Support of QoS in IP-Based Ethernet-PON

Chadi Assi\textsuperscript{1}, Yinghua Ye\textsuperscript{2} and Sudhir Dixit\textsuperscript{2}

\textsuperscript{1} CIISSE Department, Concordia University
assil@ece.concordia.ca
\textsuperscript{2} Nokia Research Center
{yinghua.ye, sudhir.dixit}@nokia.com

Abstract: Ethernet-based Passive Optical Network (EPON) technology is being considered as a promising solution for next generation broadband access network due to the convergence of low-cost Ethernet equipment and low-cost fiber infrastructure along with its ability to successfully support IP-based multimedia applications with quality of service requirement. In this paper we propose to use the multi-point control protocol (MPCP) defined within the IEEE 802.3ah task force to arbitrate the transmission of different users; dynamic bandwidth allocation (DBA) algorithms are then presented to effectively and fairly allocate bandwidths between these users. These DBA algorithms are then augmented to support differentiated services in a network with heterogeneous traffic. We conduct detailed simulation experiments to study the performance and validate the effectiveness of the proposed protocols.

I- INTRODUCTION

Over the past decade, telecommunication networks have dramatically evolved and current networks are expected to deliver, besides data services, video, voice services with QoS support [1]. Access network infrastructure connecting businesses and households to regional and national backbones has been recognized as a critical bottleneck. While deploying optical fiber to each customer would involve a high capital outlay for traditional operators with legacy networks [2], fiber-based access network solutions are promising in relieving the bandwidth bottleneck problem and supporting high bandwidth services. However, one of the biggest challenges currently facing network operators is to find a cost effective solution for supporting a broadband access that enables end-to-end networking to be completed and facilitates the transition to the broadband era.

A possible solution for the diverse requirements of multiple services involves the use of DSL technology for high-speed delivery over existing twisted pair drops in conjunction with PON feeders [3]. This network model is shown in Figure 1. Here, customer premises equipments (CPEs) are connected to the broadband access network (BAN) through DSL links over copper pair [1]. ADSL modems at the user side are used to support DSL links to the BAN. The main component in the broadband access network is the ADSL access multiplexer (DSLAM). Each DSLAM connects several hundreds of users to the BAN backbone. Here, a multiplexing scheme that provides high concentration while guaranteeing negotiated QoS will be an important asset for network operators. DSL connections are terminated at the central office (CO) or at the cabinet in the neighborhood where DSLAMs are installed.

Alternatively, the BAN is a high capacity PON that provides a common transport platform for a range of services and applications [2]. Currently, EPON [4-5] is being considered as a promising solution for the next generation broadband access network due to the convergence of low-cost Ethernet equipment and low-cost fiber infrastructure, where a passive optical network is a point-to-multipoint optical access network with no active elements in the signal path from an Optical Line Terminal (OLT) to Optical Network Units (ONUs).

The OLT connects the optical access network to the metropolitan area network (MAN) or wide area network (WAN). And each ONU is usually located at either the curb (i.e., fiber-to-the-curb; FTTC solution) or the end-user location (i.e., fiber-to-the-building and fiber-to-the-home; FTTB and FTTH), and provides broadband video, data, and voice services. In our opinion, ONUs and DSLAMs will be collocated (one hardware element); with the DSLAM providing termination of DSL connections and statistical multiplexing of traffic from different customers. The ONU, on the other hand, will interface with the PON; and implement the required MAC protocols to efficiently map user traffic into access network.

The rest of the paper is organized as follows. Background on PON and some motivations are presented in section 2. Different queue management and priority queuing mechanisms are presented in section 3. Dynamic bandwidth allocation algorithms with QoS support are presented in section 4. Section 5 presents the simulation results and section 6 concludes the work.

II- PASSIVE OPTICAL NETWORKS

In the downstream direction, the OLT has the entire bandwidth of the channel to transmit data packets and control messages to the ONUs; in this broadcast and select architecture, all active ONUs listen to the channel and only the designated ONU will deliver the received traffic to its end users. On the other hand, in the upstream direction, a PON is a multi-point to point [4] network where multiple ONUs share the same transmission channel. Here, unless some kind of regulation is implemented, data streams transmitted simultaneously from different ONUs may collide. Hence, access to the shared medium must be arbitrated by medium access control (MAC) protocols.
Fixed time division multiple access (F-TDMA) is one approach for solving the contention problem, however, due to the burstiness of Ethernet traffic, such a solution will not utilize network resources efficiently. Rather, a dynamic bandwidth allocation (DBA) scheme that adapts the size of the allocated time slot of each ONU to its buffer occupancy is more suitable. Moreover, a distinguishing feature broadband Ethernet PON is expected to support is the ability to deliver services to IP-based multimedia traffic with diverse quality of service (QoS) requirements \[5\]. Thus, bandwidth management for fair bandwidth allocation among different ONUs will be a key requirement for the MAC protocols in the emerging EPON based networks. In this paper we discuss an EPON architecture that supports differentiated services; we classify services into three priorities as defined in \[6\], namely the Best Effort (BE), the Assured Forwarding (AF) and Expedited Forwarding (EF).

Multi-Point Control Protocol (MPCP) is a MAC arbitration mechanism developed by the IEEE 802.3ah task force \[4\] to support time slot allocation by the OLT. Although MPCP is not concerned with any particular bandwidth allocation, it is a mean to facilitate the implementation of various allocation algorithms in EPON through its two-way messaging support. The protocol relies on two Ethernet control messages (GATE and REPORT) in its regular operation. GATE messages are transmitted by the OLT to allocated time slots to ONUs; whereas ONUs report their buffer status to the OLT by using REPORT messages. In this paper, we investigate how gated transmission mechanisms (MPCP) and DBA schemes can be combined with priority scheduling and queue management to implement a cost-effective EPON network with differentiated services support.

III- QUEUE MANAGEMENT AND PRIORITY QUEUEING

Bandwidth management for different traffic classes will play an important role in supporting QoS in the emerging EPON-based Diffserv-capable access network. Figure 2 shows the Queue management tasks carried out by each ONU. Each ONU maintains three separate priority queues that share the same buffering space. Packets are first segregated and classified (packet classification is done by checking the type of service (TOS) field of each IP packet encapsulated in the Ethernet frame) and then placed into the different priority queues. The queuing discipline is as follows: if an arriving packet with higher priority finds the buffer full, then it can displace a lower priority packet. Alternatively, if a low priority packet arrives and the buffer is full, then the packet is dropped. However, unless some kind of traffic policing is implemented at the ONU to regulate the flow of higher priority traffic and ensure that it conforms to its service level agreement (SLA), lower priority traffic may experience excessive delay and increased packet loss, resulting in a complete resource starvation. Thus traffic policing is required by the ONU to control the amount of traffic each user is allowed to send. After classifying the packets, they are checked for their conformance with the service level agreement and unnecessary traffic is dropped. The low priority traffic is more likely to be dropped in favor of the high priority traffic; however, control mechanisms are also necessary to control the high priority users if they exceed their agreed service contract.

Moreover, a priority-based scheduler is required for scheduling packet transmission. Strict priority scheduling mechanism schedules packets from the head of a given queue only if all higher priority queues are empty. This will affect the performance of lower-priority traffic, increasing the level of unfairness. We illustrate the operation of such scheduler via a simple example shown in Figure 3, where only one ONU is requesting transmission. At time $t_1$, the ONU sends a REPORT to the OLT requesting bandwidth based on the current buffer occupancy. Upon receiving the message, the OLT allocates a timeslot to the ONU by sending a GATE message. Assume this GATE message arrives to the ONU at $t_2$, and the transmission is scheduled to start at $t_3$. Now the
waiting time is \((t_3 - t_1)\), during which more packets may contend for the buffer.

In strict priority scheduling, the high priority traffic arriving during this period will be scheduled ahead of the reported lower priority traffic, resulting in light-load penalty [5]. To alleviate this problem, we propose a new priority-scheduling algorithm. Here, only those packets that arrived before \(t_1\) are given high priority for transmission (given also that the bandwidth of the timeslot allows for the transmission). The order of the transmission is based on their priorities. If packets arriving before \(t_1\) are all scheduled, and if the current timeslot can still accommodate more traffic, it will be allocated for higher priority traffic. This scheme will ensure fairness in scheduling packets.

IV- DYNAMIC BANDWIDTH ALLOCATION WITH QoS

The overall goal of bandwidth allocation is to effectively and efficiently performs fair scheduling of timeslots between ONUs in EPON. Each ONU periodically reports its buffer occupancy status to the OLT and requests slot allocation via REPORT messages in MPCP. Upon receiving the message, the OLT passes this information to the DBA module. The DBA module in turn performs the bandwidth allocation computation. The grant allocation table is updated by the output of the DBA algorithm. Grant instructions are then compiled into MPCP GATE messages, and transmitted to the ONUs.

We consider a PON with \(N\) ONUs. The transmission speed of the PON is \(R\) Mbps (same for both upstream link and downstream link). We denote the granting cycle by \(T_{\text{cycle}}\), which is the time during which all ONUs can transmit and report to the OLT. Note that, making \(T_{\text{cycle}}\) too large will result in increased delay for all traffic classes. On the other hand, making \(T_{\text{cycle}}\) too small will result in more bandwidth being wasted by guard intervals [5] (note that timeslots allocated to ONUs are separated by guard times, \(T_g\)). The guard intervals are necessary to provide protection for fluctuations in the round trip time (RTT) of different ONUs.

We also denote \(B_i^{\text{MIN}}\) as the minimum guaranteed bandwidth (in bytes) for ONU \(i\), i.e. the minimum bandwidth OLT allocates under heavy load operation:

\[
B_i^{\text{MIN}} = \frac{(T_{\text{cycle}} - N \times T_i) \times R_i \times W_i}{8}
\]

Where \(W_i\) is the weight assigned to each ONU based on its SLA, \(\sum_{i=1}^{N} W_i = 1\).

There are two categories of bandwidth allocation algorithms, fixed slot allocation (FSA) and dynamic bandwidth allocation (DBA). In FSA, each ONU is always allocated a minimal guaranteed bandwidth. Even one ONU has less data to transmit, then others have to wait until the granted transmission time for that particular ONU expires, thus resulting in inefficient channel utilization. Under dynamic allocation, the allocated timeslot will adapt to the requested bandwidth. Let \(R_i\) be the requested bandwidth for ONU\(i\), and \(B_i^g\) be the granted bandwidth.

One way to allocate bandwidth to ONU\(i\) is as follows:

\[
B_i^g = \begin{cases} R_i & \text{if } R_i < B_i^{\text{MIN}} \\ B_i^{\text{MIN}} & \text{if } R_i \geq B_i^{\text{MIN}} \end{cases}
\]

This approach is known as limited bandwidth allocation and has been studied by [5].

Due to the bursty nature of Ethernet traffic [5], some ONUs might have less traffic to transmit while other ONUs require more than \(B_i^{\text{MIN}}\). This results in total excessive bandwidth

\[
B_i^{\text{excess}} = \sum_{k} (B_i^{\text{MIN}} - R_i), \text{ here } B_i^{\text{MIN}} > R_i, \text{ where } M \text{ is the number of light-loaded ONUs}, \text{ which is not fully exploited under limited bandwidth allocation. To improve the above mentioned algorithm, one can exploit this excess bandwidth by fairly distributing it amongst the highly loaded ONUs as follows:}
\]

\[
B_i^g = B_i^{\text{MIN}} + B_i^{\text{excess}}
\]

\[
B_i^{\text{excess}} = \frac{B_i^{\text{excess}}_{\text{max}} \times R_i}{\sum_{k} R_k}
\]

where \(B_i^{\text{excess}}\) is the excess bandwidth allocated to ONU\(i\) and \(K\) is the number of heavily loaded ONUs. We term this algorithm DBA1 in this paper.

On the other hand, when supporting differentiated services, \(R_i\) consists of high priority, medium priority, and low priority requested bandwidth, \(H_i, M_i, L_i\). This information is made available to the OLT in the following message, \(\text{REPORT}(H_i, M_i, L_i)\).

\[
R_i = H_i + M_i + L_i
\]

Similarly, if there is no intra-ONU scheduling, the OLT can also choose to generate multiple grants, each for a specific
traffic class, to be transmitted to the ONU using a single GATE message: 
\[ B_i^g = H_i^g + M_i^g + L_i^g \], where 
\[ H_i^g, M_i^g, L_i^g \] are the bandwidths granted to the three traffic classes, respectively. Here, instead of employing priority scheduling at the ONU (intra ONU scheduling), the ONU requests the OLT to assign, within the allocated timeslot, bandwidth for each class.

One last issue the DBA is concerned with is the generation of the grant table. The DBA needs DBA_TIME to finish its computation and generate the grants table. As shown in figure 4, this mechanism results in some idle time where the PON is not utilized. This idle time is estimated as follows: 
\[ T_{idle} = RTT + DBA\_TIME \], where RTT is the round trip time.

To address this deficiency, we propose a modified grant table generation algorithm (termed DBA2); here the OLT needs to employ some early allocation mechanism in which an ONU requesting bandwidth 
\[ R_i < B_i^{MIN} \] can be scheduled instantaneously without waiting. Whereas, for those ONUs who are requesting 
\[ R_i \geq B_i^{MIN} \] the DBA module computes their bandwidth allocation after receiving all the REPORTs as shown in Figure 5. This scheme will compensate for the idle time by allocating the lightly loaded ONUs early, we expect this modified algorithm to effectively increase the channel throughput and eliminate the waiting delay, which could penalize the delay sensitive traffic.

In this section we study the performance of the different bandwidth allocation algorithms presented in the previous sections. An event-driven packet-based simulation model is developed. We consider PON architecture with 16 ONUs connected in a tree topology. The distance between the OLT and the splitter is 20 km and between each ONU and the splitter is 5 km. The channel speed is considered to be 1Gbps and the maximum cycle time to be 2ms [5]. The traffic model considered here is a mixture of Poisson traffic (for AF) and self-similar traffic (for the other two traffic classes BE and EF). The traffic profile is as follows: 20% of the total generated traffic is considered of high priority, and the remaining 80% equally distributed between low- and medium-priority traffic. Packet sizes of all traffic classes are considered to be between 64 bytes and 1518 bytes. Our simulator takes into account the queuing delay, transmission delay and the packet processing delay. The metrics of comparison are: average packet delay (AD), maximum packet delay (MD) and the throughput or channel utilization.

V- PERFORMANCE EVALUATION

We first show a comparison between a fixed and dynamic slot allocation. Although fixed timeslot allocation is simple and does not require any bandwidth allocation at the OLT, it does not exploit statistical multiplexing between different ONUs and hence it is considered neither efficient nor can achieve fairness. In contrast, dynamic bandwidth allocation is meant for efficient bandwidth allocation to achieve fairness between different ONUs (inter ONU scheduling). In Figure 6 we compare the performance of EPON under both fixed slot allocation (FSA) and dynamic allocation (DBA1).

Both figures (a and b) show that fixed slot allocation degrades the performance of the network by unfairly allocating timeslots equally to all ONUs. On the other hand, DBA1 algorithm overcomes this limitation by allowing statistical multiplexing between the different ONUs competing for bandwidth allocation.
Although DBA1 achieves better efficiency than the fixed slot allocation, it still has its limitations, because there is an idle time where the transmission channel is not utilized (see Figure 4). This idle time is equal to a round trip propagation delay, plus the DBA computation time. DBA2 improves upon this by allowing the OLT to schedule ONUs that are requesting bandwidth less than the minimum guaranteed bandwidth in an “on-the-fly” manner.

Finally, we compare the improvement in throughput when DBA2 is used. Figure 8 shows the throughput of FSA, DBA1 and DBA2. As expected, FSA has the lowest throughput (less than 50%) due to the lack of statistical multiplexing between ONUs, whereas, DBA1 and DBA2 exploit this property to improve the upstream channel utilization. Finally, DBA2 achieves a throughput of 95% (compared to DBA1 achieving 88%).