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A New Bandwidth Allocation Algorithm for EPON-WiMAX Hybrid Access Networks

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***Abstract*—Integration between Ethernet Passive Optical Network (EPON) and Worldwide Interoperability for Microwave Access (WiMAX) is a promising solution for next generation access networks. In this paper, we devise a new architecture framework for EPON-WiMAX hybrid networks that is more reliable and extend the service coverage range. In addition, we propose a new bandwidth allocation algorithm for the proposed architecture that provides per-stream QoS protection, bandwidth guarantee for real-time flows and improves the overall system performance. Through intensive simulations, we show the effectiveness of the proposed architecture and bandwidth allocation algorithm.**

I. Introduction

The complementary features of Ethernet Passive Optical Network (EPON) and Worldwide Interoperability for Microwave Access (WiMAX) make the integration of these technologies a superior solution for access networks [1], [2], [3]. There are several important factors that motivate such integration. This integration takes advantages of the both technologies; such as bandwidth and reliability of optical networks, and the mobility and flexibility of wireless networks.

In [1], [4] authors proposed four architectures for integration of EPON and WiMAX. These architectures include independent architectures, hybrid architectures, unified connection-oriented architectures, and microwave-over-fiber (MoF) architectures. Also they discussed how most of design and operational issues such as: bandwidth allocation and QoS support, network survivability, packet forwarding, handover operation, and network design and planning; can be accessed in these architectures. Integration of EPON and WiMAX were described in [5] and [6] as well. The hybrid networks in [6], [5] consist of a large WiMAX network that transmit its data through a passive optical network. Other types of optical wireless access networks were also proposed in [7], [8]. In theses architectures, a wireless Base Station (BS), can be attached directly to gateways/ONUs and sends data over an Optical Network Unit (ONU) as in the architectures proposed in [1], [6], or can be connected to gateways over through intermediate wireless BSs by taking advantage of wireless mesh networking. For this optical wireless networks, authors mainly discussed the issues of routing, load balancing, packet forwarding, and the placement of wireless BSs in wireless mesh networks.

To date, some scheduling and Bandwidth Allocation mechanisms have been proposed to support QoS and improve performance for delay sensitive traffic in EPON-WiMAX networks [2], [5], [9], [10], [11], [12]. QoS-based Dynamic Bandwidth Allocation (QDBA) [11] is incorporated with the prediction-based fair excessive bandwidth allocation (PFEBA) scheme in EPON to enhance the system performance. In addition to QDBA, the authors in [11] propose a queue-based scheduling scheme that efficiently satisfy the demand for bandwidth request and enhance the efficiency of the system. The DBA scheme in [2] enables a smooth data transmission across optical and wireless networks, and an end-to-end differentiated service to user traffics 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 (SS) level [13]. Bandwidth allocation and the support of different service flow in [12] changed the EPON MAC layer mechanism to adopt connection-oriented MAC layer structure familiar with WiMAX.

In this work, we propose a new architecture for the integrated WiMAX-EPON networks that overcomes the drawbacks of earlier architectures and extend the converge range of the network. A new bandwidth allocation algorithm that supports QoS for different services types is proposed for the proposed architecture.

The remainder of this paper is organized as follows. The new hybrid network architecture is presented in Section II. In Section III, a new bandwidth allocation for the new architecture is described. The performance evaluation of the proposed scheme is discussed in Section IV. Finally, Section V concludes this work and outlines the future work.

II. Proposed Hybrid Network Architecture

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 wireless-optical broadband-access network (WOBAN) architecture [7] consists of a wireless network at the front end, 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 Optical Line Terminal (OLT), located at the CO, with a number of ONUs, which are connected to wireless BSs from the other side. These wireless BSs form the wireless portion of WOBAN.

In the network architecture proposed in [8], the optical backhaul consists of a ring and multiple tree networks. Each tree network connects between one OLT and multiple ONUs. OLTs of all tree networks are connected to the ring network. Each ONU of any tree network is connected to a gateway router of a Wireless Mesh Network (WMN). Both architectures have many advantages, but the common drawback of both architectures is that the entire network is under the same management system; thus, the Central hup/central Office may become the system bottleneck. Moreover, in the event of link or node failures in architecture [7], the optical-wireless loses full or a large portion of network connectivity, where users' traffic will need to be re-routed. Architecture in [8] offers fault tolerance against a single link or node failure but not for two or more failures.

These drawbacks can be addressed by using a distributed management system and by making the architecture more immune against failures. In order to make optical part of the network immune against failures we can use idea of the reliable optical network solution was proposed in [14]. This architecture is known as the *Dual-Router* Architecture. In this architecture, the main access point (MAP) has dual large backbone routers (BRs). BRs collect traffic from access routers (ARs) and send it to other MAPs. Remote access routers are often dual-homed over diversely routed unprotected/protected fiber facilities. As AR-BR links are doubled and there are two routers in each MAP; IP routers can restore traffic under a variety of failures including fiber cuts, and router failures. Instead, if each AR is connected to only a single BR, in the case of link failure the AR will be isolated from the network.

In addition to overcoming the mentioned drawbacks of architectures in [7], [8], there is a need for a hybrid network architecture to extend the network converge distance of optical network beyond the typical 25 km, allowing more end-users to share an OLT link. This can be done by inserting an intermediate network between the backhaul and front end networks. 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 [15]. This will form the Optical-Optical-Wireless (OOW) architecture, where OLT is connected to a group of subOLTs instead of ONUs, and each subOLT performs the functions of OLT in its own network segment. Namely, each subOLT is connected to a group of ONUs and each ONU is connected to a wireless BS (or more). The Optical-Optical-Wireless architecture is shown in Fig. 1.

The splitter in the OOW architecture can be a WDM splitter, TDM splitter, or hybrid WDM/TDM implementation. Although this work is considering TDM splitter in order to simulate the OOW architecture and measure its performance, we recommend WDM/TDM implementation to give the network the capability to be upgraded to WDM extension.

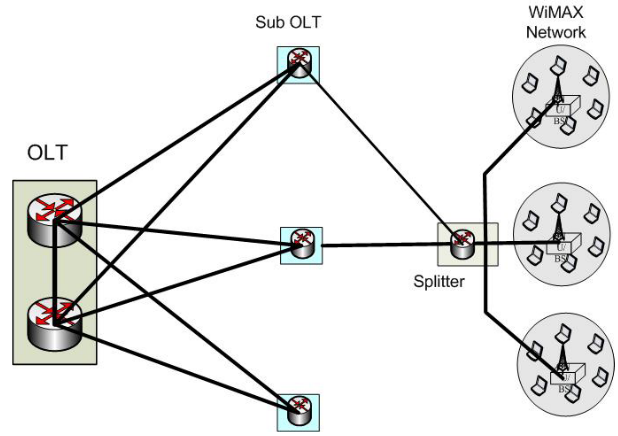

Fig. 1. Optical-Optical-Wireless architecture

As the subOLT is connected to the two routers at the OLT, one of these routers is the primary gateway of the subOLT and the second router works as the secondary gateway. The subOLT stores information about its connection status with the primary and secondary gateways, and each gateway keeps track of the connections status with all subOLTs for whom it works as primary gateway. When a subOLT has a packet in its queue, it sends the packet to its primary gateway unless the connection with this gateway is down or the Gateway is highly congested, in this case the subOLT sends the packet to the secondary gateway. When an OLT receives a packet for a subOLT, packet received by the subOLT's primary gateway, to forward the packet, primary gateway checks the connection with the subOLT, if it is up and has a reasonable transmission time it sends the packet; otherwise the packet is sent to the subOLT through the secondary gateway. The same operation is done for the router that is connected to the splitter, as it is connected to both the primary and secondary subOLTs. Also the splitter should have the ability to de-multiplex in downstream direction and multiplex in upstream direction to select between primary and secondary subOLT connections.

Only the first stage (CO to Splitters) of the architecture is more reliable in case of failures, as the second stage (Splitters to ONU/BS) compensate for failure by user mobility in the wireless part. In the case of failure in ONU/BS or its fiber connection, users served by this ONU/BS can move to another working ONU/BS. The connection between optical and wireless networks can be according to one of the integration architectures in [1]; independent architecture, hybrid architecture, unified connection-oriented architecture, or microwave-over-fiber (MoF) architecture.

III. BANDWIDTH ALLOCATION

In this section we present a new bandwidth allocation algorithm for the Optical-Optical-Wireless hybrid network architecture in Fig. 1; here the ONU and the WiMAX BS are integrated in a single system box (ONU-BS), according to hybrid architecture in [1].

As users are mostly serviced through WiMAX part of the network, the bandwidth allocation algorithm should support all service types defined in WiMax standard, namely 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).

The WiMax part of the hybrid network works as the traditional WiMax network. The BS manages the bandwidth allocation and scheduling. However, the wireless part in the proposed protocol differs from the stand-alone WiMAX network in three aspects: First, a stand-alone WiMAX serves connection admission requests in first-come-first-serve manner, whereas the proposed protocol for the hybrid architecture, serves these requests on priority based. Second, in the stand-alone WiMAX, the scheduler manages packets, by scheduling all the packets of the first SS in the time slot assigned to this SS; then it schedules all the subsequent SSs packets in sequence until it consumes all available bandwidth. Whereas in the proposed protocol, the scheduler allocate the highest priority type's packets from all SSs first, followed by next level priorities until it schedules all packets or reaches the end of available bandwidth. Third, the stand-alone WiMAX does not change its frame duration to meet the delay requirement of the connection whereas in the proposed protocol frame size is not fixed; the schedule changes the frame size if this does not affect the current active connections.

Bandwidth allocation is performed according to the total capacity (in bps) allocated for BS (C_{BS}). In hybrid network, C_{BS} is different than that in the traditional WiMAX network. The traditional WiMAX network assumed that the backhaul capacity that connects BS to the rest of the network (optical line), C_{BS_bh}, is greater than traditional wireless channel capacity. Hence C_{BS} depends only on wireless capacity of the BS, C_{BS_wl} . In hybrid network C_{BS_bh} varies from cycle to cycle dependent on the bandwidth allocated to the ONU to which the BS is attached to, therefore

$$C_{BS} = min(C_{BS\_wl}, C_{BS\_bh}). \quad (1)$$

Bandwidth Allocation is a three level algorithm, the first level of Bandwidth allocating runs at the BS, the second level runs at the ONU, and the third level runs at the subOLT of the OOW architecture. As the subOLTs connect to OLT in a point-to-multipoint manner, OLT does not need to run a bandwidth allocation algorithm. Only a switching mechanism, like Ethernet switching, is needed to multiplex subOLTs' traffics in upstream direction and de-multiplex traffic to one of subOLTs in downstream direction.

A. BS Bandwidth Allocation (BSBA)

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

$$F_l = min(2C_i^d)\forall i \in N. \quad (2)$$

Where N is the group of connections currently running at the BS; C_i^d is the delay limit of the connection ***i***. F_l must be related to the min delay requirement of all connections.

After setting the frame size, different types of connections are scheduled as follows:

- BSBA assigns bandwidth according to the strict priority principle, where service types priorities from highest to lowest are UGS, ertPS, rtPS, nrtPS, then 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 stay within its traffic contract.
- To provides per-stream QoS guarantee, BSBA allocates each stream a bandwidth that meets its QoS requirements.
- 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 requested bandwidth (fixed time duration) based on their fixed period requirement.
- rtPS traffic: 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.
- nrtPS traffic: BSBA applies weight fair queue (WFQ) service discipline to this service type. Each nrtPS gets bandwidth based on the weight of the connection (ratio between the connection's nrtPS average data rate and total nrtPS average data rates).
- BE traffic: The remaining bandwidth is equally allocated to each BE connection.

B. Bandwidth allocation at the ONU (ONUBA)

Bandwidth allocation for the Optical part of the hybrid network is initiated at the ONU. The ONU receives data from the BS(s) and the 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 8 priorities Queues (PQ). These PQs have different priority levels and are described as follows:

a) UGS queue: holds data of UGS connections and holds the highest priority.
b) ertPS queue: holds ertPS connections data and has second level of priority. The size of this queue is the actual bandwidth request of ertPS connections and it

differs from the minimum amount reserved for ertPS as we will discuss later.

c) rtPS-s-dead queue: this queue has the third level of priority and holds data packets of rtPS connections with deadline time in the next cycle.
d) rtPS-l-dead queue: holds data packets of rtPS connections with deadline time later than next cycle and comes in forth level of priority. This queue will be scanned periodically to move packets with deadline in next cycle to the rtPS-s-dead queue.
e) nrtPS queue: for data of nrtPS connections and comes in fifth level of priority.
f) Under-test queue: holds data of the connections that are accepted by the BS and its performance is monitored to check if it is eligible for final admission or not. This queue holds data for all types of connections and sorts them according to their priority levels, e.g. UGS, ertPS, rtPS, then nrtPS. It is in sixth level of priority.
g) New-connections queue: holds bandwidth requirements on new connections that can not be admitted by the BS. It contains 2 elements for each connection; one element for bandwidth requirement and second for frame size required to satisfy delay requirement of connection. Data of connections in queue are sorted in ascending order according to required frame size. This queue has seventh level of priority.
h) BE queue: holds data of BE connections and comes in 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, and total of mean data rates of all rtPS connections. This information is updated when a new connection is finally admitted by BS and when one of the running connections completes service.

When an ONU requests bandwidth from the subOLT, it sends a report message with 10 fields; please note that one report can carry up to 13 fields. The essential bandwidth information (UGS queue size + minimum ertPS rates + mean rtPS rates) is available in the first field, and the difference between the size of the second queue and min_ertPS bandwidth is available in second field. The difference between size of the third queue and mean_rtPS bandwidth is filled in the third field. The size of fourth queue is stored in the fourth field. The fifth and sixth fields of the report message carry the expected rates for the ertPS and rtPS queues; here the ONU does not only request bandwidth for existing data of ertPS and rtPS, but also requests additional bandwidth for predicted upcoming data between sending report message and arriving of grant message. The remaining four fields of the report message include the sizes of the queues from five to eight, respectively. The subOLT grants bandwidth to the ONU; the ONU divides this bandwidth among PQs.

C. Bandwidth Allocation at subOLT (subOLTBA)

First the subOLT sets its cycle time (T_{s_cycle}) to the minimum frame size of all BSs.

The subOLT allocates bandwidth to the ONUs based on total capacity that it is assigned by the OLT. The subOLT allocates Bandwidth to the ONUs as follows:

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

$$B_{min} = B_{UGS} + B^{min}_{ertPS} + B^{sdl}_{rtPS}. \tag{3}$$

where B_{UGS} , B^{min}_{ertPS} , and B^{sdl}_{rtPS} are the bandwidth requested for UGS, ertPS-min, and rtPS-c-dead queues, respectively.

b) Then, the subOLT tries to satisfy the bandwidth requests for the rest of the queues as follows:
   i) First calculate the remainder capacity C_{rem} ; then tries to satisfy the requirements of ertPS; every ONU i will be granted $B^{rem}_{i,ertPS}$. This allocation is based on the unsatisfied portion of the ertPS requests $C^{rem}_{i,ertPS}$ and C_{rem} hence,

$$B^{rem}_{i,ertPS} = min(C^{rem}_{i,ertPS}, \frac{C^{rem}_{i,ertPS} \times C_{rem}}{\sum_k C^{rem}_{k,ertPS}}). \tag{4}$$

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

c) After assigning all requests to all queues, if $C_{rem} > 0$, it is divided among ONUs according to their total requests weight.
d) ONU is granted B^{total}_{ONU} that is the sum of all component grants in previous steps.
e) If all new connections requests can be satisfied by the subOLT available bandwidth, $C_{s\_OLT\_total}$, these connections requests will be allocated to the requested ONU and the connection will be placed under-test. Any connection that can be accepted will be removed from the queue. If it requires a frame size that cannot be satisfied by current cycle time, the cycle time will be changed according to new frame size. Conversely, any connection that cannot be admitted based on $C_{s\_OLT\_total}$, is rejected.

IV. PERFORMANCE EVALUATION

To simulate the proposed OOW architecture and the proposed Bandwidth Allocation algorithm for this architecture, we use ns-2 simulation software [16] and WiMAX module for ns-2 [17] developed by *The National Institute of Standards and Technology*. We simulate a segment of the network that consists of 6 ONU/BS connected to a subOLT through 10 Gb/s fiber optic. In this network, each BS serves 4 SSs and each SS has 7 UGS, 8 ertPS, 7 rtPS, 9 nrtPS, and 5 BE connections. Although we do not simulate the OLT - subOLT segment of

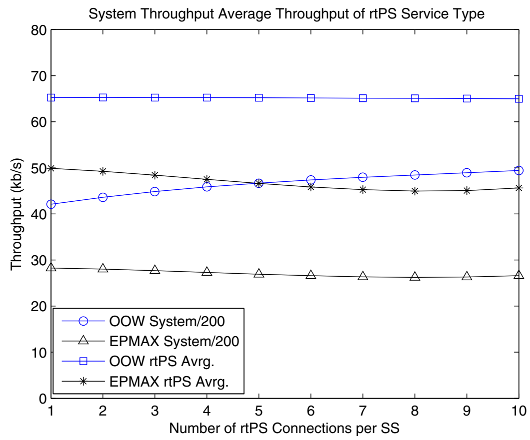

Fig. 2. System and Average of erPS Throughput

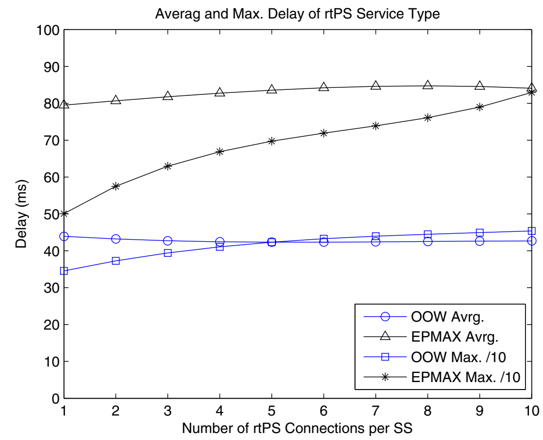

Fig. 3. Average and Max. Delay of rtPS type

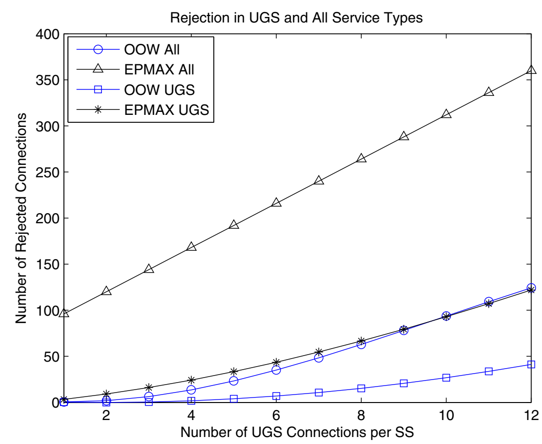

Fig. 4. Rejection in UGS and all service types

the OOW architecture in this work, but presented results give a reasonable measure of the architecture's performance. This is due to the fact that the OLT - subOLT segment provides almost fixed capacity.

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 as (EPMAX).

The average throughput of rtPS traffic and the system throughput are shown in Fig. 2. Fig. 2 shows that the rtPS' throughput in OOW outperforms that in EPMAX (30% to 44% improvement). The average throughput of rtPS in OOW is constant while average throughput of rtPS in EPMAX decreases slightly as the number of connections per SS increases. Moreover, Fig. 2 shows that the total system throughput in OOW is generally greater than the total system throughput in EPMAX (47% to 69% higher). Furthermore, the system throughput in EPMAX decreases slightly or at least remains constant as the number of connections per SS increase. Meanwhile, the system throughput in OOW increases as the number of connections per SS increases. This shows better OOW bandwidth utilization.

Average and max delays of rtPS are shown in Fig. 3. From Fig. 3 we see that the maximum delay of rtPS in OOW is less than the maximum delay of rtPS in EPMAX. The average delay in EPMAX is almost double of that in OOW. Average delay in OOW decreases slightly as the number of connections per SS increases. Whereas in EPMAX, average delay increases as the number of connections increase. Delay decreases as number of connections increases because more packets from each service type's queue are transmitted together in the same frame and this minimizes the delay. The number of packets that can be transmitted in the same frame is limited by both frame size and traffic rate. So the average delay in OOW firstly decreases as number of connections increases, when the maximum number of packets that can be accommodated in one frame is reached; the delay remains constant. In EPMAX, the average delay decreases for the same reasons as in OOW. But also, delay increases due to the fact that when many packets are transmitted from each SS and as EPMAX transmits SSs packets in sequence. Therefore, higher priorities packets of SSs not serviced early in the cycle have to wait longer. So the average delay firstly increases as number of connections increases, when the decreasing factor become more effect than increasing factor; the delay starts in decreasing.

UGS connections in both EPMAX and OOW are granted fixed bandwidth. However, as network congestion affects on the connections admission in the network, so it is reasonable to compare the number of rejected connections in OOW and EPMAX. The number of rejected connections is shown in Fig. 4. Fig. 4 shows that OOW admits more connections than EPMAX. Jitter distribution [18] of connection 3 in SS1 (randomly selected) is measured and shown in Fig. 5. The graph shows that in OOW the jitter is centered at 40 ms whereas in EPMAX the jitter is distributed over the rang from few milliseconds to 300 ms.

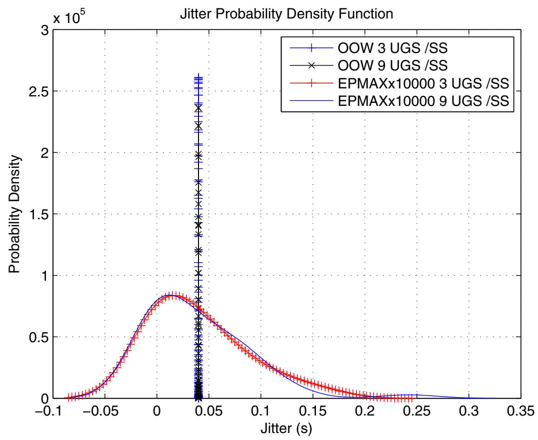

Fig. 5. Jitter pdf of connection 3 SS1.

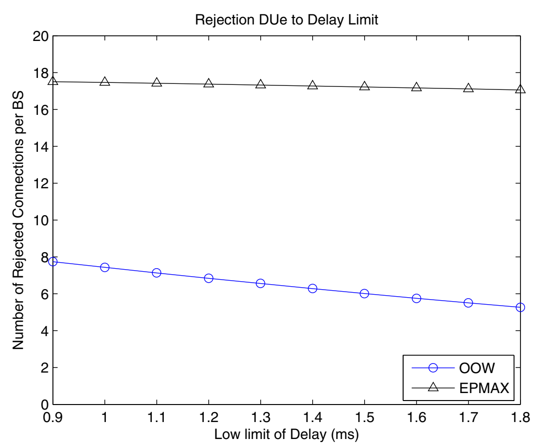

Fig. 6. Rejection in UGS Type due to Delay Limit

Computing the number of rejected connections due to delay requirement of the connection is a good measure of performance. Here number of connections is kept fixed and their data rates guaranteed to be satisfied by bandwidth of the network. Minimum delay of a connection will vary and the number of connection rejected is measured. Min delay requirement of each connection is generated randomly between Min_Delay and 10 mS. in Fig. 6, the number of rejected connections are plotted as Min_Delay is changed from 0.9 to 1.8 ms. The Number of rejected connections in EPMAX is higher than the number of rejected connection in OOW. This because OOW can change the frame size to meet the delay requirements of a connection request, but EPMAX does not.

V. Conclusion

EPON-WiMAX integration is a promising solution for next generation access network. In this paper, we have proposed a new Optical-Optical-Wireless architecture for EPON-WiMAX hybrid network. In addition, we have proposed a new bandwidth allocation algorithm. Through intensive simulation experiments, we showed the effectiveness of the proposed scheme. In future work, another architecture (Optical-Wireless-Wireless) will be proposed for EPON-WiMAX hybrid network. Joint MAC for both Optical-Optical-Wireless and Optical-Wireless-Wireless architectures and take care about channel errors in WiMAX will be proposed.

References

[1] G. Shen, R. Tucker, and C. Chae, "Fixed mobile convergence architectures for broadband access: Integration of epon and wimax," *IEEE Communications Magazine*, vol. 45, pp. 44–50, August 2007.

[2] K. Yang, S. Ou, G. Ken, and H.-H. Chen, "Convergence of EthernetPON and IEEE 802.16 Broadband Access Networks and its QoS-Aware Dynamic Bandwidth Allocation Scheme," *IEEE Journal of Selected Areas in Communications (JSAC)*, vol. 27, pp. 101 – 116, Feb 2009.

[3] X. Bai, A. Shami, and Y. Ye, "Robust QoS Control for Single Carrier PMP Mode IEEE 802.16 System," *IEEE Transactions on Mobile Computing*, vol. 7, pp. 416–429, April 2008.

[4] G. Shen and R. Tucker, "Fixed Mobile Convergence (FMC) Architectures for Broadband Access: Integration of EPON and WiMAX (invited)," in *Network Architectures, Management, and Application V*, vol. 6784, (Wuhan, China), pp. 678403–1–678403–13, SPIE, Nov 2007.

[5] Y. Luo, S. Yin, T. Wang, Y. Suemura, S. Nakamura, N. Ansari, and M. Cvijetic, "QoS-Aware Scheduling over Hybrid Optical Wireless Networks," in *Optical Fiber Communication and the National Fiber Optic Engineers*, pp. 1–7, 25–29, March 2007.

[6] Y. Luo, T. Wang, S. Weinstein, M. Cvijetic, and S. Nakamura, "Integrating Optical and Wireless Services in the Access Network," in *OFC*, (Anaheim, CA), p. NThG1, March 2006.

[7] S. Sarkar, S. Dixit, and B. Mukherjee, "Hybrid Wireless-Optical Broadband-Access Network (WOBAN): A Review of Relevant Challenges," *LIGHTWAVE TECHNOLOGY*, vol. 25, pp. 3329 – 3340, Nov 2007.

[8] W. Shaw, S. Wong, N. Cheng, K. Balasubramanian, X. Zhu, M. Maier, and L. Kazovsky, "Hybrid Architecture and Integrated Routing in a Scalable Optical-Wireless Access Network," *LIGHTWAVE TECHNOLOGY*, vol. 25, pp. 3443 – 3451, Nov 2007.

[9] F. Alsolami and P. Ho, "A Novel Two-level Hierarchical Scheduling Scheme for Integrated WiMAX and EPON," in *ICS 2008*, DSpace FC University, Jan 2009.

[10] Y. Yan, H. Yu, H. Wang, and L. Dittmann, "Integration of EPON and WiMAX Networks: Uplink Scheduler Design," in *SPIE 2008*, vol. 7137, pp. 713704–1, International Society for Optical Engineering, 2008.

[11] I. Hwang, "Advanced Dynamic Bandwidth Allocation and Scheduling Scheme for the Integrated Architecture of EPON and WiMAX," in *10th Mobile Data Management: Systems, Services and Middleware*, pp. 655 – 660, MDM '09, 2009.

[12] T. Tang, G. Shou, Y. Hu, , and Z. Guo, "Performance Analysis of Bandwidth Allocation of Convergence of WiMAX and EPON," in *Networks Security, Wireless Communications and Trusted Computing*, vol. 1, pp. 662 – 665, NSWCTC '09, 2009.

[13] X. Bai, A. Shami, and C. Assi, "On the Fairness of Dynamic Bandwidth Allocation Schemes in Ethernet Passive Optical Networks," *Journal of Computer Communications*, vol. 29, pp. 2123–2135, July 2006.

[14] G. Li, D. Wang, J. Yates, R. Doverspike, and C. Kalmanek, "Detailed study of IP/reconfigurable optical networks," in *First International Conference on Broadband Networks*, BROADNETS'04, 2004.

[15] A. Shami, X. Bai, N. Ghani, and C. Assi, "QoS Control Schemes for Two-Stage Ethernet Passive Optical Access Networks," *IEEE Journal On Selected Areas In Communications*, vol. 23, Aug 2005.

[16] "http://www.isi.edu/nsnam/ns/." Web available.

[17] "http://www.antd.nist.gov/seamlessandsecure/toolsuite.html." Web available.

[18] X. Bai, A. Shami, C. Assi, and N. Ghani, "Jitter Performance in Ethernet Passive Optical Networks," *IEEE/OSA Journal of Lightwave Technology*, vol. 23, pp. 1745–1753, April 2005.