On the Prediction of EPON Traffic Using Polynomial Fitting in Optical Network Units

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Abstract: *We propose a traffic prediction algorithm that reduces the packets delay in Ethernet Passive Optical Networks (EPONs). The algorithm relies on Multi-Point Control Protocol (MPCP) message and traffic monitoring at the Optical Network Units (ONUs) and utilizes the monitoring information to predict the accumulated burst size using higher order least-mean-square polynomial approximations. The simulation of the algorithm shows that it achieves a delay improvement of over 30% without any further modification in the communication and bandwidth assignment procedure of the EPON.*

1. INTRODUCTION

Passive optical networks (PONs) [1],[2] are an attractive solution for the deployment of next-generation access networks, due to their low implementation cost, simple operation and high-line rates made possible by the capacity of optical fibers. Ethernet Passive Optical Networks (EPONs) in particular, which represent the convergence of low-cost Ethernet equipment and low-cost fiber infrastructure, find widespread application in local and metro area networks, supporting the fiber infrastructure that is being installed within the scope of fiber-to-the-home, building and curb (FTTC) end-user access. In an EPON network, multiple optical network units (ONUs) access the shared channel to reach the optical line terminal (OLT) through a passive optical splitter. To arbitrate the multiple ONU accesses, an effective bandwidth allocation scheme is required. The interleaved polling scheme with adaptive cycle time (IPACT) [3], [4] is implemented at the OLT. IPACT periodically receives bandwidth requests from all connected ONUs and allocate transmission slots accordingly. The average cycle time in IPACT contributes to the PON system latency, since ONUs are served in a round-robin fashion and each ONU must wait for the full cycle duration before being served again. Thus, the average cycle time and consequently the delay, depends on the bandwidth allocation scheme implemented by IPACT. In general, bandwidth allocation schemes can be categorized as fixed or dynamic. Fixed bandwidth allocation (FBA) schemes [5] utilize equal size time-slots and offer a fixed time-slot to each ONU irrespective of its traffic load. The ONU-to-OLT (upstream) communication channel is therefore reserved even when the actual ONU traffic is not sufficient to fully utilize the slot and this bandwidth underutilization leads to transmission gaps and increased frame service times. On the other hand, dynamic bandwidth allocation (DBA) [6], [7] assigns the bandwidth in an adaptive fashion based on the current traffic load of each ONU. The idea in DBA schemes, such as the one implemented in IPACT, is to re-distribute bandwidth from light-load to heavy-load ONUs within a single cycle duration and consequently fully utilize the available capacity, thus reducing the overall PON latency.

An improvement on the PON latency can be obtained by means of traffic prediction, a technique that has been widely studied in both wireline and wireless networks [14]. During the time of bandwidth negotiation, and in particular during the interval that lasts from the moment the ONU sends the bandwidth requirement until the moment it can start sending the buffered data. More data will arrive at the ONU buffer that time and will remain in the buffer until the next cycle. As a result these will not be taken into account when the bandwidth request was sent. OLT-based traffic prediction relies on estimating future "on-average" bandwidth requirements for all ONUs in the network based on their previous bandwidth requests. A key drawback of OLT-based prediction, however, is that it may not accurately identify, and therefore respond, to rapid changes in the ONU traffic. On the other hand ONU-based prediction, can be performed within a single cycle, since ONUs are able to constantly monitor incoming traffic, and therefore can adapt to traffic changes significantly faster.

Predictive techniques establish a mathematical model that processes the series of data packets in order to estimate the future traffic flow. A large variety of traffic prediction algorithms for EPONs have been proposed in the last years, in order to improve the bandwidth allocation strategy and the total system performance [7], [8]. These prediction techniques can be executed at the side of OLT [9], [10] or the ONUs [4],[11],[12], with the pros and cons of each approach that have been described earlier. The technique proposed in [9] consists of a two-stage bandwidth request scheme. In the first stage, DBA is performed for the next cycle at the ONU level_assigning bandwidth to the ONUs that have more unstable (difficult to predict) traffic. In this way it becomes easier to reduce the prediction error by shortening their waiting times. In the next stage, a linear prediction-based excess bandwidth request is done for the more stable ONUs. At the OLT, the proportionally available bandwidth for an ONU is allocated to related traffic classes, strictly based on their respective requests ordered by their priority. In [10], the authors propose a prediction process that is based on genetic expression programming to reduce the queue size variation and the packet delay. Taking a different approach [4], [11], [12] propose prediction techniques that are applied at the ONUs. In [4], a limited sharing with traffic prediction scheme was proposed and shown to enhance DBA process. For ONU-based traffic prediction another approach was presented in [11] where authors propose a linear class-based prediction model that tries to estimate the incoming traffic until the next polling cycle. This model uses information from previous bandwidth requests in order to predict bandwidth request at each ONU in the network, according to the OLT priority classes. The effect of long-range dependence of internet traffic in the prediction was studied in [12]. While the prior works have used complicated prediction techniques at the ONUs, the estimates they produce refer to a single parameter, that is the bandwidth to be allocated, which is however a complex metric (ratio of data size over time duration).

Within the context of ONU-based traffic prediction, we propose a novel algorithm for decreasing latency in EPONs. Our algorithm (a) approximates the frame arrivals within the duration of a single EPON cycle using least-mean-square polynomials and (b) estimates the duration of the upcoming cycle via a least-means-squares adaptive filter. Subsequently, the two quantities are combined to produce the amount of data that the ONU will have accumulated by the time the next bandwidth assignment from the OLT (GATE message) arrives. The ONU then communicates the predicted rather than the actual data to the OLT in the REPORT message), thus providing the DBA mechanism with a more informed guess of its traffic requirements. We show via simulation that the incorporation of the proposed prediction methods in the EPON operation can reduce the frame delay from 25% up to 30% when compared to the standard operation of the limited and gated versions of Interleaved Polling with Adaptive Cycle Time (IPACT), depending on the traffic load and the burstiness of the incoming traffic. Moreover, this significant performance benefit is obtained by applying the prediction algorithms locally at the ONUs and without any further modification on the Multi-Point Control Protocol (MPCP) procedures or the operation of IPACT. At the same time the proposed solution exhibits a low computational complexity, which is a particularly appealing feature when considering the ONU processing capabilities and associated cost.

The rest of the paper is structured as follows: Section 2 presents our proposed traffic prediction technique and its scope of application in EPONs. Section 3 details the simulation setup that was utilized to evaluate the performance of the prediction method. Section 4 discusses the results that have been obtained in terms of latency. Finally, Section 5 concludes the main contributions of this paper.

2. PREDICTION ALGORITHM BASED ON ONU

In the standard EPON operation, the communication between the OLT and the ONUs takes place by means of an interleaved polling scheme with variable cycle time (IPACT). IPACT operates in successive cycles, and during each respective cycle the OLT sends GATE messages that carry bandwidth grants to all ONUs in the EPON. The ONUs respond to the GATE messages and send their data in a co-ordinated fashion, as specified in the GATE messages, so as to achieve collision free transmissions in the upstream direction. In addition to their data, the ONUs also inform the OLT about their bandwidth requirements (buffer sizes) via REPORT messages and the IPACT cycle ends upon the reception of the REPORT messages from all ONUs in the EPON. At that time, the OLT executes a dynamic bandwidth allocation (DBA) algorithm to calculate the grants of the next cycle, and a new exchange of GATE and REPORT messages ensues. As a result, the DBA does not take into account (a) data that have been accumulated at ONUs that are served near the beginning of the cycle and are forced to report early, or (b) data that will be accumulated at ONUs that are served towards the end of the upcoming cycle and will receive a late grant. This leads to an additional delay of a cycle time, which can be particularly significant especially in IPACT variations with increased or infinite maximum cycle durations.

The additional delay can be reduced in a straightforward manner by having each ONU perform a prediction exactly before the generation of the current REPORT message by estimating its buffer occupancy for the instant it will receive the next GATE message. The ONU can then use the REPORT message to communicate the prediction to the OLT rather than the actual (current) buffer size. Our proposed prediction algorithm of the ONU buffer size can be summarized as follows:

- *Step 1*: Constantly monitor the incoming traffic from hosts in a log file until a GATE message has been received from the OLT.
- *Step 2*: Upon the reception of the GATE message keep a record of its arrival time $T(n\text{-}1)$.
- *Step 3*: Utilize the traffic log to estimate the instantaneous buffer size $B(t)$.
- *Step 4*: Utilize the arrival times of previous GATE messages to predict the arrival time of the next GATE message $T(n)$.
- *Step 4*: Combine $B(t)$ and $T(n)$ to calculate the expected buffer size $B(n)$ at the reception of the next GATE message.
- *Step 4*: Transmit the allocated number of frames in the received GATE and then issue a REPORT message that carries the bandwidth request $B(n)$.
- Step 5: Reset the traffic log to the remaining buffer size and re-start from Step 1.

The presented algorithm requires the estimation of two key parameters: (a) the instantaneous ONU buffer size $B(t)$, and (b) the arrival time of the next GATE message $T(n+1)$. The estimation of the instantaneous buffer size is performed by monitoring the incoming frames that arrive between REPORT messages. To this end, the ONU creates a log of the frame size S_i and the arrival time t_i for each frame that is received. Each frame arrival corresponds to an increase of the number of bytes B_i that are stored at the ONU buffer, following:

$$B_i = B_{i-1} + S_i, \quad (1)$$

while the remaining queue size B_0 after the ONU transmission at t_0 is used to initialize Eq. (1). Given (1), a k^{th} degree polynomial equation that correlates the buffer size $B(t)$ and the elapsed time t is can be calculated by the (t_i, B_i) pairs, according to:

$$B(t) = a_0 t^0 + a_1 t + a_2 t^2 + ... + a_k t^k \quad (2)$$

where the coefficients a_0, $a_{1,...,}$ a_k in the above polynomial are calculated in a least-mean-squares fashion by:

$$\begin{bmatrix} 1....t_1{}^k \\ 1...t_1{}^k \\ ...... \\ 1...t_n{}^k \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ .... \\ a_k \end{bmatrix} = \begin{bmatrix} B_0 \\ B_1 \\ .... \\ B_n \end{bmatrix} \text{ Or } T * \mathbf{A} = B \quad (3)$$

The ONU is able to predict its queue status at any given future time t and up to the next GATE message. The exact arrival time of the next GATE message, however, is not known when the ONU creates the REPORT message and as a result the ONU has to estimate it, as well. To this end, the ONU monitors the arrival times of GATE messages and predicts the arrival time of the next GATE $T(n)$ by means of a normalized least-mean-square (NLMS) prediction filter which is given by:

Table 1 Simulation Parameters

<table>
<tr><th></th><th>Symbol</th><th>Description</th><th colspan="2">Value
(Limited - IPACT)</th></tr>
<tr><td rowspan="6">Physical Layer Parameters</td><td>N_{ONU}</td><td>Number of ONU’s</td><td colspan="2">8</td></tr>
<tr><td>N_{host}</td><td>Number of ONU Hosts</td><td colspan="2">15</td></tr>
<tr><td>d</td><td>ONU distance</td><td colspan="2">10 km</td></tr>
<tr><td>R_d</td><td>Downstream Line Rate</td><td colspan="2">10 Gb/s</td></tr>
<tr><td>R_u</td><td>Upstream Line Rate</td><td colspan="2">1 Gb/s</td></tr>
<tr><td>R_n</td><td>Host Line Rate</td><td colspan="2">100 Mb/s</td></tr>
<tr><td rowspan="2">IPACT Parameters</td><td>T_{max}</td><td>Max Cycle Time</td><td>2 ms</td><td>Unlimited</td></tr>
<tr><td>W_{max}</td><td>Maximum Grant Size</td><td>82.500 bytes</td><td>Unlimited</td></tr>
<tr><td rowspan="2">Traffic Parameters</td><td>a (a_{ON}, a_{OFF})</td><td>Pareto parameter</td><td colspan="2">1.2, 1.5, 1.8</td></tr>
<tr><td>b (b_{ON}, b_{OFF})</td><td>Pareto parameter</td><td colspan="2"><table><tr><th>a</th><th>b_{ON}</th><th>b_{OFF}</th></tr><tr><td>1.2</td><td>0,00000375</td><td>0,00014 -0,000495</td></tr><tr><td>1.5</td><td>0,00000375</td><td>0,001493-0,000493</td></tr><tr><td>1.8</td><td>0,00000375</td><td>0,0016-0,00048</td></tr></table></td></tr>
<tr><td rowspan="2">Prediction Parameters</td><td>p</td><td>NLMS order</td><td colspan="2">25</td></tr>
<tr><td>M</td><td>NLMS step size constant</td><td colspan="2">0,0001</td></tr>
</table>

$$\hat{T}(n) = \sum_{i=1}^{p} w_n(i) \cdot T(n-i) \tag{4}$$

where p is the filter order and $w_n(i)$ are the filter co-efficients that are updated at every cycle.

$$w_n(i) = w_{n-1}(i) + M \cdot e(n-1) \cdot \frac{T(n-i)}{\sum_{k=1}^{p} \left(T(n-k)\right)^2}, \quad i = 1, \ldots, p, \tag{5}$$

$$e(n-1) = T(n-1) - \hat{T}(n-1),$$

the NLMS step size M has a constant numeric value (Table 1).

3. SIMULATION SETUP

The performance of our proposed algorithm was verified via simulation experiments using the OMNET++ open source simulator [13]. In our setup, a standard EPON architecture interconnected an OLT with eight ONUs at distances of 10 km, while the EPON rates were considered asymmetric (10 Gb/s downstream - 1 Gb/s upstream). MPCP protocol forms a type of master-slave REPORT/GATE mechanism, which means that requirements are put forward by each ONU and are arbitrated by the optical line terminal (OLT). The communication model was based on existing OMNET++ models that provide the basic MPCP functionalities at the OLT and ONUs. Two IPACT allocation schemes were implemented at the OLT, namely, the limited and the gated version.

For the limited-IPACT implementation, OLT grants an upper bounded transmission window size per ONU. On the other hand, in case of gated-IPACT, OLT allocates the estimated requested bandwidth for each ONU in our network. The incoming traffic for the purpose of the simulation was fed to each ONU from an optical switch that aggregated frames from fifteen independent hosts (sources) Figure 1. The hosts transmitted data in the form of fixed size 1000 byte Ethernet frames at a

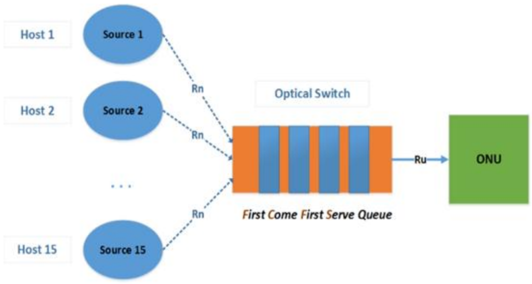

Figure 1: Simulation model

line rate R_n of 100 Mb/s. Each of the hosts generated data frames independently of each other, according to an ON/OFF traffic model. This traffic model also known as Pareto distribution consist of two different periods for each host, an ON (busy) and an OFF (idle) period. Due to the form of the Pareto distribution, ON (busy) periods were always followed by OFF (idle) periods. The mathematical formula of the distribution is described in Eq. 6:

$$f(x) = \frac{a \cdot b^{a}}{x^{a+1}} \qquad (6)$$

Parameters a and b relate to the average busy time durations and idle time durations, T_{ON} and T_{OFF} respectively (eq. 7).

$$T_{ON} = \frac{a_{ON} \cdot b_{ON}}{a_{ON} - 1}, \qquad T_{OFF} = \frac{a_{OFF} \cdot b_{OFF}}{a_{OFF} - 1}. \qquad (7)$$

The values that were used in our simulations for the parameters a_{ON}, b_{ON} and a_{OFF}, b_{OFF} of the ON and OFF periods, respectively, are presented in Table 1. These values resulted in ON-OFF periods with durations at the msec time scale, which corresponds to a single IPACT cycle, since an access-oriented PON is not expected to remain idle for several successive IPACT cycles. Given the above average busy and idle periods of each host, it was possible to calculate the offered loads ρ in the PON from the number of ONUs (N_{ONU}), the number of hosts per ONU (N_{host}) and the individual host load (ρ_{host}) as :

$$\rho = N_{ONU} \cdot N_{host} \cdot \rho_{host} \cdot = N_{ONU} \cdot N_{host} \cdot \frac{T_{ON}}{T_{ON} + T_{OFF}} \qquad (8)$$

4. RESULTS

We have conducted two sets of simulations experiments. The first set compares the limited IPACT algorithm without prediction to our

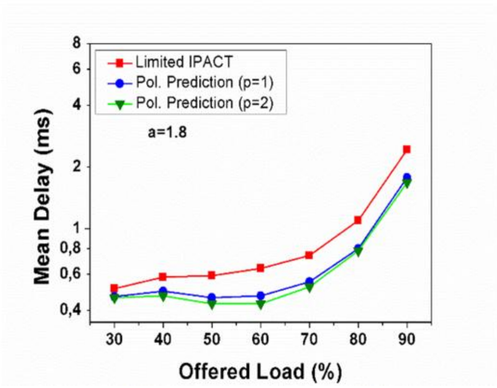

Figure 2: Mean Delay for low burstiness traffic

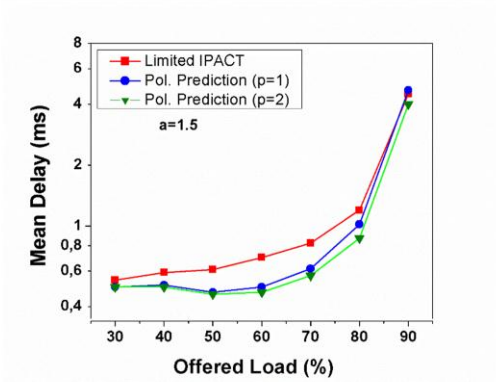

Figure 3: Mean Delay for mediun burstiness traffic

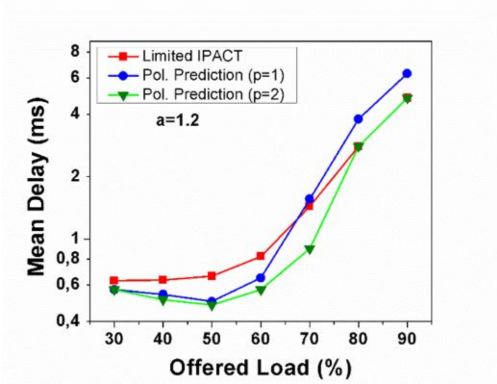

Figure 4: Mean Delay for high burstiness traffic

corresponding scheme that uses prediction algorithms. The second set of simulations evaluates the performance of gated-IPACT algorithm without prediction against our prediction algorithms.

For the purposes of the simulation, three different traffic burstiness scenarios that correspond to low, medium burst and high burst (*a* = 1.8, 1.5, 1.2, respectively) were used. Moreover, we evaluated the prediction algorithm for polynomials of degree equal to one (i.e., linear prediction) and two, since higher degree for the polynomials lead to severe prediction inaccuracies that negatively affected the EPON performance. The respective results are shown in Figure 2-4 for the limited-IPACT and Figure 5-7 for the gated-IPACT.

The results clearly demonstrate that the Limited-IPACT performs in a superior fashion when prediction based reports are sent by the ONUs. A percentile delay reduction of over 25% is observed for medium offered loads around 0.6, while a smaller benefit is observed as the load becomes lighter. For higher loads, prediction only has a minor beneficial impact when the traffic is relatively smooth (*a*=1.8 and 1.5). As the traffic becomes significantly bursty (*a*=1.2), the proposed linear prediction algorithm can be detrimental in terms of latency, mainly because the cycle durations become irregular and the GRANT arrival times are not correctly calculated by the NLMS. As a result, ONUs request the largest possible grant and IPACT performs in a TDMA manner with maximum duration bandwidth grants. For quadratic prediction the delay results improve in all cases, even for a highly bursty traffic profile (Figure 4) and the delay reduction is improved by up to 30% for medium offered loads around 0.6. As the load increases, the prediction benefit reduces to under 10%; still, it is important to notice that quadratic prediction tends to correct the detrimental effect of liner prediction with increasing burstiness.

A similar behavior is observed for gated-IPACT in Figure 5-7; the proposed linear prediction mechanism improves the average delay in this IPACT variation by 25% for medium loads as shown in the simulation results. An important difference with limited-IPACT, however, is becoming evident for bursty traffic (*a*=1.2) and at heavy loads; in this regime even more extended bandwidth grants are requested by the ONUs and are allowed by the OLT, due to the fact that gated-IPACT does not pose an upper limit on the size of the grants. As a result, the average delay is also increased by a significant factor. An even better performance for the case of gated-IPACT is observed for quadratic prediction. As it can be seen

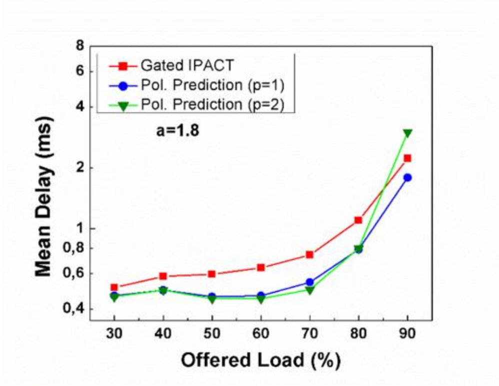

Figure 5 : Mean Delay for low burstiness traffic

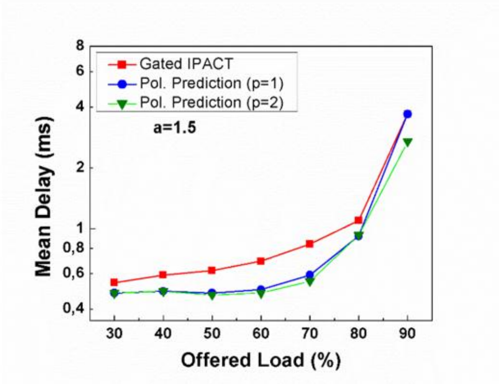

Figure 6 : Mean Delay for medium burstiness traffic

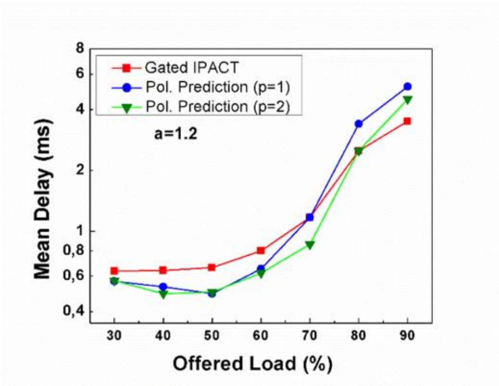

Figure 7: Mean Delay for high burstiness traffic

from the delay results, an improvement of 26% can be achieved in medium offered loads from 0.5 to 0.7 for all degrees of traffic burstiness. Moreover, when the offered loads increase, the utilization of second order polynomials provides a better delay performance from its linear counterpart. Especially for medium burst traffic (a=1.5) the delay is able to achieve profits up to 27%, around 0.8. Finally, in accordance with the limited-IPACT results quadratic prediction algorithm exhibits better stability at high loads.

5. CONCLUSION

We presented an ONU based prediction method that is applicable in EPONs. The method relies on the application of polynomial fitting and the Normalized Least Mean Square (NLMS) algorithms for the estimation of the instantaneous ONU load and IPACT cycle duration, respectively, to predict the ONU buffer size at the time of its next transmission. We showed via simulations that if the predicted (estimated) buffer size, rather than the actual size, is reported to the OLT then a significant (over 25%) average delay reduction can be realized over standard EPON when a linear based prediction algorithm is used. Also when the prediction method uses a second order polynomial (nonlinear prediction algorithm) the average delay improvement is over 30% for all degrees of traffic burstiness. Moreover, the proposed techniques are totally compatible with the bandwidth reporting and allocation mechanisms that have been standardized in EPONs, as well as with other popular well-IPACT variations (Limited and Gated).

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