Evaluating a QoS-aware MAC protocol for packet-oriented GPON access network

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Abstract: - Standardization efforts under way for the specification of Passive optical networks (PONs) at Gbps speeds concentrate on the transportation of bursty IP traffic. The tendency to extend the successful Ethernet solutions into the local loop must be accompanied by enhancements towards support of different Quality of Service levels since demand for multimedia services is increasing quickly in the targeted residential areas. In this paper, the implications of the introduction of variable packet based framing in the access PON and bandwidth sharing schemes are presented first and then a QoS-aware MAC mechanism that dynamically adapts the bandwidth distribution to traffic demand is proposed. Computer simulation results allow the evaluation of the algorithm.

Key-Words: - MAC, QoS, PONs, access, simulation results

1 Introduction
The future growth of the telecommunication industry depends on the capacity increase of the local loop. Although the prime issue on this seems to be the demand for suitable services, this is not independent of the technical platform of the local loop, which affects the cost per Mbps, which is intertwined with the acceptance of services. In the efforts to remove the bottleneck of the local loop, its photonisation has always been the ultimate goal. Despite the failure of past efforts to massively deploy optical transmission in residential areas [1] and the recent downturn in the telecommunication industry, this target has not been abandoned as witnessed by the on going standardisation work in the EFM initiative of the IEEE and the GPON of FSAN. The reason is that the advantages of photonic transmission become stronger as service rates increase and costs drop. In all techno-economic studies it is observed that the cost per Mbps comes fast down when the line rates per customer go above 1Mbps range. This is no surprise since at such high demand for broadband services, the cost of Fiber In The Loop (FITL) would be easily amortised, beating sooner or later all other competitive technologies. However, the emergence of residential demand for such high rates with customers willing to pay the relevant tariffs is arguable at present. Past expectations of a decade ago predicting killer applications requiring rates above 1Mbps per home by the year 2000 are way out of target. The shadow of these past failures amidst the recent downturn in the telecommunications industry has made all key players very cautious but still does not thwart the efforts of optics to conquer the last bastion of copper and the spearhead for this objective is the PON. Since the inception of PONs at BT labs in the late 80’s, they have been touted as the most promising architecture for the photonisation of the residential local loop. Despite continuous effort since that time, the promise of massive deployment of fibre in the loop is still just a few years away. Like a mirage, it has remained just a few years away, for more than a decade now with the roadmaps shifting further back in time as years went by without bringing the desired objective any closer to realisation. On the other hand one of the results was that the telecommunication industry was credited time which provided the opportunity to design transport schemes optimized for the packet-based traffic generated by the proliferating nowadays IP applications. This is evidenced by the attempt of IEEE EFM working group to standardize the transportation of pure Ethernet packets over the access infrastructure. On the other hand, the FSAN group pursues packet-optimised transportation (maintaining at the same time the possibility to carry ATM cells) to allow for a smooth migration from ATM PON [7] infrastructure to packet-based PONs. The approach of the two presents also some differences in philosophy with the EFM relying on the QoS mechanisms embedded in Ethernet (i.e.
802.1Q and 802.1p) for service quality, while FSAN incorporates peculiar bandwidth control mechanisms to offer strict QoS guarantees to voice or video applications. The high operator revenues from leased line and voice services have contributed to this attitude.

The role of the Medium Access Control protocol in the operation of an FSAN compliant Gbps PON (GPON) system, like the one developed in the framework of the IST GIANT project [2], will be discussed in the following section, while in section 3 a MAC algorithm offering QoS guarantees while maximizing bandwidth utilization will be presented. The assessment follows in section 4 based on computer simulations. Finally, conclusions are drawn in section 5.

2 Operation of a packet-oriented GPON

In tree-shaped systems, sharing of the upstream (from customer to network) channel is usually effected through TDMA multiplexing. A Medium Access Control (MAC) protocol, as in [3], is employed to arbitrate the access to the common medium. The traffic generated by the end users, located behind the Optical Network Units (ONUs) arrives at the ONUs’ queues and waits for an upstream transmission permit. Since the ONUs are not aware of the traffic conditions at neighboring ONUs, it is the MAC controller residing at the Optical Line Termination that controls the upstream transmissions, sending permits to the ONUs. The result is depicted in Figure 1: each ONU transmits at the time designated by the received permit. When the transmissions of the ONUs are combined at the coupler at time t2, no collisions occur. In the same figure, the different kinds of overheads that may be attached to an upstream transmission are shown. Namely, every ONU transmits the Physical Layer Overhead each time it transmits in the upstream, while other overhead, such as the PLOAM and queue reporting are subject to permits scheduled by the MAC controller.

Emerging GPONs intend to support 128 ONUs, each establishing multiple upstream traffic flows, which in total can be up to 4K. The different traffic flows originating from the same ONU can be associated with different service parameters, application or user-oriented attributes. In the downstream, the transmission is performed in frames of fixed duration equal to 125µs. In each downstream frame, a field that allocates upstream bandwidth covering an upstream frame time span, is included. This field indicates the traffic flows from which data are allowed to be transmitted. Defining that the byte will be the bandwidth allocation quantum, for an upstream rate of 1.24Gbps, the MAC controller has to decide about the allocation of 19440 bytes within each frame.

![Figure 1: Upstream transmission in a tree-shaped PON system](image-url)
The inefficiency in the transport of packet traffic over an ATM system stems from the 5-byte ATM header inserted every 48 bytes of payload. Although someone could claim that to overcome this inefficiency integral Ethernet packets should travel in the upstream (with 0 bytes of overhead), this shifts inefficiency from overhead transmission to control information transmission since each ONU has to announce to the OLT the packet length of each packet waiting at its queues, so that the MAC controller appropriately schedules permits.

This drawback is aggravated by the fact that more than half the packets generated in a LAN are of 64 bytes. Compromising the two options, variable size transmissions are allowed while the attachment of a header to allow for segmentation and re-assembly of the packets is indispensable. As will also be described later, FSAN allows an ONU to be assigned bursts of thousands of bytes, to increase transportation efficiency for bursty traffic.

Except from the collision free operation in the upstream thanks to the reservation approach, the MAC controller affects the quality of service the end users experience since the portion of permits it schedules for each ONU, represents the portion of bandwidth assigned to it, while the permit intervals affect the observed delay. The MAC protocol is a global scheduler in the PON, which uses information about the temporal properties of the queues at the ONU s and information related to the contracted service parameters between the end users and the OLT to dynamically assign the bandwidth in a way satisfying the QoS guarantees maximizing at the same time efficiency.

3 The MAC algorithm

The design of a MAC algorithm capable of supporting different quality of service level in a packet-oriented system is based on the same considerations as in an ATM based system, also mentioned in [5] and includes the following:

- The service parameters are negotiated at flow activation phase and are taken into account as long as the flow is active.
- It is unacceptable to mix delay-sensitive with best effort traffic, so a limited number of Quality of Service classes are defined. The QoS class and other -possibly user defined- attributes are used to classify traffic in separate queues in each ONU.
- To dynamically allocate the bandwidth achieving high utilization, information about the queue status is announced to the MAC controller independently for each traffic flow forming “request matrix” at the OLT.
- A suitable algorithm based on some kind of prioritization is needed.

FSAN and ITU-T have adopted four types of service i.e. four Traffic CONTainers (T-CONT) for ATM PONs [4], and these are also kept for the packet-based GPON. We briefly describe them here to allow for a better understanding of the algorithm in the sequence. T-CONT 1 is serviced through periodical permissions emulating leased lines, where throughput is fixed and delay variation zero. T-CONT type 2 enjoys throughput guarantees while delay variation is limited but not zero. Its service is based on periodical permits upon request, so that, although the respective resources are always available, when the flow is inactive, these are allocated to other flows for increased utilization. For T-CONT 3 a minimum service rate is guaranteed while surplus sources are allocated up to a maximum upon availability and request, offering a better than best-effort service. Finally, T-CONT 4 is used for plain best-effort traffic where no guarantees apply.

We will not elaborate on the above considerations, since these have been exhaustively discussed in [5,6] for an ATM based Hybrid Fiber Coaxial system. Instead we will focus on the intricacies of packet-based systems.

The main difference is that it is not the cell the unit of allocation but the byte. Also service parameters are not described as rate limits (peak, mean and sustainable) but are expressed by burst size and repetition intervals. For example, the peak rate is expressed as a certain number of bytes B every time T. For an ATM system, B would be set equal to 53 bytes and T would be calculated accordingly. In a packet-based system, to increase efficiency (since a layer-2 PON header is attached in each payload transmitted in the upstream), B would be chosen much higher for a video application, where packets of thousands of bytes are generated for a short period, while silence follows. As a result, the choice of B depends on higher layers properties and for this reason, it is chosen using a signaling procedure at flow activation phase. For the translation of the minimum rate, in B and T, it is the worst case delay that plays the key role. For the MAC controller, the parameters associated with each flow include the above-mentioned parameters as well as the QoS class and are provided to the MAC chip by a microprocessor, since they are not modified in real-time.

Other intricacies include the minimum payload assigned which is not limited to 53 bytes and the queue length reported which can be expressed either in bytes or in a greater quantum to decrease the reporting field width.
The algorithm executed in each frame time, in a pseudo-code form follows. It has been assumed that the peak rate is expressed in Maximum Bytes (MB) per minimum Permit Interval (mPI) and the minimum rate is expressed in minimum Bytes (mB) per Maximum Permit Interval (MPI). Also, in the following pseudocode, the allocation of overheads and the update of requests is not shown, to allow focusing on PON client layer payloads service.

```plaintext
Frame bytes:=19440
/** inspect all T-CONT 1, 2 and 3 Max Permit Interval timers ***/
for I:=1 to 4K
    if MPI(I)=1 then
        Service_MPI(I)
        MPI(I):=MPI_negotiated_value;
    Else
        MPI(I):=MPI(I)-1;
/** process Service_MPI(I)**/
if T-CONT(I)=1 then
    { tempB:=mB;}
Else
    { Temp_B:=min{mB, Request(I)}
    Frame_bytes:=Frame_bytes-tempB;
    Assign(I, tempB)
/** having completed the MPI inspection which results in the allocation of the guaranteed part of bandwidth the surplus bandwidth allocation for T-CONT 3 and 4 is enabled ***/
/** inspect all T-CONT 3 requets ***/
for I:=1 to 4K
    if T-CONT(I)=3 and Request(I)>0 and frame_bytes>0 then
        allocate_surplus(I)
/** inspect all T-CONT 4 requets ***/
for I:=1 to 4K
    if T-CONT(I)=4 and Request(I)>0 and frame_bytes>0 then allocate_surplus(I)
/** allocated_surplus(I)**/
if mPI(I)=0 then
    Assign(I, min(MB, Request(I))
    Frame_bytes:=Frame_bytes- min(MB, Request(I));
    mPI(I):=mPI(I)_negotiated_value;
/** inspect all T-CONT 2, 3 and 4 min Permit Interval timers ***/
for I:=1 to 4K
    mPI(I):=mPI(I)-1;
```

4 Simulation Results

In this section we show representative simulation results for the second, third and fourth service types, since for the first service type the results are deterministic. The OPNET simulation tool was used to prepare the model of our system consisting of 32 ONU's, each capable of establishing multiple queues. The reporting frequency coincided with the service frequency (resulting in a piggy-backing like scheme) and the overhead for each transmission has been assumed equal to 80 bytes.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>ONU offered Load (Mbps)</th>
<th>T-CONT Total Load (Mbps)</th>
<th>Access delay (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>17,874</td>
<td>2</td>
<td>572</td>
</tr>
<tr>
<td>1b</td>
<td>17,874 with varying packet size</td>
<td>2</td>
<td>572</td>
</tr>
<tr>
<td>2</td>
<td>2 T-CONT 2 queues generating 8.3, 1 T-CONT 4 queue generating 8.3</td>
<td>2,4</td>
<td>798.6</td>
</tr>
<tr>
<td>3</td>
<td>2 T-CONT 2 queues generating 15.3, 1 T-CONT 4 queue generating 15.3</td>
<td>2,4</td>
<td>2900</td>
</tr>
<tr>
<td>4</td>
<td>2 T-CONT 2 queues generating 13.3, 1 T-CONT 3 queue generating 13.3</td>
<td>2,3</td>
<td>1280</td>
</tr>
<tr>
<td>5</td>
<td>Dynamically changing</td>
<td>2,4</td>
<td>Described in text</td>
</tr>
</tbody>
</table>

Table 1: The parameters and results of the simulation scenarios
A subset of the scenarios carried out to test the efficiency of the algorithm in the MAC protocol is described in Table 1. In scenario 1, the total offered load is uniformly distributed over the ONUs and injected as T-CONT 2 type traffic. The simulation duration and the mean source rate were identical for 1a and 1b and equal to 0.3s and 17.894Mbps. The main difference is the type of sources used: substituting CBR sources with VBR of the same mean rate in scenario 1b, generating packets of size uniformly distributed between 64 and 1500 bytes (which are the most popular sizes in Ethernet LANs) at fixed time intervals, the observed delay increases but remains below 2ms. This illustrates the dynamic tracking of queues performed by the MAC controller based on the queue reporting. It should be stressed here that the delay budget for an access network for real-time voice applications is 3 ms. Taking into account that the propagation and processing delays within the PON is less than 500µs, the simulation results show that the traffic from voice applications could be serviced through T-CONT 2.

In scenario 2, T-CONT 2 and T-CONT 4 traffic is offered, with the total load below the system capacity. As shown in Figure 2, both T-CONT 2 (bold line and light dotted line) and T-CONT 4 traffic (bold dotted line) is totally serviced, since the total offered load is within capacity.

![Figure 2: Queuing delay for scenario 2](image2)

This is reversed, when the offered load is above capacity, as happens in scenario 3. T-CONT 2 queues should remain un-aware of congestion while T-CONT 4 queues are expected to suffer the congestion. The simulation results are shown in Figure 5 where the delay of higher priority queues (T-CONT 2) shown at the top of the figure varies less than 0.0002s with the average not exceeding 0.0014s while the delay observed by best-effort (T-CONT 4) traffic (shown at the bottom of the figure) increases (i.e. this queue is unstable).

![Figure 3: T-CONT 2 and 4 performance for scenario 3](image3)

The performance precedence of T-CONT 2 queues over T-CONT 3 is illustrated in scenario 4, where the total T-CONT 2 offered load is 851.2 Mbps and is uniformly distributed among 64 queues while the T-CONT 3 offered load is 425.6 Mbps, also uniformly distributed among 32 queues. The total load is above capacity and in Figure 4 we can see the results for queuing delay that are absolutely aligned with the expected ones. The average queuing delay for higher priority queues is 0.0014 sec while the others are increasing constantly, with the slope representing the minimum service rate assigned.

![Figure 4: T-CONT 2 and 3 performance for scenario 4](image4)
To test the reaction of the MAC protocol to dynamic traffic changes, scenario 5 was carried out. For the first 0.1 sec time span, 32 T-CONT 2 and 32 T-CONT 4 queues are active generating 15Mbps and 10Mbps traffic respectively. The total offered load (800Mbps) is within capacity, which results in limited delay for both traffic classes (top T-CONT 2, bottom T-CONT 4 of Figure 5). When (at 0.1sec) 32 more T-CONT 2 queues are activated generating 8Mbps each, they observe almost constant delay (as shown at the middle part of the figure), since the MAC protocol sets at the disposal of T-CONT 2 the bandwidth necessary for the total service of T-CONT 2.

![Figure 5: Access delay measurements for scenario 5](image)

5 Conclusions
Emerging GPONs intend to offer a flexible access platform optimized to carry IP traffic supporting at the same time different Quality of Service levels as necessary to fulfill the diverse application requirements. The intricacies of these systems have been discussed and a MAC algorithm that dynamically adapts the bandwidth based on contracted parameters and the temporal traffic properties has been proposed. This algorithm proves to adapt the bandwidth distribution to the varying sources requirements and its fast reaction to changes has been illustrated.

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References