind our proposal of a joint MAC protocol for RPR-EPON WiMAX.

Moreover, our proposed architecture, which was introduced in the previous chapter, cannot employ a combination of the proposed MAC protocols for RPR-EPON and EPON-WiMAX for the following reasons:

1. These protocols are not concerned with the source or destination of data that they manage. For example, the MAC for RPR-EPON manages the data from WiMAX in the same manner that it does for the data of users served by the ONU of EPON.

2. In combination, these protocols are not concerned with the end-to-end QoS of streams.

3. These protocols do not work jointly; in Chapter 3, we proved how a joint MAC improved the performance of the architecture, so parts of the proposed MAC should function collaboratively.

The final motivation for proposing a MAC protocol for our suggested RPR-EPON-WiMAX hybrid architecture is the need for a protocol that responds to new modifications in the architecture and capitalizes on its advantages. Since the proposed architecture tries to improve the reliability of the network by providing dual-entry for each EPON segment on the ring network, the proposed MAC protocol should be integrated with the architecture, both benefitting from the architecture as well as improving its performance.

5.2 General specifications of the proposed MAC Protocol

In this MAC protocol, we consider the PMP WiMAX in the front end and the TDM EPON. Moreover, we account for the fact that the ONU and WiMAX BS are integrated in a single system box (ONU-BS) according to the hybrid architecture in [10].

As users are mostly served through the WiMAX part of the network, the MAC protocol should support all service types defined in the WiMAX standard, including the Unsolicited Grant Service (UGS), real-time Polling Service (rtPS), extended real-time Polling Service (ertPS, defined in 802.16e), non-realtime Polling Service (nrtPS) and best-effort (BE).

In this joint MAC protocol, we need to consider that the BS of the WiMAX network, similar to that in the EPON-WiMAX network, has a front-end capacity that depends on the wireless interface of the BS and a backhaul capacity that is provided through the ONU over a fiber link. Also, the OLT has a front-end capacity that depends on the fiber link connecting the OLT to the ONUs and a backhaul capacity that the OLT can use over the rings. For both the BS and the OLT, the effective capacity is the minimum of front and backhaul capacities.

In order to preserve the comprehensiveness of the system, we assume that all streams are sourced and destined within the architecture. Hence, the MAC protocol is not concerned with the existence of the hotspot central office and its performance. Moreover, this protocol does not include the MAC of standard RPR ring-nodes, as they do not affect the performance of the architecture, especially when they are not the source or destination of any data.

5.3 Distributed Admission Control

The proposed admission control has two levels: the first level runs at WiMAX BS and the second level runs at the OLT that connects the EPON to the RPR ring. Some streams are initially admitted by the WiMAX BS and temporarily tested to guarantee that they can run safely. Other connections need to be admitted by the OLT before they send or receive any data in the network.

5.3.1 Admission Control at WiMAX BS

By considering PMP in the WiMAX, the AC for the BS is the same as that for the BS in EPON-WiMAX, as discussed in Section 3.3. This AC procedure can be summarized as follows:

- If the bandwidth and delay requirements of the stream cannot be satisfied by the wireless data rate of the BS, the stream is rejected.
- If the stream requirements are satisfied by both the wireless data rate and the backhaul data rate that the BS can use over the EPON network through the ONU, the stream is initially accepted in the network and its performance is monitored for a temporary period of time.
- If a stream's requirements can be satisfied by the wireless data rate of the BS but not satisfied by the backhaul data rate, it is inserted into the waiting queue and its requirements are sent to the OLT for admission.
- The QoS requirements of streams in the waiting queue are sent to both the Pri-OLT and the Sec-OLT of the segment. As will be discussed later, each stream can be admitted by any OLT.
- When the ONU/BS unit receives a new allocated bandwidth, it verifies all waiting streams and testing streams with the new backhaul data rate.
- For streams that are undergoing testing, those whose requirements are not satisfied by the new backhaul data rate are rejected. Conversely, streams whose requirements are satisfied by the new data rate are admitted into the network if they passed the testing period.
- Waiting streams are checked against new backhaul data rate; any stream whose requirements are satisfied by the new rate is accepted to undergo testing. Streams

whose requirements are not satisfied after the maximum waiting period are rejected.

As mentioned in Section 3.3.3, the type of connection request determines whether or not both delay and bandwidth requirements are satisfied. Since the BE does not entail delay requirements or bandwidth guarantees, all BE streams can be admitted directly by the BS and cannot be forwarded to the OLT for admission. For the UGS, a stream may be admitted if its mean data rate can be supported by the current system. The rtPS, ertPS and nrtPS are admitted according to mean data rate in order to save network bandwidth. Specifically, the nrtPS connection has no delay requirements, so only the bandwidth requirement needs to be satisfied. However, the rtPS and ertPS connections have both bandwidth and delay requirements.

5.3.2 Admission Control at OLT

The OLT admits streams according to its effective data rate. Unlike that of the EPON-WiMAX network, the effective data rate of the OLT not only depends on the capacity of the fiber connection between the OLT and the splitter, but it also depends on the data rate that the OLT can use on the RPR ring. In the proposed architecture, each EPON segment can be served through two OLTs. Specifically, fewer streams of the EPON segment are served through each OLT and its fiber connection. When the fiber connection from the OLT to the splitter possesses similar characteristics to that in EPON-WiMAX, the backhaul date rate on the ring of the OLT has a more effective role in admission control. Consequently, the front-end data rate of the OLT will not be an issue in normal operation status, but it can be an issue in the case of failure. As a general rule, the OLT considers both front and backhaul data rates when admitting a stream. Both the Pri-OLT and the Sec-OLT of the segment receive admission requests from all streams requiring admission by the OLT. Each stream can be admitted by either of the two OLTs.

The AC procedure differs according to the working status of the OLTs. Specifically, the OLT executes the AC procedure differently depending on whether it is in normal working condition or in failure status.

OLT AC in the case of failure

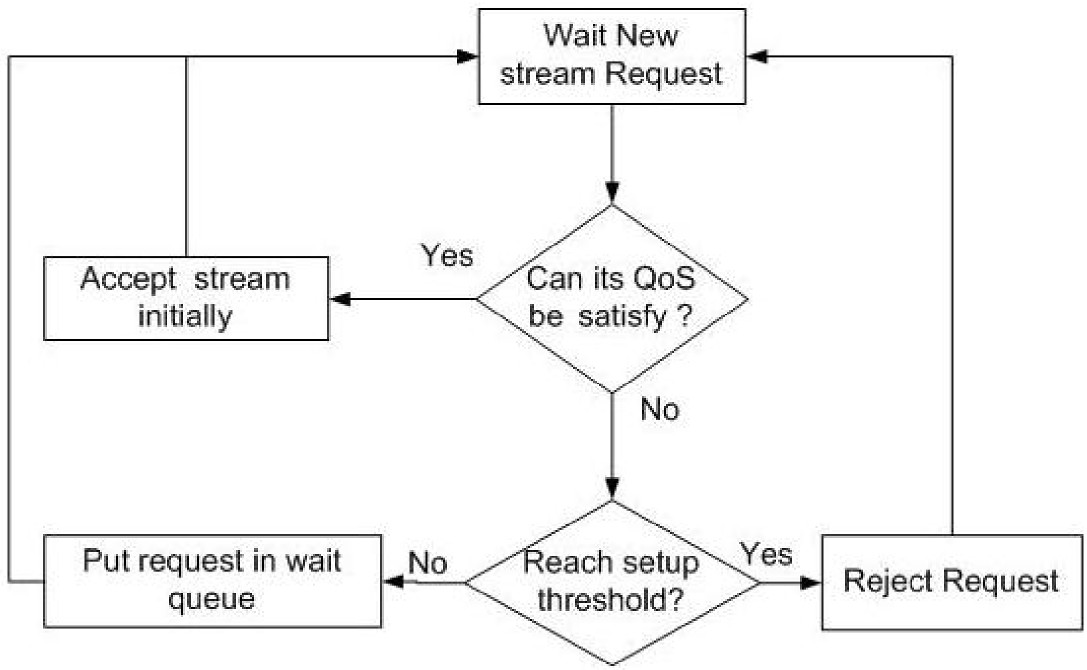
This AC procedure is executed in situations where the OLT or one of its connections fails. For instance, the fiber connector between OLT and the splitter or the connections of the OLT on the ring could break down. The working OLT of the segment executes the AC similar to that of the BS, where the data rate of the fiber connection in EPON is considered as the front data rate and the backhaul data rate of the OLT is the data rate that it can use over the RPR ring. The OLT AC in the case of failure consists from three parts: admit new stream (Figure 5.1(a)), handling the resolve of the failure (Figure 5.1(b)), managing waiting and not finally admitted streams (Figure 5.1(c)). The streams are admitted according to the following procedure:

- If a bandwidth requirement can be reserved and a delay requirement can be satisfied, a stream is initially accepted. However, if this stream requires a new cycle time to satisfy its delay requirements, these requirements are only satisfied if the cycle time can be changed so that none of the running streams are affected. For newly accepted streams, the required resources are considered as temporary, making the stream conditionally accepted at the WiMAX BS. By allocating resources as temporary, the OLT has the ability to reject the stream at a later time if it cannot maintain its resources. This scenario can occur in the case that the OLT serves other segments and when other OLTs of this segment fail.

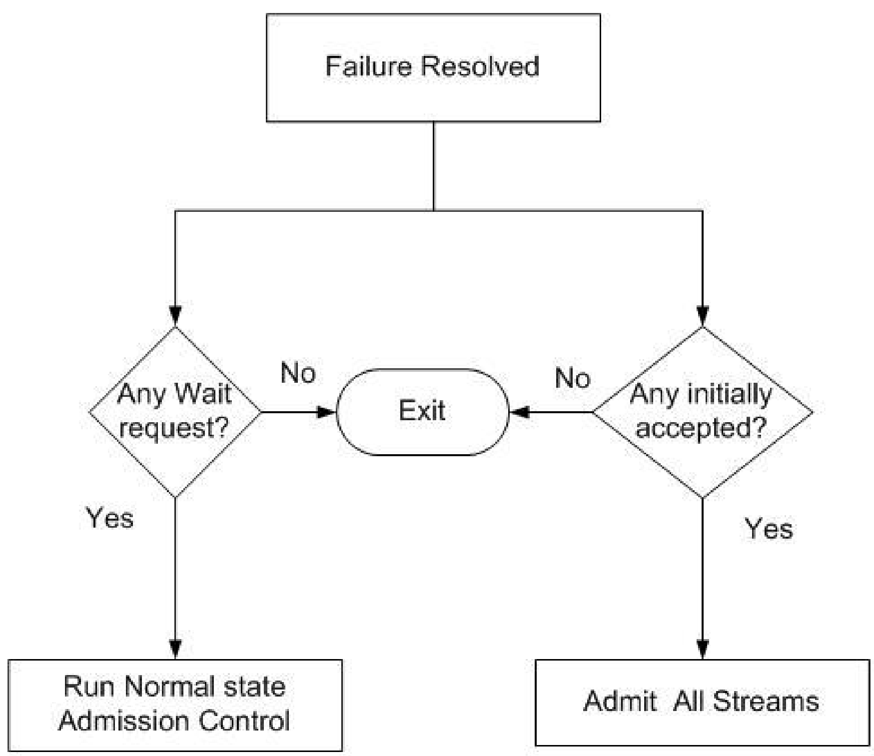
- Streams cannot be accepted or rejected according to the current date rate. Based on the date rate, streams that are not accepted immediately should wait in case the failure condition can be resolved. As a result, AC should be concerned with the maximum allowed setup time of streams, as they should not wait long period before being admitted or rejected.

- Waiting streams are checked periodically, and those that have reached their setup time threshold or have spent their maximum waiting time are rejected.

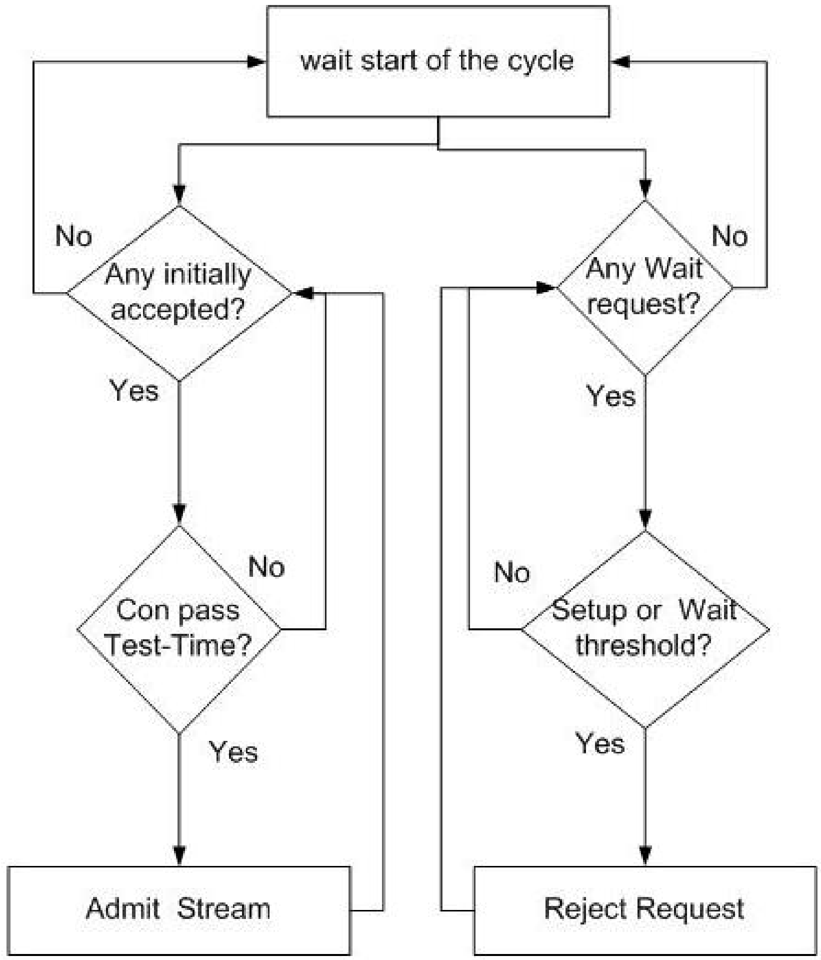
- The resources of initially accepted streams are permanently reserved when these streams are admitted into the network.



(a) admit new connection.



(b) handling failure resolve.



(c) manage waiting and initially accepted connections.

Figure 5.1: OLT admission control in case of failure.

- When the failure condition is resolved, all initially accepted streams are finally admitted into the network. Waiting streams are admitted as those in the normal working state.

OLT AC in case of normal operation

When both OLTs and their connections are working normally, the front data rate of the OLT is not an issue and streams are admitted according to the backhaul data rates of the OLTs. The AC in this case consists from four parts: admit new stream (Figure 5.2(a)), managing waiting requests (Figure 5.2(b)), managing initially accepted streams (Figure 5.2(c)), and handling the failure situation (Figure 5.2(d)).

The two OLTs cooperate to admit streams according to Figure 5.2 as follows:

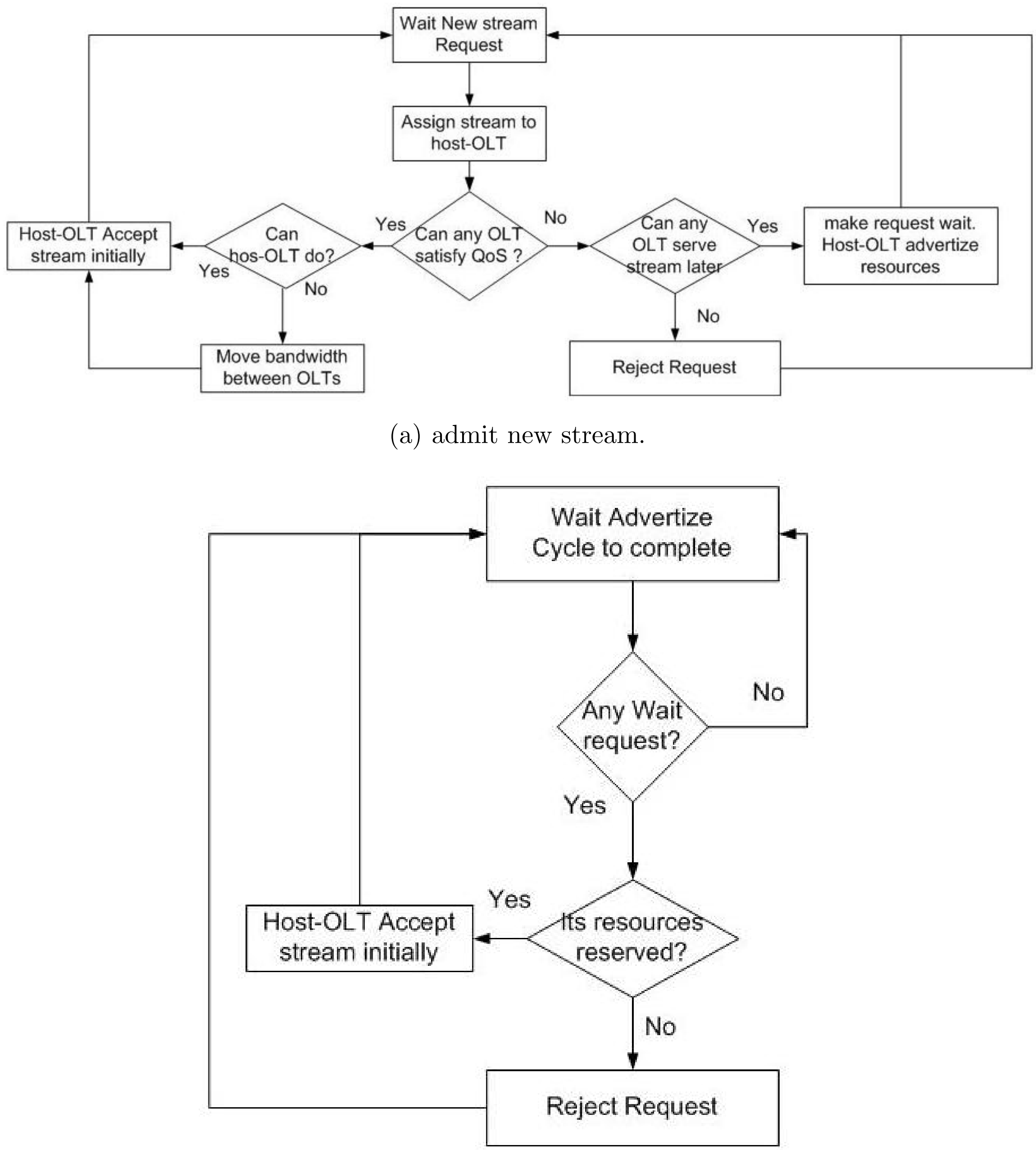
1. Each stream should be assigned to the OLT, known as the host-OLT, which provides the preferred route for the stream based on the routing algorithm. In particular, the stream route provided by the host-OLT should have a maximum delay less than or equal to the delay requirement of the stream

2. As each OLT in the segment acquires sufficient information about the other OLT, it should be checked against the network operation in Section 4.1.6, so that it can decide if the other OLT can accept the stream, and similarly, it can make this decision for itself.

3. A stream is rejected for two reasons; first, it is rejected if it cannot be accepted by the current data rate of both OLTs and neither OLT can reserve its required resources any longer. Secondly, a stream is rejected if the current cycle time of the host-OLT does not satisfy the delay requirement of the stream and the cycle time cannot be changed to meet the delay requirements without any degradation in the QoS of running streams. In this case, the rejection is final, as the stream can no longer be considered for admission.

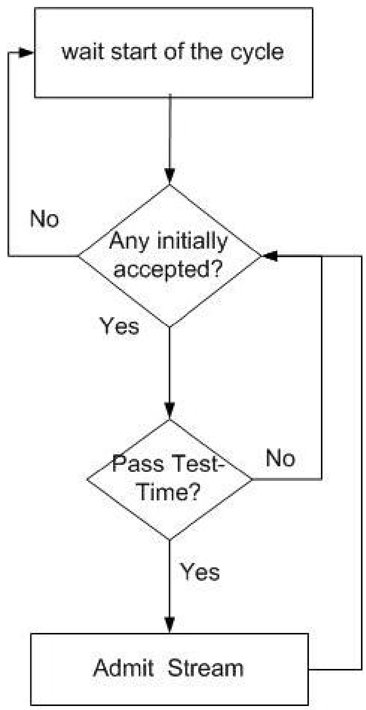
4. If the current data rate of OLTs cannot accommodate the stream but the required resources can be reserved, the host-OLT advertises the required resources. If the required resources are not reserved after the advertisement phase, the stream is rejected; otherwise, the stream is accepted, as in Step 6.

5. If a stream can only be accommodated by the current data rate of the non-host-OLT, the stream can be accepted, but its acceptance will cause the network performance to become degraded. In this case, a part non-host-OLT data rate is released and reassigned to the host-OLT, which accepts the stream, as in Step 6.

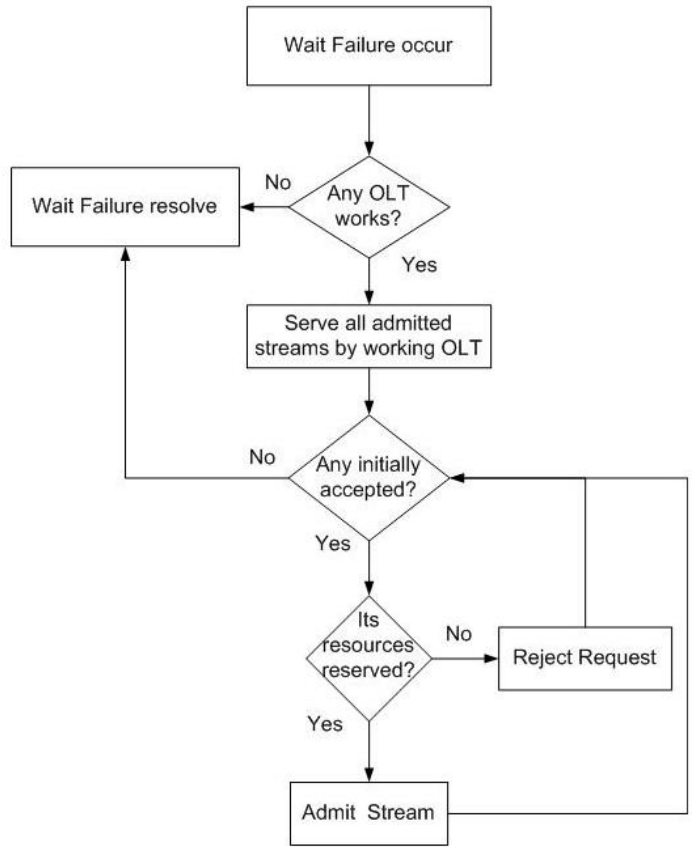


(a) admit new stream.

(b) managing waiting requests.



(c) managing initially accepted streams.



(d) handling the failure situation.

Figure 5.2: OLT Admission Control in Normal Operation.

6. If a stream can be accommodated by the current data rate of the host-OLT or both OLTs, the stream is initially accepted by the host-OLT. However, since stream is not accepted permanently, the probability of failure in the segment is not an issue.

7. Initially accepted streams, like those undergoing testing, are admitted permanently after a specific waiting time.

Since the initial acceptance of a stream indicates that its required bandwidth is temporarily reserved, its treatment is dependent on its type. Unfortunately, all request types received by the OLT need to reserve bandwidth. Specifically, the BE stream, which has no bandwidth requirement, does not need to be admitted by the OLT. Thus, for all types, streams are initially accepted and then permanently admitted.

5.4 Multi-level Dynamic Bandwidth Allocation (MLDBA)

The proposed Dynamic Bandwidth Allocation (DBA) is a three level algorithm: the first level runs at the WiMAX BS, the second level runs at the EPON ONU, and the third level runs at the OLT connecting the EPON to the RPR-ring of the architecture.

5.4.1 Bandwidth Allocation of BS

For the BS, the bandwidth allocation is the same with the DBA as it is with the EPON-WiMAX networks of Section 3.4.1. In the DBA, the BS bandwidth allocation is summarized as follows:

- Based on the values defined in the WiMAX standard, the BS sets its frame size to the value that satisfies the delay requirement of all streams served by the BS
- The BS allocates bandwidth to service types according to its available data rate, which is the minimum of the front data rate of the wireless interface and the backhaul data rate that the BS can use over the EPON through ONU.
- The BS assigns bandwidth according to the strict priority principle, where the priorities of service types, from highest to lowest, are UGS, ertPS, rtPS, nrtPS, and BE. In order to prevent higher priority connections from monopolizing the network, traffic policing is included in each SS. This policing forces the connection's bandwidth demand to stay within its traffic contract.
- The BS reserves a portion of its bandwidth to serve the BE traffic.
- Each UGS connection is assigned a constant bandwidth, which it receives periodically based on its fixed bandwidth requirement.

- The BS allocates requested bandwidth for each ertPS connection based on its fixed period requirement.
- The BS applies the earliest deadline first (EDF) service discipline to rtPS traffic, where packets are served according to their deadlines.
- The BS applies the weight fair queue (WFQ) service discipline for nrtPS service types.
- The remaining bandwidth for the BS is equally allocated among BE connections.

5.4.2 Bandwidth allocation of ONU

In the process of bandwidth allocation, ONU functions to restrict data from service types in classified queues and to request the required bandwidth for transmitting this data from the OLT. Hence, the ONU receives data from the BS(s) and from users connected directly to the ONU. Moreover, it classifies data to suitable queues on the basis of its QoS requirements. Each ONU has queues with eight different priority levels; there is one priority-level queue for each service type of UGS, ertPS, and nrtPS, as well as BE service types of BS. For rtPS, ONU has two priority-level queues: one for packets with deadlines in the next cycle and another for packets whose deadlines are not imminent. Finally, the other two priority-level queues are for connections that are undergoing testing and new connections that cannot be accepted by the BS and need to be admitted by the OLT.

In the proposed architecture, the ONUs are connected to two OLTs. Each set of ONU streams is served through one of the two OLTs; hence, the ONU should have two sets of priority-level queues: one for each OLT. In addition, the ONU stores a variety of information, including the total data rates of all UGS connections, the total minimum data rates of all ertPS connections, and the total mean data rates of all rtPS connections. This information is updated when a new connection is admitted by the BS and when one of the running connections completes service.

The ONU sends a bandwidth request to each OLT. Specifically, the bandwidth request is sent in a report message, as demonstrated in Figure 3.5. In addition to containing the current data size for the ONU, the report message indicates the predicted size of the arriving rtPS and ertPS data streams, as shown in Section 3.4.2. Hence, the ONU sends two report messages: one to each OLT. The report messages broadcast to both OLTs and each OLT receives the message destined to its MAC address.

Each OLT grants bandwidth to the ONU, which divides the bandwidth among priority-level queues by the scheduler, as previously explained in Section 4.3.1.

5.4.3 Bandwidth Allocation of OLT

The OLT BA has two main parts: the first part allocates bandwidth among the ONUs and second part reserves the required bandwidth on the ring.

Bandwidth Allocation of OLT in EPON

To allocate bandwidth among the ONUs, each OLT, primary and secondary, executes the Bandwidth Allocation algorithm similarly to that of the subOLT in the EPON-WiMAX, as shown in Section 3.4.3. First of all, the cycle time of the EPON segment is set to satisfy the required frame size of all BSs attached to ONUs in the segment. At the same time, the data rate corresponding to this cycle time should be sufficient for serving all streams in the segment. The cycle time is divided into two sub-cycles, one for each OLT. Hence:

$$T_{EPON\_cycle} = T_{Pri-OLT\_sub\_cycle} + T_{Sec-OLT\_sub\_cycle} \tag{5.1}$$

where each sub-cycle of $T_{Pri-OLT\_sub\_cycle}$ and $T_{Sec-OLT\_sub\_cycle}$ satisfies both delay and bandwidth requirements for streams served through its normally-functioning OLT. Thus, the length of each sub-cycle is related to the frame sizes required by streams that are served by this OLT:

$$T_{OLT\_sub\_cycle} = \begin{cases} \eta * \min(F_l) & \forall(streams\ served\ by\ OLT) \quad if\ OLT\ work \\ 0 & \quad if\ OLT\ fail \end{cases} \tag{5.2}$$

where η is a constant that depends on the ratio between the BS data rate and the rate for the of fiber connection of the OLT.

After the setting of cycle time, OLTs allocate bandwidth as follows:

a. First, the OLT assigns the basic bandwidth part for each ONU. This part is the sum of the bandwidth requested for UGS, the minimum required bandwidth for ertPS, and the bandwidth required to send rtPS packets with deadlines in the next cycle.

b. Then, the OLT tries to satisfy the bandwidth requests for ertPS, rtPS, the predicted ertPS and rtPS, nrtPS, interim connections, new connections, and BE requests.

c. After assigning all requests to all queues, any remaining bandwidth is divided among the ONUs according to their total request weight.

The OLT allocates bandwidth among the ONUs according to its available capacity. Specifically, the available bandwidth consists of the minimum of the front bandwidth, which is based upon the capacity of the fiber that connects the OLT to ONUs, and the bandwidth that the OLT can allocate over the RPR-ring network.

Bandwidth Allocation of OLT over the ring

According to the network operation in Section 4.1.6, when a new stream needs to be established in an EPON segment, the details of the stream are sent to both the Pri- and Sec-OLT. Hence, both OLTs contain sufficient information about all streams run in the segments. According to this information, each OLT allocates part of its total capacity for the EPON segment on the ring network. In general, the OLTs reserve bandwidth on the ring as follows:

- Each OLT tries to reserve bandwidth on the ring for non-fairness eligible (NFE) traffics. as no reservation is required for fairness eligible (FE) traffics, which are served through the amount of unreserved bandwidth that the OLT can use.

- In order to prevent the starvation of FE traffic, the OLTs reserve a maximum of $(1-\delta)$ of the ring capacity, where δ of the ring capacity is left for FE traffic.

- Each OLT reserves C_{OLT_min} on the ring, which is

$$C_{OLT\_min} = \min(B_{OLT\_req\_min}\ ,\ W_{OLT} * C_{Ring}). \tag{5.3}$$

  where $B_{OLT\_req\_min}$ is the sum of bandwidth required for the A0, A, and B_{CIR} classes. These bandwidths are mapped to the bandwidth requested for UGS, the minimum bandwidth required for ertPS, and the bandwidth required for sending packets with a short deadline in rtPS queues. The OLT weight (W_{OLT}) is calculated as the ratio of the required OLT bandwidth to the total required bandwidth

$$W_{OLT} = \frac{B_{OLT\_req\_min}}{\sum_{all\ OLTs} B_{OLT\_req\_min}}. \tag{5.4}$$

  C_{Ring} is the total data rate available over the ring.

- The remainder data rate available (C_{Ring_rem}) over the ring is the sum of the unreserved data rate and the unused bandwidth of all OLTs

$$C_{Ring\_rem} = C_{Ring\_un\_resv} + \sum_{all\ OLTs} B_{OLT\_unused}. \tag{5.5}$$

  This is divided among the OLTs to serve FE traffic according to the weight of the FE traffic for the OLT; hence

$$C_{OLT\_FE} = \frac{B_{OLT\_FE\_Size} * C_{Ring\_rem}}{\sum_{all\ OLTs} B_{OLT\_FE\_Size}}. \tag{5.6}$$

  where $B_{OLT\_FE\_Size}$ is the size of all FE traffics of the OLT

- The total bandwidth for each OLT is

$$B_{OLT} = C_{OLT\_min} + C_{OLT\_FE}. \tag{5.7}$$

- The total capacity (C_{EPON}) allocated for each EPON segment over the RPR-ring is the sum of bandwidths allocated to its Pri-OLT and Sec-OLT:

$$C_{EPON} = B_{Pri-OLT} + B_{Sec-OLT}. \tag{5.8}$$

- The C_{EPON} on the ring is composed from αC_{EPON} due to the Pri-OLT and the $(1-\alpha)C_{EPON}$ due to the Sec-OLT. The α ratio depends upon the traffic serviced by each OLT; this ratio can be changed in the case of failure, as some traffic may be rerouted between OLTs.

5.5 Performance Analysis of the Proposed Solution

This section will utilize simulation experiments to evaluate the performance of the proposed architecture implementing the suggested MAC protocol. Furthermore, the experiments will verify the effectiveness of the proposed MAC protocol. In the simulation, we apply the following assumptions:

(1) Each SS is equidistant from the BS.

(2) A line of sight is available over each wireless link.

(3) All wireless channels are error free.

(4) In the EPON segments, each ONU is equidistant from the OLT(s).

(5) The OLTs are equally spaced over the ring, and the EPON segments are equally distributed around the ring.

(6) The RPR standard ring nodes are neither the source nor the destination of data; hence, they do not reserve any bandwidth over the ring.

(7) The arrival of service flow occurs randomly with uniform distribution throughout the simulation, and the lifetime of each stream is chosen randomly with uniform distribution between the minimum lifetime and the maximum lifetime.

Specifically, we will test the system performance in two scenarios:

(1) Regular operation - in this scenario, the sum of the required data rates for all running streams does not exceed the system capacity. This experiment aims to test the connection level of the QoS enforcement capability for the proposed MAC protocol. Particularly, we hypothesize that

   (a) The maximum delay of any connection is less than the maximum latency constraint of the connection

   (b) The average throughput of any connection is no less than its minimum reserved data rate or equal to the offered rate of this connection

(2) Overloaded network - in this scenario, the sum of the required data rates for incoming streams can exceed the system capacity. Accordingly, this experiment aims to test the performance of the admission control for the proposed MAC protocol. In order to further test the effectiveness of the admission control, we will also change the delay requirements of the incoming streams while maintaining the required data rates to measure the effect of changing the frame duration and cycle time. Specifically, we hypothesize that

   (a) The proposed MAC protocol demonstrates effective bandwidth utilization

   (b) The stream rejection can be minimized by changing the frame duration and cycle time according to the delay requirements

5.5.1 Un-integrated and Un-protected System (UN-IRPEW)

In order to highlight the advantages of the proposed architecture and MAC protocol, we also simulated another system that we refer to as Un-integrated and Un-protected RPR-EPON-WiMAX (UN-IRPEW). This UN-IRPEW system merely implements the standard specifications of RPR, EPON, and WiMAX without any integration among them. Moreover, the architecture of the UN-IRPEW system does not implement the protection scheme. In general, the key properties of this UN-IRPEW system include:

(1) Each EPON segment is connected to the ring network through only one OLT.

(2) There is no integration between the MAC protocols of RPR, EPON, and WiMAX. Rather, each MAC protocol is run separately, and the MAC protocols of EPON and RPR serve WiMAX streams in the same way they serve the data from individual users.

(3) All streams are only admitted through the WiMAX part of the network. Requests for admission are granted on a first-come-first-serve basis.

(4) In WiMAX, the frame duration cannot be changed to satisfy the delay requirements of a connection.

(5) The schedulers of WiMAX and EPON are station-based schedulers. Accordingly, they schedule all possible packets of a station in its assigned time slot and then schedule packets for the next station.

(6) When this system allocates bandwidth, it does not predict future incoming data for time-sensitive traffic.

5.5.2 Simulation Model

To simulate the proposed architecture and the suggested MAC protocol, we used NS-2 simulation software [45]. Specifically, we used the NS-2 WiMAX module developed by The National Institute of Standards and Technology [46] as the basis for our developed WiMAX module, as seen in Appendix A.2. Also, we created modules to simulate both EPON and RPR in NS-2, as demonstrated in Appendices A.3 and A.4. To obtain the required measure, we simulated the network in Figure 5.3 for the proposed architecture, referred to as IRPEW, and the network in Figure 5.4 for the other architecture, named UN-IRPEW.

Each network consists of 4 EPON segments connected by an RPR-ring that has 10 nodes. Specifically, each EPON segment has 4 ONU/BSs connected to OLT(s) through 10 Gb/s fiber optic. In our architecture, each segment is served through two OLTs, but no OLT serves more than one segment. Conversely, each EPON segment

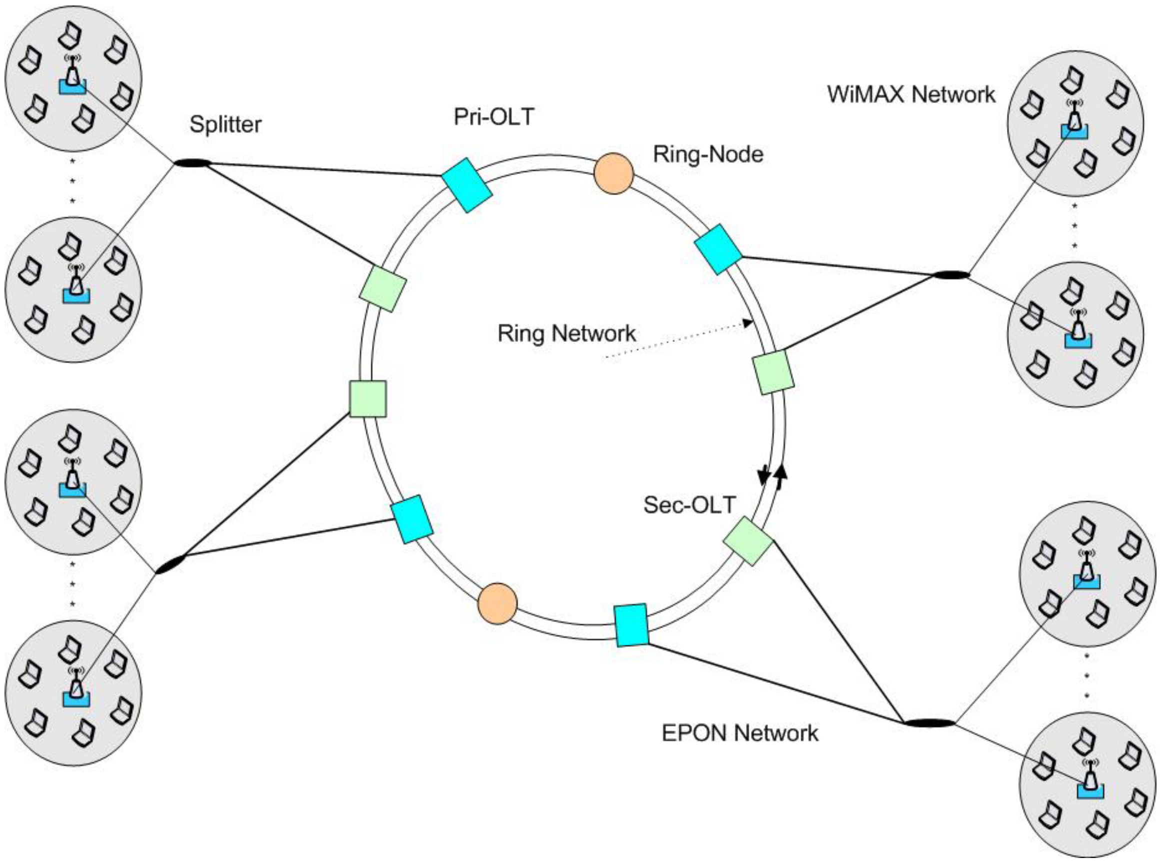


Figure 5.3: Network model of the proposed architecture

in the other architecture is served through only one OLT. In the WiMAX section of these networks, each BS serves 4 SSs and each SS has 7 UGS, 8 ertPS, 7 rtPS, 9 nrtPS, and 5 BE connections. Although the proposed MAC protocol includes both uplink and downlink directions, in the simulation model, we test only the uplink part which is the most critical; hence, all connections are in the uplink direction, originating from each SS.

In the simulation, WiMAX PHY is OFDM-TDMA, and we use packets with a fixed size of 320 bytes. The QoS parameter settings of the service types are listed in Table 5.1.

At the beginning of the simulation, the frame duration of the WiMAX and the cycle time of EPON are set to 5ms and 20ms, respectively. In the proposed system, the ratio between the frame duration and the cycle length is maintained if the frame

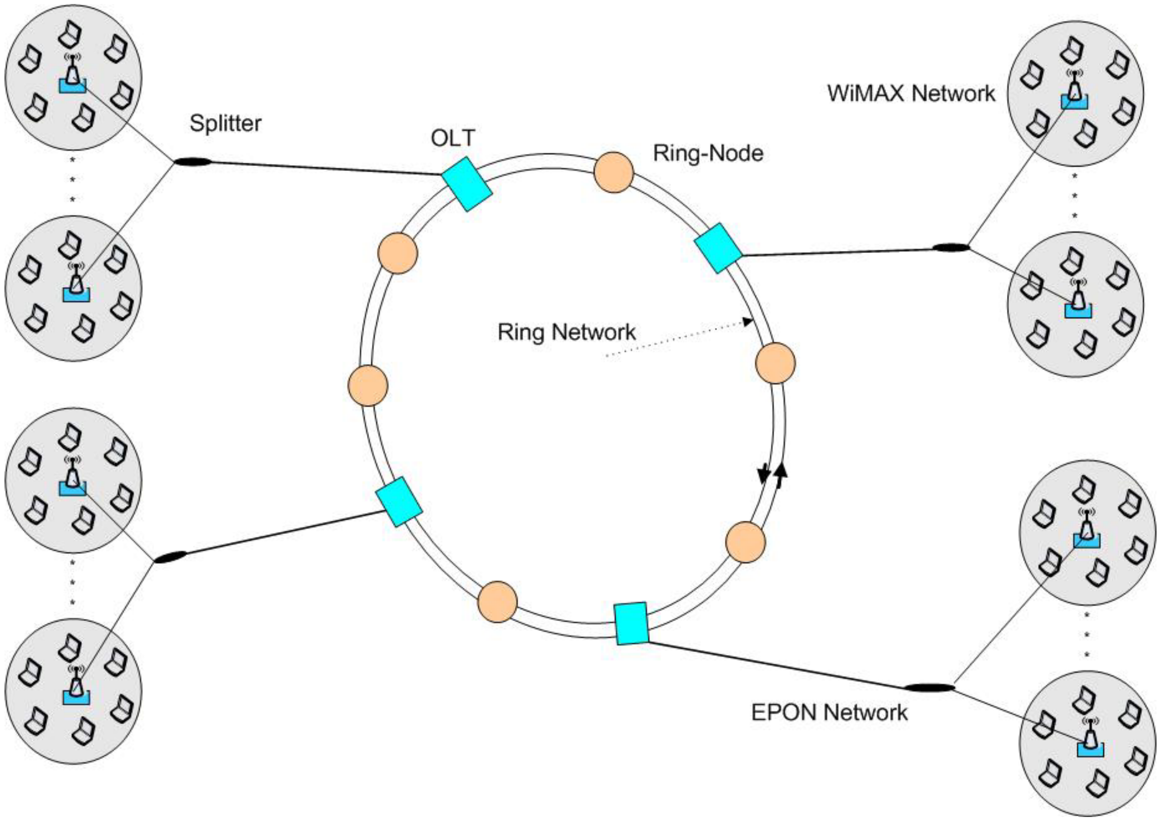


Figure 5.4: Network model of un-integrated RPR-EPON-WiMAX architecture

duration is changed to meet the delay requirement.

The NS-2 built-in exponential traffic model with parameters in Table 5.1 is applied to simulate the traffic flow offered to all connections, except for UGS ones, which are simulated as CBR models. The run time for each simulation experiment is 15 seconds, and each experiment runs 5 times. Thus, the results are observed as the average outcome of these runs.

5.5.3 Results and Discussion

5.5.3.1 Regular Operation

In this scenario, we run the simulation to test the compliance of measured service parameters for each service type with predefined QoS parameters. Specifically, for two service types, UGS and rtPS, we measure the average throughput and compare

Table 5.1: QoS Parameter Settings for the RPR-EPON-WIMAX Simulation

	UGS	**ertPS**	**rtPS**	**nrtPS**	**BE**
Offered rate (Mbps)	1.0	1.4	2.3	1.5	2.3
Max sustained rate (Mbps)	0.5	1.0	1.0	1.0	1.0
Min reserved rate (Mbps)	0.5	0.5	0.5	0.5	N/A
Max latency (s)	0.6	0.4	0.15	N/A	N/A

them with the minimum data rate for each service type. Moreover, we measure the average delay in comparison to the maximum latency, and we assess the maximum delay to ensure that no packet is delayed more than its allotted limit. Finally, the total throughput and network utilization are measured to indicate the extent to which network resources are used efficiently.

Figures 5.5 and 5.6 illustrate the average throughput of the UGS, the highest priority service type, and the rtPS, the third-level priority service type. In particular, the graphs demonstrate that

(1) In both graphs, IRPEW provides more throughputs for service types than UN-IRPEW. However, when the network has a light load, as shown in Figure 5.5, the UGS throughput in IRPEW is slightly lower than that of UN-IRPEW; this discrepancy is due to the overhead introduced by IRPEW.

(2) IRPEW is still capable of ensuring the minimum reserved traffic rate of the rtPS and UGS connections. As demonstrated in Figures 5.5 and 5.6, the throughput curves of both service types in IRPEW are maintained above the minimum reserved traffic rate for each service type. However, this is not the case with UN-IRPEW, as the throughput of rtPS falls under the minimum required data rate, as shown in Figure 5.6.

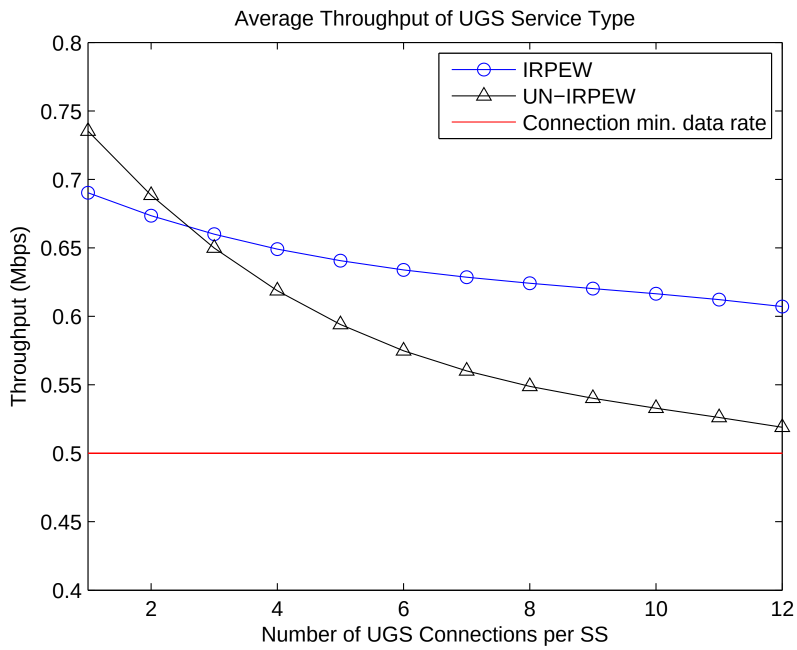


Figure 5.5: Average throughput of UGS service type in regular operation.

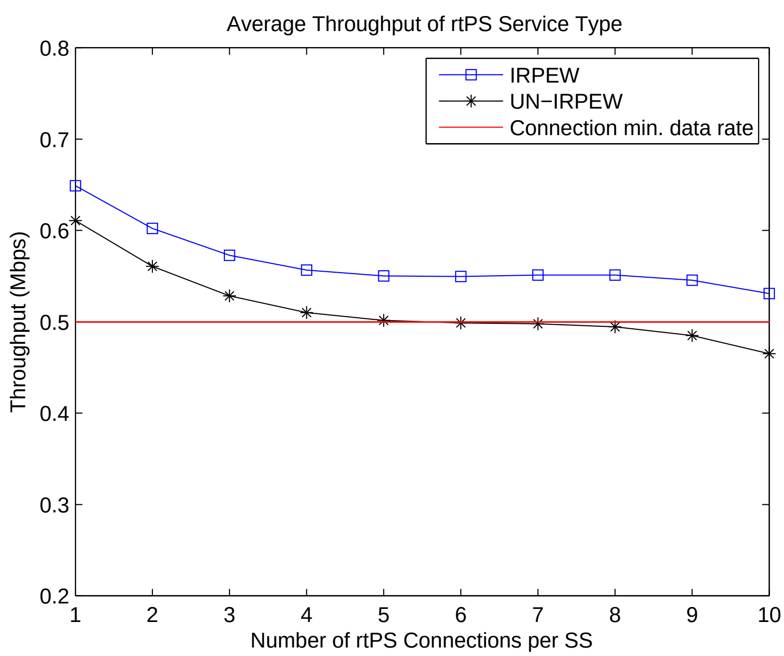


Figure 5.6: Average throughput of rtPS service type in regular operation.

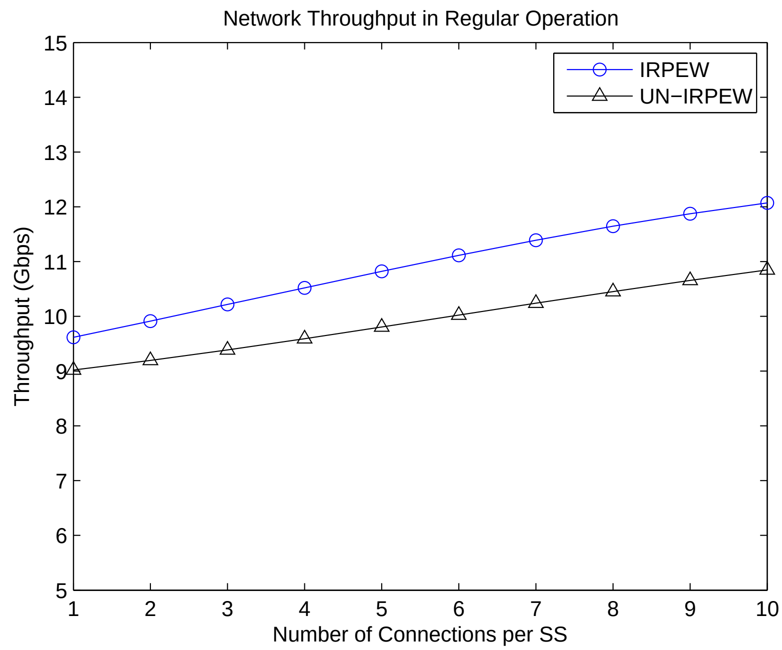


Figure 5.7: system throughput in regular operation.

Some observers may believe that IRPEW maintains the required data rates for UGS and rtPS but not for other service types. However, Figure 5.7 shows that IRPEW provides a higher throughput for the entire system than UN-IRPEW. Furthermore, as Figure 5.8 demonstrates, IRPEW utilizes the network bandwidth more efficiently than UN-IRPEW. Hence, even though IRPEW does not necessarily maintain the required data rates for other service types, it nevertheless provides the best possible service. Moreover, Figures 5.7 and 5.8 prove that although IRPEW introduces additional overhead, especially in the scheduler, as many gaps are inserted between the data, it improves the efficiency of network resource utilization.

Figure 5.9 shows the delays of the UGS service type, and Figure 5.10 illustrates the average delay of the rtPS type. Although the average delays of UGS in both the IRPEW and UN-IRPEW systems are below the maximum latency of the service type, the maximum delay in UN-IRPEW exceeds this limit. As a result, some packets exceed the permitted delay for this service, potentially rendering them useless.

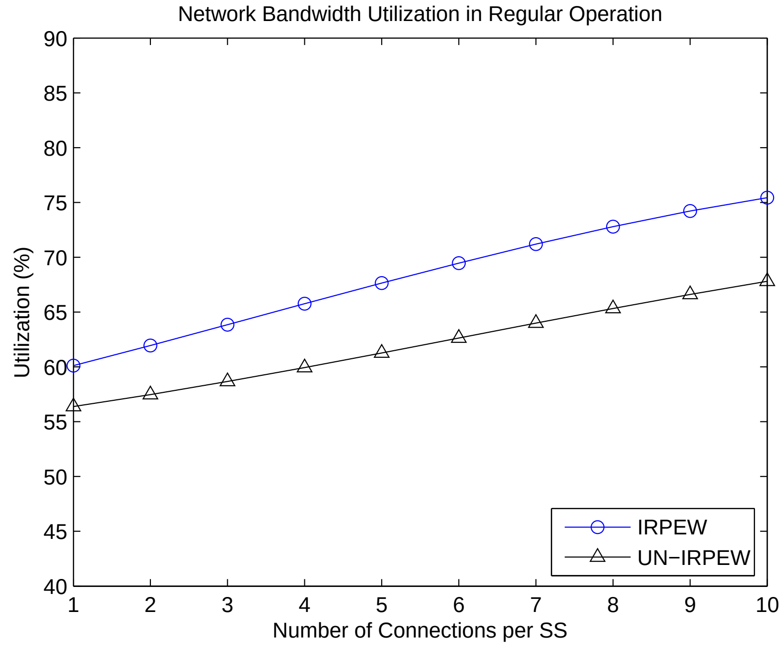


Figure 5.8: Network Bandwidth Utilization in regular operation

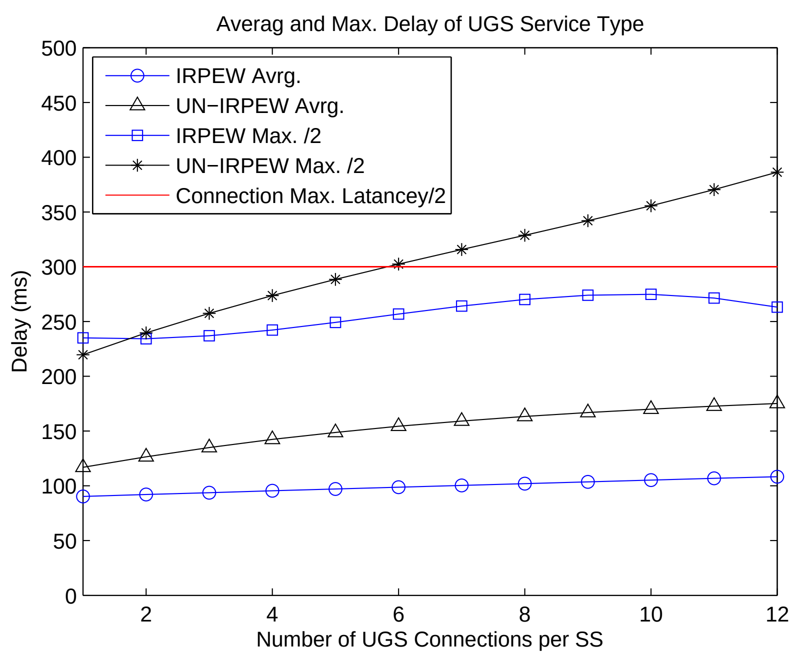


Figure 5.9: Delay of UGS service type in regular operation

Figure 5.10 demonstrates that unlike UN-IRPEW, IRPEW keeps the average delay of rtPS under its limit. Hence, after a specific point of network loading, UN-IRPEW does not satisfy the QoS requirement for rtPS, while IRPEW satisfies this QoS requirement over a wide range of network loads. Moreover, the graph shows that while IRPEW can still satisfy the QoS requirement for increased network loading, the delay in IRPEW increases slightly with a greater load. Therefore, this simulation scenario has verified the hypothesized performance for IRPEW.

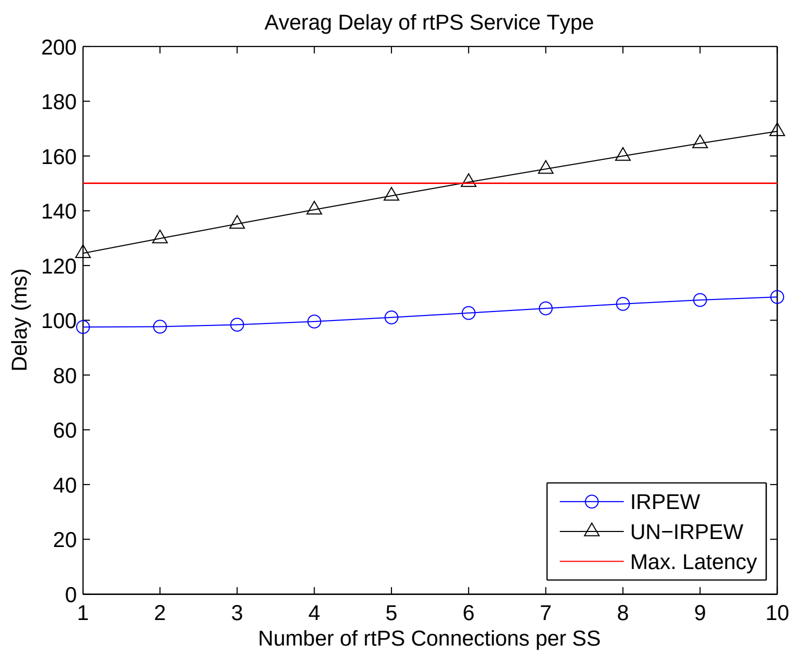


Figure 5.10: Average Delay of rtPS service type in regular operation

5.5.3.2 Loaded network

This scenario evaluates the ability of the MAC protocol to manage the network resources even when the incoming traffic exceeds the allowed data rate of the network. Specifically, we measured how the MAC protocol admits streams in the network in order to utilize the network resources efficiently. Hence, we measured the rejection of all service types and rejection in the most important service types in terms of the number of incoming connection changes. Also, we determined the network bandwidth

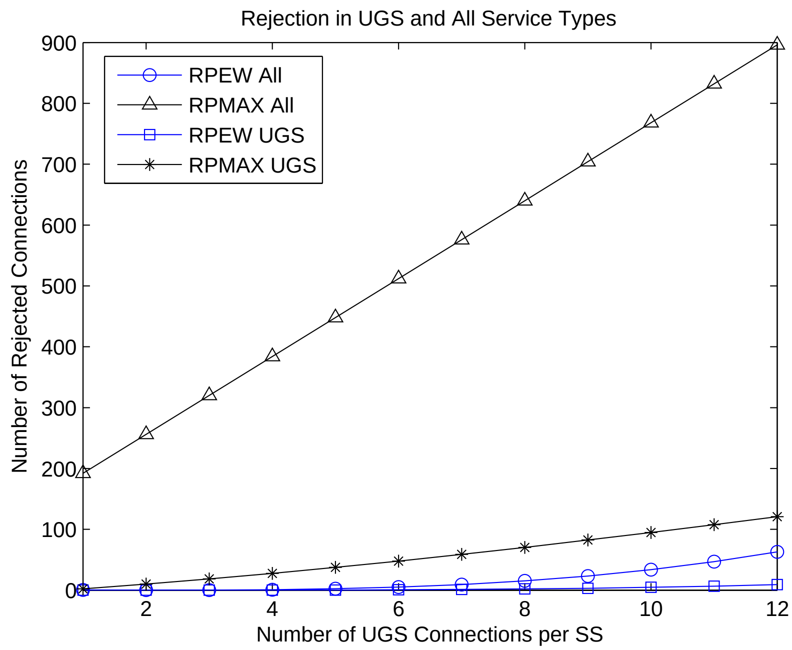


Figure 5.11: Connections Rejection in loaded operation

utilization according to the admitted connections. Finally, we assessed the rejected connections that resulted from delay requirements in order to verify the benefits of changing the frame duration and/or the cycle time to meet delay requirements.

Figure 5.11 shows the number of rejected connections increasing as the required data rate of streams increases. Specifically, the graph focuses on UGS, the service type with highest priority, to verify how the two systems manage the priorities of various service types. The figure demonstrates that under the same conditions of network loading, IRPEW admits more UGS streams than UN-IRPEW. Moreover, IRPEW does not admit UGS streams on account of other service types; thus, IRPEW admits more streams of all service types. As a result, IRPEW uses network bandwidth more efficiently than UN-IRPEW, as illustrated in Figure 5.12, which visualizes network bandwidth utilization under the same network loading as that in Figure 5.11.

Figure 5.13 shows the network rejection when the required data rate of the incoming streams is kept within the available bandwidth of the network but the delay requirement changes. Specifically, the graph measures the number of rejected connec-

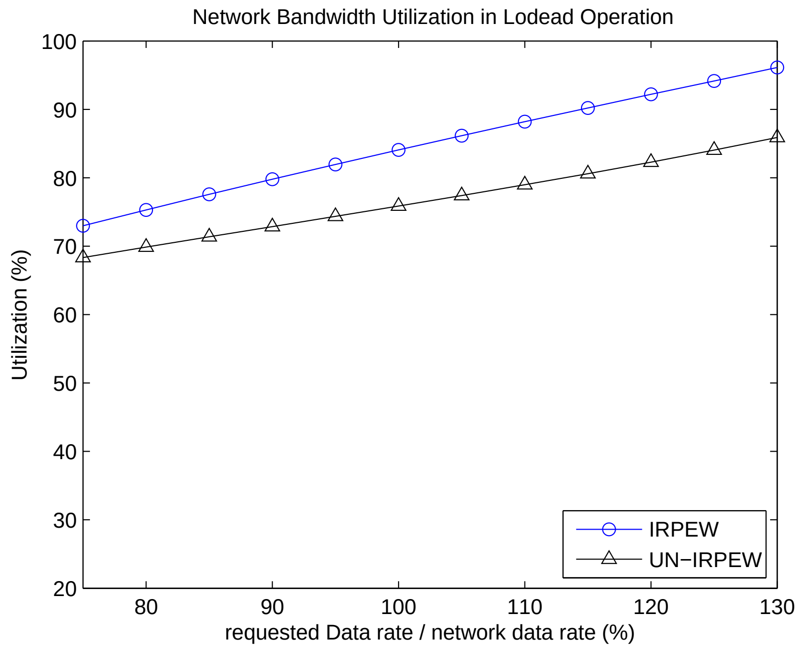


Figure 5.12: Network Bandwidth Utilization in loaded operation

tions as the required delay limit changes compared with the length of the cycle time. Hence, the EPON cycle time and the WiMAX frame duration are related, as explained in Section 5.4.3. In general, UN-IRPEW rejects many more streams than IRPEW. UN-IRPEW may reject a stream because its delay requirement cannot be satisfied even though the available bandwidth can accommodate this stream. However, IRPEW can change the cycle and/or frame setting to satisfy the delay requirement of the stream.

5.5.3.3 Light load penalty

Since the proposed MAC protocol is based on priority queues, it is subject to the *light-load penalty phenomenon* [42], where low priority queues experience a substantial delay when a light load is served by the network. However, the proposed MAC protocol accounts for this phenomenon by predicting the incoming traffic of time-sensitive service types. Hence, low priority service types do not have to wait a long time to be served.

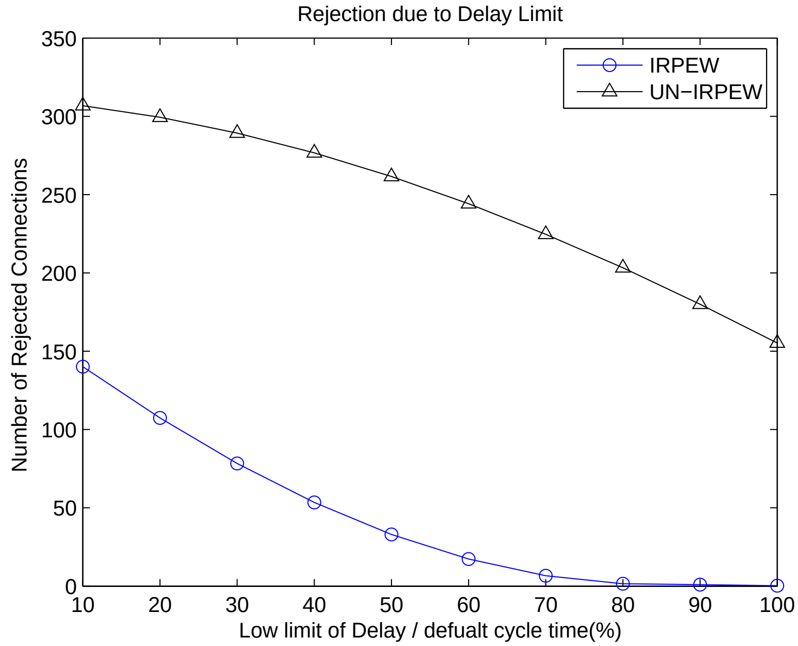


Figure 5.13: Rejection due to violation of delay limits.

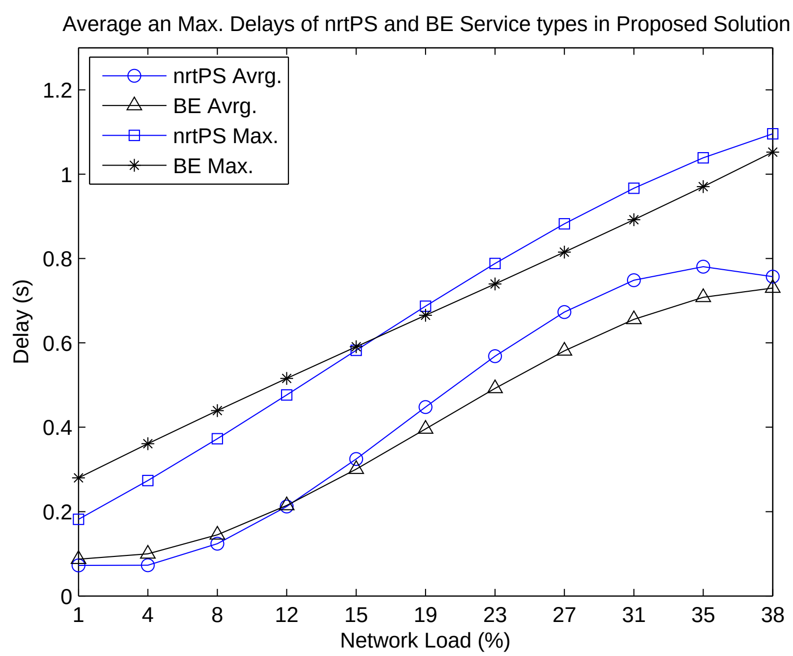


Figure 5.14: Delays of nrtPS and BE service types

Figure 5.14, which presents the delays of nrtPS and BE service types, the lowest priorities in the system, shows that the average and maximum delay of both types are increased as their network load changes from 1 to 38% of the total network load. Hence, the proposed MAC protocol does not suffer the light-load penalty phenomenon. Moreover, Figure 5.14 indicates the ability of the proposed MAC protocol to avoid BE traffic starvation. After a specific point, the network loading delays of BE traffic goes below that of nrtPS traffic, which is a higher priority. This phenomenon results from the fact that the MAC protocol reserves a quota of system bandwidth for BE traffic. If the delays of BE are required to be higher than those of nrtPS, this phenomenon can be controlled by decreasing the BE quota.

5.6 Summary

In this chapter, we presented the MAC protocol for our proposed RPR-EPON-WiMAX architecture from the previous chapter. First, we provided reasons as to why the MAC protocol was necessary and explained its general specifications. Subsequently, we presented the proposed admission control, which is distributed over the BS of WiMAX and the OLT that connected the EPON to the RPR ring. The proposed AC admits streams in one or two steps and considers the network state in order to ensure that the newly admitted stream does not affect the running streams. Furthermore, we presented the Dynamic Bandwidth Allocation, which is implemented in the BS, ONU, and OLT. The DBA enables each connection's contracted QoS parameters to control the service provided to the connection, which ensures the end-to-end connection QoS guarantee. Lastly, we utilized simulations to evaluate the performance of the proposed MAC protocol running on the suggested architecture. The simulation results have firmly verified the expected performance of the proposed solution.

Chapter 6
Conclusion and Suggestions

In this thesis, we have conducted a preliminary examination of Optical-WiMAX hybrid networks and the QoS provisioning for traffic service types over these networks. This chapter briefly concludes the discussions from the previous chapters and proposes possible research extensions based on this work.

6.1 Contributions

Existing literature has studied the EPON-WiMAX hybrid network as an access network solution due to its attractive characteristics. In Chapter 3, we proposed a solution for the EPON-WiMAX hybrid access network, including the architecture and a MAC protocol. Consequently, we concluded that suitable network architecture is a key factor in the effectiveness of the proposed solution. Also, the compatible MAC protocol is important for effectively utilizing the advantages of the architecture to achieve the best performance for the hybrid network. In particular, the powerful EPON-WIMAX hybrid network architecture should be scalable, reliable, support packet routing and forwarding, enable smooth protocol adaption and allow QoS support for efficient bandwidth sharing. Our proposed architecture provides reliability by deploying a protection mechanism in the critical part of the architecture: the OLT and its feeder fiber in the EPON. As a result of this deployment, the architecture contains a high fault tolerance against node and fiber failure. Moreover, the proposed architecture extends the coverage area of the hybrid network and makes the network accessible to more end users in both urban and rural regions. The integration of the architecture's end points, the WiMAX's BS and the EPON's ONU, in a one box and according to a well studied technique provides the ability to effectively share the

network bandwidth. Also, this integration provides a good protocol adaption, which enables the MAC protocol to support end-to-end QoS over the architecture.
Chapter 3 also introduces the joint MAC protocol, emphasizing the importance of considering the entire network architecture in the MAC protocol and distributing the functionalities of this protocol among the network parts. Furthermore, the necessary cooperation among the parts of the MAC protocol is examined in order to improve the performance of the network. In particular, the process of distributing the Admission Control results in an admission scheme that efficiently utilizes the resources of the network while it also satisfies the required QoS of the connections. By implementing the bandwidth allocation in a multi-level manner, the end-to-end QoS of connections over the network is guaranteed. Finally, the process of scheduling packets from stations based on service types assists in satisfying the QoS of connections according to the sensitivity of their services.

Since EPON-WiMAX is an approved solution for the access network and RPR is a good candidate for the metro network, the integration of RPR, EPON, and WiMAX is a viable solution for metro-access network bridging. In Chapter 4, we proposed the architecture for the RPR-EPON-WiMAX hybrid network and suggested a scheduler and routing algorithm for the proposed architecture. Accordingly, we emphasized the conclusions from Chapter 3, stating the importance of the suitable architecture for the hybrid network and its effect on the network performance. In addition, we emphasized that all parts of the architecture should be at the same level of reliability. Although RPR is reliable against node and connection failure and the reliability of WiMAX has no significant impact on the system, the poor reliability of EPON can result in a low reliability for the entire architecture. Hence, the proposed architecture improves the reliability of the network by increasing the reliability of the EPON section. In order to maximize the advantages of the proposed architecture, the suggested routing mechanism in Chapter 4 considers the conditions over the entire network while selecting the route through both the WiMAX and optical parts in a way that minimizes the delay and balances the load. While each hop in the route should select best available path, it should also consider whether or not this path leads to the best overall route. Based on our study of the proposed scheduler, we learned that it is important to map among the service classes so that they are unified over the entire architecture.

In Chapter 5, we proposed a MAC protocol for the RPR-EPON-WiMAX architecture. The proposed MAC protocol includes Dynamic Bandwidth Allocation and Distributed Admission Control; in addition, the protocol aims for compatibility with the architecture in order to maximize its performance. Furthermore, Chapter 5 examines the effective distribution of MAC protocol functionalities over the parts of the architecture. Also, it examines the cooperation among MAC protocol components as well as their cooperation with the scheduler and the routing protocol for the architecture. Although the scheduler inserts many gaps between traffic data, resulting in bandwidth waste, its cooperation with the MAC protocol results in effective bandwidth utilization. Similar to Chapter 3, Chapter 5 concludes that the MAC protocol's flexibility in setting its parameters results in a strong utilization of network resources. Specifically, network utilization is enhanced by the admission control's ability to change the WiMAX frame duration and/or the EPON cycle time to admit a stream while bandwidth is available.

6.2 Future Work

In this research work, we proposed, implemented and evaluated several solutions for Optical-WiMAX hybrid networks and QoS provisioning over these networks. This section proposes possible research extensions as future directions for this study.

1. In Chapter 3, we proposed two architectures for EPON-WiMAX networks and a proposed MAC protocol for the OOW architecture. Future work will suggest the MAC protocol for the OWW architecture.

2. The MAC protocols in this thesis only consider WiMAX networks that are free of channel errors. However, future work can propose a MAC protocol that is concerned with WiMAX channel errors, especially in the case of poor channels that can dramatically affect the OWW architecture performance for EPON-WiMAX networks.

3. In the proposed solutions, only the PMP mode of WiMAX is considered. Solutions involving the mesh WiMAX, including the architecture and the MAC protocol, need to be studied, especially since network management and resource allocation is different in the mesh mode. Specifically, these solutions are more suitable for rural regions.

4. An RPR-EPON-WiMAX solution that employs WDM EPON can be examined, as the proposed solution in this thesis focuses mainly on TDM EPON.

5. Since some literature proposes the PRP-WIMAX integration, a comparative study is needed to examine the respective integration complexities of RPR-EPON-WiMAX and RPR-WiMAX in order to determine which of the two hybrid networks yields the best performance.

6. In this thesis, the performance of the proposed solutions is evaluated through the simulation, and the mathematical analysis of these solutions can be examined.

7. This thesis tries to maintain the QoS that are provided by WiMAX over the integrated network. Conversely, future studies can attempt to maintain EPON QoS over EPON-WiMAX networks or RPR QoS over RPR-EPON-WiMAX networks.

8. A framework that studies the mechanisms of QoS enabling in Optical-WiMAX networks can be proposed. In particular, these mechanisms should concentrate on the following aspects:

   - How can QoS mechanisms available in each standard be integrated to implement QoS mechanism(s) for hybrid networks?
   - What is the best mapping between services queues in each integrated standard?
   - What is the best mapping between services types in WiMAX and Classes of Services (CoS) in EPON? Specifically, which service type in WiMAX associates with which header type of CoS in EPON when encapsulated

WiMAX packets in the EPON frame make these packets scheduled correctly by the bridge (switch) in EPON network? Also, the same question can be explored when considering EPON and RPR.

- What is the ideal way to integrate in DiffServ and IntServ?
- What is the best number for service queuing in EPON as a middle tier between RPR and WiMAX?
- Which mechanism is better for making QoS: station-based or service-type based?
- How does each service type request or grant its bandwidth requests?
- What is the best bandwidth allocation and scheduling mechanism to guarantee QoS?

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Appendix A
Simulation Tools

This Appendix provides an overview of the simulation tools used in this thesis work. It starts with the description of the simulation tool namely NS-2 network simulator. Then, it describes models that we devoloped to simulate WiMAX, EPON, and RPR in NS-2. Finally, the appendix provides some common details on simulation runs carried out in the thesis work.

A.1 Network Simulation NS-2

This thesis work uses the second version of, free open source,“Network Simulator” (which is widely known as NS-2) for simulative network analysis. NS-2 provides benchmark support for simulations on a wide variety of applications, traffic models, and protocols on both wired and wireless networks. NS-2 written in C++ with an OTcl interpreter and uses object oriented design approach. It uses a discrete event simulation technique to carry out network simulations. Discrete event simulation is generally applied to model a system that changes its states (of interest) instantaneously at discrete points of time whenever events occur. In this system, events, which occur at random instants of time, are arranged in sequential order according to their time of occurrence, with most imminent event as the head of the list.

To perform simulations in NS-2, details of simulation are provided through a script written in tool command language (Tcl). The Tcl script will be an input to the OTcl interpreter which is the fore end of NS-2. The actual simulation is carried out in the back end software written in C++. The main objective of this OTcl/C++ split language programming is to derive the advantages of both languages [52]. The code written in C++ runs fast but any small changes to the code requires compilation and linking, which takes considerable amount of time. OTcl is just an interpreter which is convenient for such small changes such as reconfiguration of network scenarios.

Many documents in [45] about NS-2 description and how it works and how a models can be implemented in NS-2. Good tutorial about using Ns-2 is provided in [53]. A set of good examples of simulating in NS-2 and how trace files can be analyzed in order to obtain the required result can be found in [54].

NS-2 includes many of networks environment from both Wired and Wireless worlds. Unfortunately, NS-2 does not implement WiMAX, EPON, or RPR networks. We developed our own models to simulate these networks in NS-2. The EPON and RPR models implement the MAC layers of these Standards, while the WiMAX model implements the Physical layer in addition to the MAC layer.

A.2 WiMAX model

The developed WiMAX model is based on a model developed by *The National Institute of Standards and Technology* [46] which is based on the IEEE 802.16 standard (802.16-2004) and the mobility extension 80216e-2005. This model implements the following features of the WiMAX standard:

- WirelessMAN-OFDM physical layer with configurable modulation
- Time Division duplexing (TDD)
- Management messages to execute network entry (without authentication)
- Default scheduler providing round robin uplink allocation to registered Mobile Stations (MSs) according to bandwidth requested
- IEEE 802.16e extensions to support scanning and handovers
- Fragmentation and reassembly of frames

But among the missed features which are important to this thesis work:

- Admission Control (AC)

- QoS service types defined in the standard
- Scheduler that care about QoS of service flows
- ARQ (Automatic Repeat Request)
- Periodic ranging and power adjustments

Also the implemented Bandwidth Allocation and flow handler in this model does not fit the need of this thesis work.

In our developed model we add some of missed features and replaced the bandwidth allocation algorithm with a suitable one. Specifically, developed model implements QoS service types, admission control algorithm, Qos scheduler, and Bandwidth allocation mechanism.

A.2.1 QoS service types

the model implements the five service types defined in the IEEE 802.16 standard: UGS, ertPS, rtPS, nrtPs, and BE. In order to implement these service types, the model add a class that specify a QoS of a flow (ServiceFlowQoS class) which determin the required parameters of flow in terms of Delay, Data rate, Burst length, and jitter. ServiceFlowQoS is embedded in the ServiceFlow member of the Connection Class which implements connection in the model. In addition, model assigns a priority level to the connection according to the QoS of its ServiceFlow member. To maintain the required QoS of a connection, the classifier in the model is modified to classify packets according to QoS parameters of the flow to which they belong. Both BS and SS have five priority queues to buffer packets of different service types.

The QoS level of the flow are specified at the setup time of this flow. below is how to add ugs flow in Uplind direction with Minrate, Maxdelay, and Burst, between bass station and SS

```
[BS set mac_(0)] add-flow up UGS Minrate Maxdelay Burst cid
[ss get_addr]
```

A.2.2 Admission Control

The implemented Admission control considers both Data rate and Delay requirements of the flow. When SS requests to add a new flow, AC ensure that the required Data rate can be provided by both SS and BS. In case that Data rate is available, AC checks to ensure that the required delay can be satisfied according the current frame duration. If the delay can be satisfied, flow is accepted. Otherwise, if the frame duration can be changed to satisfy the delay without any QoS violation of running flows, the frame duration is changed and the flow is accepted, otherwise the flow is rejected.

A.2.3 Scheduler

The model implements schedulers for both BS and SS. SS scheduler manages transmitting its data to BS in uplink direction and BS scheduler manages transmitting data to SSs in the downlink direction. The model implements both the station-based scheduler and service-type-based scheduler. In station-based scheduler, each SS assigned a time slot in uplink within which it schedule its data of all service types, may but not necessary based of priority of these service types. In downlink, BS sends all possible data packet to a SS in a slot time dedicated for this SS, and then it moves to the next SS.

In the service-type-based scheduler, each SS assigned up to five time slots in each direction, during each time slot data packets of a specific service type are transmitted.

Time slots assigned to SSs according to Bandwidth Allocation mechanism which implants one of DBA proposed in Sections 3.4.1 and 5.4.1.

Here we only explained our additions to the WiMAX model. Details on these model and which parameters can be configured and how are available in documents of [46]. A complete example of using WiMAX model in the simulation will be provided in A.5.

A.3 EPON model

Unfortunately, none has implemented EPON for Ns-2 yet. Hence EPON model is scratched from zero. This model has two main classes to implement OLT and ONU. These classes implement IEEE 802.3ah standard. Operations in EPON model can be summaries as follows:

- OLT broadcast data packets in the downlink direction, all ONUs receive this data but only ONU with dedicated MAC address forward this data to its client.
- OLT divids the cycle time among ONUs in the uplink direction according their bandwidth demands based on DBA proposed in Section 3.4.3 or 5.4.3.
- In each time-slot in uplink only one ONU can transmit, hence when receive a grant message; ONU sets its start and stop of transmission.
- Scheduling of service types can be done according to station-based or service-type based like what is in WiMAX model.

EPON model is used through `CreateEPON` command in NS-2 . `CreateEPON` takes parameters:

- Two nodes: one is desired node (OLT or ONU) and the other is connecting node.
- MacType: this specifies the desired node is OLT or ONU.
- Delay
- Data rate.

Example in Figure A.1 shows how create EPON segment of OLT and 4 ONUs connected through 1Gb fibers and limit delay to 5 μs.

Using EPON model in practical simulation is provided in A.5.

```
# Parameter for the Epon
set opt(qsize) 100
set opt(bw)    10000Mb
set opt(delay) 0.005 ms
set opt(ifq2)  Queue/DropTail
set opt(mac)   Mac
set opt(olt)   Mac/802_3ah/OLT
set opt(onu)   Mac/802_3ah/ONU
set opt(chan2) Channel

for {set i 0} {$i < 6} {incr i} {
  set Cnodes($i) [$ns node]
}

set olt [$ns CreateEPON $Cnodes(1) $Cnodes(0) $opt(olt)
$opt(delay) $opt(bw)]

for {set i 2} {$i < 6} {incr i} {
  set onu_epon([expr &i - 2]) [$ns CreateEPON $Cnodes(&i)
$Cnodes(0) $opt(onu) $opt(delay) $opt(bw)]
}
```

Figure A.1: A Tcl script for create EPON network

A.4 RPR model

Rice group implement RPR model for NS-2 [55] but this implementation has the following limitations:

1. It supports single-queue or dual queue mode. For single-queue mode, access delay timer is not considered, and How to determine if it is first time congested not considered

2. All packets are considered as Class C packets.

3. Routing: There is no real routing actually. All the data packets are forced to go through inner-ring, and control packets are forced to go outter-ring.

4. TTL to congestion is only roughly calculated.

```
CreateRPRRing $Node-no $delay $bandeidth  \
              -QueueMode $opt(queue-mode)\
              -FairMode $opt(fair-mode)\
              -STQSize   $opt(STQ_size)\
              -AgingInterval $opt(aging_interval)\
              -AdvertiseInterval $opt(advertise_interval)]
```

Figure A.2: A Tcl command to create RPR ring

5. Configuration of some parameters like queue size, prop delay, etc. are are fixed values. tcl interface need to be provided to configure these parameters.

   Our model overcomes these shortcomings. Specifically,

- It implements all service Classes defined in IEEE 802.17: A, B, and C classes.
- It implements the routing algorithm proposed in section 4.2.2.
- It provides the required tcl interface for parameter configuration.
- It considers access delay in all operation modes.
- It calculates TTL exactly dependent on the path length between source and destination.

In addition to these improvements, this model gives the RPR ring the ability to connect with other networks. This feature requires the RPR nodes to classify packets depending on their destination to ring packets and out-ring packets. Ring packets are simply send over the ring and the destination of the packet cares about get them and removing them from the ring. For out-ring packets, the gate-in node (source of the packet if it generated from a ring node or the ring-node that firstly receive the packet) needs to specify the best gateway node for the packet and send the packet to the gateway MAC address. Gateway receives and removes packets that originally destined to it, while forward other packet outside the ring.

The RPR is created using `CreateRPRRing` command which takes number of nodes, bandwidth of the ring, queue mode, Fair mode, queue size, aging interval, and advertise interval as parameters as shown in Figure A.2.

Using RPR model in practical simulation is provided in A.5.

A.5 Example of Simulation

A Tcl script for simulating RPR-EPON-WiMAX similar to that in Figure 5.3 in NS-2 is given in Figure A.3. The script First sets the global parameters of simulation between lines 1 - 12. Parameters of the ring part are set between lines 14 - 20. Paremeters setting of EPON are given between lines 22 - 30 of the code. While parmeters of WiMAX and configration of its PHY and scheduler are given in range of 32 - 57 of the code.

The instance of a `Simulator` class is created in line 79 and passed to `ns` variable. Now the variable `ns` can be used to call all the methods of the class `Simulator`. The next line 80 in the code calls for the new trace format to be used. Trace files are set in lines 84 and 86. The new instance of `Topography` is created using the variable `topo` in line 88. The next line 89 loads a flat grid with dimensions 1600×1600. Then addressing type is set for hierarchical routing and domain, cluster, nodes in each cluster, numbers are set between lines 91 - 101. RPR part of the architecture is created in lines 108- 114. OLTs of EPON networks are created in part 138 - 152 and connected to the RPR ring through a group of nodes which created in the range 124-136. Node configuration changed to WiMAX BS in lines 156- 171. Then OUN/BS units are created and connected to OLTs in lines 172 - 202. The node configuration set to WiMAX SS in lines 204 - 207. SSs are created and connected to BSs in lines 209 - 238. Data flows are created and their QoS parameters are set in lines 240 -261.

The procedure `finish` is used to end the simulation by resetting the nodes and closing the trace files. This procedure is scheduled to run given by `at` command in line 263. Any line that starts with # sign is commented and is not part of the simulation. Finally `$ns_ run` starts the simulation.

```
set output_dir  Work/My-RPR-Epon-WiMAX/res/rtps/
set pktsz 320

# set global variables
set gap_size 0.08 ;#compute gap size between packets
set con_start 20
set traffic_start 25
set traffic_stop  40
set simulation_stop [expr $traffic_stop + 15]
#set simulation_stop 2

set opt(bw) 10000Mb

# Parameter for the ring
set opt(queue-mode) DUAL
set opt(fair-mode)  AGGRESSIVE
set opt(STQ_size)   256000
set opt(aging_interval) 0.0002
set opt(advertise_interval) 0.01
set opt(num_stations)  10    ; #nuber of nodes in the ring

# Parameter for the Epon
set opt(qsize)    100
set opt(bw2)      30000Mb
set opt(delay)    0.001ms
set opt(ifq2)     Queue/DropTail
set opt(new)      Mac
set opt(olt)      Mac/802_3ah/OLT
set opt(onu)      Mac/802_3ah/ONU
set opt(chan2)    Channel

# Parameter for wireless nodes
set opt(chan)     Channel/WirelessChannel    ;# channel type
set opt(prop)     Propagation/TwoRayGround   ;# radio-propagation model
set opt(netif)    Phy/WirelessPhy/OFDM       ;# network interface type
set opt(mac)      Mac/802_3                  ;# MAC type
set opt(ifq)      Queue/DropTail/PriQueue    ;# interface queue type
set opt(ll)       LL                         ;# link layer type
set opt(ant)      Antenna/OmniAntenna        ;# antenna model
set opt(ifqlen)   50                         ;# max packet in ifq
set opt(adhocR)   DSDV                       ;# routing protocol
set opt(x)        1600                 ;# X dimension of the topography
set opt(y)        1600                 ;# Y dimension of the topography

# Configure Wimax
WimaxScheduler/BS set dlratio_ 0.2
Mac/802_16 set debug_ 0
Mac/802_16 set frame_duration_ 0.005 ;
Mac/802_16 set queue_length_ 500
Mac/802_16 set client_timeout_ 50 ;#to avoid BS disconnecting the SS

#define coverage area for base station: 500m coverage
Phy/WirelessPhy/OFDM set g_ 0.25
Phy/WirelessPhy set Pt_ 0.025
Phy/WirelessPhy set RXThresh_ 2.025e-12 ;# 500m radius
Phy/WirelessPhy set CSThresh_ [expr 0.9*[Phy/WirelessPhy set
RXThresh_]]
```

```
set EPON_NO 4 ;# number of EPON segments in the network
set BS_No   4 ;# number of BS/ONUs in each EPON segment
set SS_No   4 ;# number of SSs served by each BS

set Wl_n_n [expr $EPON_NO * $BS_No * $SS_No ] ;# No. of wireless nodes
set Wl_n_n [expr $EPON_NO * $BS_No + $Wl_n_n ];

# number of wire nodes ( ring and Epon )
set epon_nodes [expr $BS_No + 2 ]
set W_n_n [expr $EPON_NO * $epon_nodes + $opt(num_stations) ] ;

#defines function for flushing and closing files
proc finish {} {
        global ns tf cf output_dir nb_mn
        $ns flush-trace
        close $tf
        close $cf
      exit 0
}

#create the simulator
set ns [new Simulator]
$ns use-newtrace

#open file for trace
set tf [open $output_dir/out.res w]
$ns trace-all $tf

set cf [open $output_dir/connrcd.tr w]
#create the topography
set topo [new Topography]
$topo load_flatgrid $opt(x) $opt(y)

# set up for hierarchical routing
$ns node-config -addressType hierarchical
;# domain number
AddrParams set domain_num_ [expr $EPON_NO * $BS_No + 1 ]
;# cluster number for each domain
lappend cluster_num 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1

AddrParams set cluster_num_ $cluster_num
# number of nodes for each cluster
lappend eilastlevel [expr $W_n_n + 2 ] 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7
AddrParams set nodes_num_ $eilastlevel

# Create God
create-god [expr $W_n_n + $Wl_n_n ]

set i $opt(num_stations)

#Create RPR
set nodelist [$ns CreateRPRRing $i $opt(delay) $opt(bw2) 0.0.0 \
                -QueueMode $opt(queue-mode)\
                -FairMode $opt(fair-mode)\
                -STQSize   $opt(STQ_size)\
                -AgingInterval $opt(aging_interval)\
                -AdvertiseInterval $opt(advertise_interval)]
```

```
set index_ 0
foreach ssrc $nodelist {
        set nodes($index_) $ssrc
        incr index_
}

set varr $nodes([expr $index_ - 1 ])
set wire_id  $opt(num_stations)

for {set i 0} {$i < [expr $EPON_NO ]} {incr i} {
  set Cnodes($node_idx) [$ns node 0.0.$wire_id]

  $ns duplex-link $Cnodes($node_idx) $nodes($ring_idx) $opt(bw)
$opt(delay) DropTail
  incr ring_idx
  $ns duplex-link $Cnodes($node_idx) $nodes($ring_idx) $opt(bw)
$opt(delay) DropTail
  $varr epon-addr [expr $i + 1 ] [expr $ring_idx - 1 ] $ring_idx
  incr wire_id
  incr node_idx
  set Cnodes($node_idx) [$ns node 0.0.$wire_id]
  incr wire_id

  # Create OLT
  set olt_epon($i) [$ns CreateEPON $Cnodes([expr $node_idx - 1 ])
$Cnodes($node_idx) $opt(olt) $opt(delay) $opt(bw)]
  incr ring_idx
  incr node_idx

  for {set j 1} {$j <= [expr $BS_No - 0 ]} {incr j} {
      set Cnodes($node_idx) [$ns node 0.0.$wire_id]
      $ns duplex-link $Cnodes($node_idx) $Cnodes([expr $node_idx - $j
]) $opt(bw) $opt(delay) DropTail

      incr wire_id
      incr node_idx
  }
}

puts "wired nodee and OLTs created and connected to the ring"

# set node configration to WiMAX BS
$ns node-config -adhocRouting $opt(adhocRouting) \
                -llType $opt(ll) \
                -macType Mac/802_16/BS \
                -ifqType $opt(ifq) \
                -ifqLen $opt(ifqlen) \
                -antType $opt(ant) \
                -propType $opt(prop)     \
                -phyType $opt(netif) \
                -channel [new $opt(chan)] \
                -topoInstance $topo \
                -wiredRouting ON \
                -agentTrace ON \
                -routerTrace ON \
                -macTrace ON  \
                -movementTrace OFF
```

```
for {set i 0} {$i < [expr $EPON_NO - 0 ]} {incr i} {
   for {set j 0} {$j < [expr $BS_No - 0 ]} {incr j} {
      set bs_x [expr $e_x + $xbs * $bs_d ]
      set bs_y [expr $e_y + $ybs * $bs_d ]

     #create BS
     set BS($Bs_c) [$ns node [expr $Bs_c + 1 ].0.0]
     $BS($Bs_c) random-motion 0
     #provide some co-ord (fixed) to base station node
     $BS($Bs_c) set X_ $bs_x
     $BS($Bs_c) set Y_ $bs_y
     $BS($Bs_c) set Z_ [expr $Bs_c * 100 ].0

     #create ONU and attach it to BS
     set onu_epon($onu_idx) [$ns CreateEPON $BS($Bs_c) $Cnodes([expr
$node_idx + $j ]) $opt(onu) $opt(delay) $opt(bw)]

      #inform ONU/BS about serving OLT
     [$BS($Bs_c) set mac_(0)] set-node-olt-addr [$BS($Bs_c) node-addr]
[$Cnodes([expr $node_idx - 2 ]) node-addr]

     $ns at [ expr $Bs_c * 0.1 ] "[$onu_epon($onu_idx) set mac_] set-
olt-h [$Cnodes([expr $node_idx - 2 ]) node-addr] [$BS($Bs_c) node-addr]
"
     incr Bs_c
     incr onu_idx
   }
   set node_idx [expr $node_idx + $BS_No ]
}

puts " BSs and ONUs have been created"

# creation of the mobile nodes
$ns node-config -macType Mac/802_16/SS \
                -wiredRouting OFF \
                -macTrace ON        ;# Mobile nodes cannot do routing.

for {set i 0} {$i < [expr $EPON_NO - 0 ]} {incr i} {
   for {set l 0} {$l < [expr $BS_No - 0 ]} {incr l} {
      #set the channel for BS
      [$BS($Bs_c) set mac_(0)] set-channel [expr $ch_no ]

      for {set k 0} {$k < [expr $SS_No - 0 ]} {incr k} {
         #create SS
         set SS($SS_c) [$ns node [expr $Bs_c + 1 ].0.[expr $SS_c + 1 ]]
         $SS($SS_c) random-motion 0
         #attach SS to basestation
         $SS($SS_c) base-station [AddrParams addr2id [$BS($Bs_c) node-
addr]]

         $SS($SS_c) set X_ $ss_x
         $SS($SS_c) set Y_ $ss_y
         $SS($SS_c) set Z_ [expr $Bs_c * 100 ].0
         #set the channel for BS
         [$SS($SS_c) set mac_(0)] set-channel [expr $ch_no]
         incr SS_c
      }
```

```
            incr Bs_c
            incr ch_no

            if { $ch_no > 7 } { # only channels 0 - 7 defined in WiMAX
               set ch_no 0
            }
            puts "   "
            puts "   "
        }
}

#Create service flows
for {set i 0} {$i < [expr $EPON_NO - 0 ]} {incr i} {
     for {set l 0} {$l < [expr $BS_No - 0 ]} {incr l} {
        for {set k 0} {$k < [expr $SS_No - 0 ]} {incr k} {
           #create ugs flows
           for {set j 0} {$j < [expr $ugs_no]} {incr j} {
                  estab-service-flow $Bs_c $SS_c up ugs [new
Agent/WMUDP] [new Agent/Null] [new Application/Traffic/CBR] 500000
1000000 0.005 0.0005 [$arrival_ value] [$size_ value] $ugs_peer
$ugs_d_ep $src_epon
           }

           #create ugs flows
           for {set j 0} {$j < [expr $nrtps_no - 1 ]} {incr j}  {
                  estab-service-flow $Bs_c $SS_c up nrtps [new
Agent/WMUDP] [new Agent/Null] [new Application/Traffic/Exponential]
500000 1000000 0.005 0.0005 [$arrival_ value] [$size_ value]
$nrtps_peer $nrtps_d_ep $src_epon
           }
        }
    }
}

$ns at $simulation_stop "finish"

# Run the simulation
puts "Running simulation for [expr $Wl_n_n ] mobile nodes..."
$ns run
puts "Simulation done."
```

Figure A.3: A Tcl script for RPR-EPON-WiMAX simulation.

A.6 Summary

This appendix provides an overview of the simulation tools used in this thesis work. Models to implement RPR, EPON, and WiMAx in NS-2 are explained. The network model setup and simulation in NS-2 network simulator is shown through description of Tcl script. The given Tcl script presents examples of traffic source, agent, topology, WiMAX node configuration that are required for simulation. This Tcl script is a configuration file that is an input to the back end network simulator software written in C++. The actual details of simulations are in the back end C++ software which is run time efficient.

Curriculum Vitae

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Publications

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[1] **A**. Ahmed, X. Bai and A. Shami, Chapter 6:"WiMAX Networks" in "Broadband Access Networks: Technologies and Deployments," A. Shami et al (Editors), pp. 117-148, *Springer Science+Business Media* DOI 10.1007/978-0-387-92131-0_6, 2009.

Journal Submission:

[1] **Abdou Ahmed** and Abdallah Shami, "EPON-WiMAX Hybrid Access Networks: Architecture and MAC Protocol," submitted to Journal of Optical Communications and Networking.

[2] **Abdou Ahmed** and Abdallah Shami, "RPR-EPON-WiMAX Hybrid Network: Solution for Access and Metro Networks," submitted to Journal of Optical Communications and Networking.

Refereed Conference Proceedings:

[1] **Abdou Ahmed** and Abdallah Shami, "A New Bandwidth Allocation Algorithm for EPON-WiMAX Hybrid Access Networks," *Global Telecommunications Conference, 2010. GLOBECOM '10. IEEE*, vol., no., pp.1-6, Miami, Florida, USA, December 2010..

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