17th IEEE Mediterranean Electrotechnical Conference, Beirut, Lebanon, 13-16 April 2014.

# Towards a Fair and Efficient Downlink Bandwidth Distribution in XG-PON Frameworks

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***Abstract*—Fairness assurance in modern access networks constitutes a focal point of interest since it dramatically affects the quality of the provided services to the final users. Traffic balancing entails fair bandwidth distribution along with efficient service provisioning, inaugurating a challenging tradeoff between the system throughput and fairness. In this paper, the downlink scheduling effectiveness in modern passive optical networks (PONs) is examined, adopting the ten-gigabit passive optical network (XG-PON) architecture deployed in a tree topology. Considering that the tree topology implies a broadcast nature of data delivering in the downlink direction, the tradeoff between the efficiency and fairness becomes even more compelling, bearing in mind that the distance the broadcast data propagate between the source and users' destination is highly differentiated. In order to remedy this situation two effective scheduling schemes are proposed, namely the shortest propagation processing time (SPPT) and the shortest weighted propagation processing time (SWPPT). Both algorithms are extensively assessed, while the obtained results indicate that the proposed algorithms assure a fair and effective downlink schedule.**

***Keywords—downstream; fairness; passive optical networks; round trip time; scheduling; XG-PON;***

## I. INTRODUCTION

The ongoing proliferation of passive optical networks (PONs) put into effect the numerous advantages of optical networking such as huge bandwidth, cost-effective deployment, and scalability in modern access networks. Typically, a PON is structured in a tree topology, where multiple users are connected to the backbone network. The main interface interconnecting the PON with the backbone network is governed by the optical line terminal (OLT). Users are directly connected to optical network units (ONUs), which in turn are hooked up with the OLT. The interconnection is viable by using a passive optical splitter/combined between the OLT and the multiple ONUs. Thus, the tree shape is realized by the OLT forming the root and the ONUs denoting the leaves of the tree. This type of topology engages two distinct directions, namely the downlink direction, where data travel from the OLT to the ONUs, and the uplink direction, where ONUs forward users' data to the OLT.

One of the most attractive research topics is pertinent to the handling of the shared fiber link between the OLT and the splitter/combiner. Given that collisions are not allowed across the network, the management of the bandwidth distribution in the uplink direction intends to effectively design access solutions to resolve this limitation. For instance, time division multiple access (TDMA) strategies are devised to provide efficient access sharing of the common fiber link [1].

On the other hand, the downlink direction implies a broadcast data delivery [2]. At first sight, downlink scheduling seems a trivial objective. The most common scheduling policy to advance the traffic from the OLT to the ONUs is the first come first served (FCFS) method, where the earliest arrived data packet is chosen to be forwarded. Assuming a symmetric tree where all ONUs are located in identical distances from the OLT, the FCFS policy may be the optimal one. However, the (PON) framework comes to offer wired connectivity to broad geographical areas, engaging multiple users located at different areas [3]. The heterogeneity of the ONU location in relation to the introduced propagation delays, from and to the OLT, may reveal a considerable mismatch: the downlink bandwidth distribution may induce fairness impairment and various deficiencies such as highly variant average packet delay.

In this work, we endeavor to resolve this mismatch by introducing two effective downlink scheduling policies. We adopt the newest member of the ITU-T family of PON standards [4], namely the ten-gigabit PON (XG-PON) framework. The main objectives of the proposed policies are a) provision of fairness assurance and b) function of an efficient

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*This work has been funded by the NSRF (2007-2013) SynergasiaII/EPAN-II Program "Asymmetric Passive Optical Network for xDSL and FTTH Access," General Secretariat for Research and Technology, Ministry of Education, Religious Affairs, Culture and Sports (contract no. 09SYN-71-839).*

dynamic bandwidth allocation (DBA) in the downlink direction. The rationale behind the two policies lies in the propagation time involvement during the scheduling decision making. We devise the shortest propagation processing time (SPPT) policy where the main criterion of creating the schedule is the round trip time (RTT) of each ONU implicitly and the shortest weighted propagation processing time (SWPPT), where the effectiveness of the ONUs' RTT is explicitly calculated as a weighted parameter. Simulation results demonstrate that the proposed policies are able to support improved downlink scheduling in all aspects.

The remainder of this paper is organized as follows. Section II presents background information about the XG-PON standard. Section III describes the related work presented so far in the literature. Section IV elaborates on the proposed scheduling policies along with their design and operation. Section V validates the proposed schemes by means of extensive simulation experiments. Finally, Section VI concludes this paper.

## II. XG-PON FRAMEWORK

This Section is devoted for providing preliminary information about the adopted system architecture, i.e., the XG-PON framework. ITU-T G.987.3 recommendation presents the focal layer of the XG-PON framework, namely the XG-PON transmission convergence (XGTC) layer. Assuming point-to-multipoint optical access infrastructure, ITU-T specifications define that for at least one direction the nominal data rate of 10 Gbps is supported to end users. In particular, the downlink flow supports the nominal rate of 9.95328 Gbps, while the upstream rate is 2.48832 Gbps. The operation of the downlink streaming is quite defined. The OLT is responsible for broadcasting a fixed size downstream frame every 125 μs. The duration of the downstream frame, in accordance with the given downstream rate, corresponds to 155520 Bytes. However, this size includes coding and control information. Physical synchronization block (PSB) fields come first in downstream (PSBd) and upstream (PSBu) transmission respectively, intending to synchronize the corresponding bit streams. Then, the XGTC header follows including control information.

In the downlink direction the PSBd field holds 24 Bytes, while the XGTC field has variable length, depending on the number of involved ONUs. Specifically, the XGTC field contains the HLend part having fixed length of 4 Bytes, informing about the header length, the bandwidth management (BWMap) part, including the resource allocation for the uplink direction destined to the ONUs, having variable length of $8 \cdot N$ Bytes, where $N$ is the number of ONUs, and the physical layer OAM messaging (PLOAMd) part, where control messages between the OLT and the ONUs are included, having length equal to $48 \cdot M$ Bytes, where $M$ is the number of included messages. The data filed follows the XGTC header, which contains data allocations for each user/port, known as Alloc-ID, of all ONUs. Excluding the PSBd field, the downstream frame transfers 155496 Bytes, where 135432 Bytes belong to data traffic and 20064 Bytes are dedicated to parity bytes following the Reed Solomon, RS(248,216) code. Thus, the OLT is responsible of allocating $135432 - 4 - 8 \cdot N - 48 \cdot M$ Bytes to the connected ONUs per downstream frame.

## III. RELATED WORK

The downlink scheduling in XG-PON systems is not well investigated so far. The majority of the efforts, found in the literature, either neglect the aforementioned issues or focus on other PON paradigms, such as Ethernet PON (EPON). EPON constitutes a popular PON paradigm, however, the downlink operation is quite different against XG-PON. It is based on independent control messages like the GATE and the REPORT messages while no periodical broadcast streaming is conceded. Hence, the investigation of the downlink scheduling issue is dramatically depends on the adopted PON system. In [5] the authors propose a downlink allocation scheme for providing fairness in the downstream transmission control protocol (TCP) throughput among diversely located ONUs. To this end, a similar technique is employed in [6]. Investigating the uplink point of view, the authors in [7] face the unfair upstream allocation in EPONs by manipulating the TCP throughput for achieving both high efficiency and fair utilization of the passive optical line. A Similar technique is presented in [8].

Even though the recommendations by the ITU-T pinpoint the usage of fair and efficient quality of service (QoS-based) DBA schemes for both directions, the investigation of the downlink scheduling management has received a little attention. We endeavor to cover this gap by proposing two fair and efficient downlink allocation schemes in order to enhance modern XG-PON access networks.

## IV. PROPOSED POLICIES

### A. Aim and Objectives

Scheduling deals with the allocation of resources to tasks over given time periods and its goal is to optimize one or more objectives [9]. In this work, the scheduling policy aims at providing a fair and efficient downlink broadcast. A fair scheduler ensures that all ONUs are equally treated. In the context of this paper, an equal treatment means that all ONUs receive equally divided bandwidth having the same latency on receiving it. Hence, the main objectives of this work are a) the assurance of a fair downlink scheduling process and b) the provision of a high-throughput broadcast.

### B. System Model

The specified XG-PON framework consists of an OLT and $N$ ONUs. We define the problem of fair and efficient downlink scheduling as a deterministic model considered a number of jobs and a single machine. The number of jobs, denoted by $r^i$, represents the data packets that are buffered into the OLT queue waiting for broadcasting to ONU $i$. The single machine is realized by the OLT. The machine is periodically processes the existing jobs, i.e., every 125 μs. The machine is capable of accommodating traffic equal to $C$ Bytes. As in Section II mentioned, the available resources are defined as $C = 135432 - 4 - 8 \cdot N - 48 \cdot M$ Bytes, where $M$ stands for the number of included messages. Furthermore, the RTT values of each ONU are represented by the vector

TABLE I. SYMBOL NOTATION

| Symbol | Definition |
|---|---|
| $N$ | Number of ONUs |
| $M$ | Number of PLOAM messages |
| $r_i$ | Data packets destined to ONU $i$ |
| $C$ | Total available capacity (Bytes) |
| $RTT$ | Round Trip Time of each ONU (sec) |
| $p_r$ | Processing time of data packet $r$ (sec) |
| $s_r$ | Packet size of data packet $r$ (bits) |
| $rt_r$ | Reception time of data packet $r$ (sec) |
| $w_r$ | Waiting time of packet $r$ in the OLT buffer (sec) |
| $S$ | The arranged set of scheduled data packets |
| $d_r$ | Distance of the devoted ONU of data packet $r$ from the OLT (km) |
| $W_r$ | Normalized weight of data packet $r$ |

$RTT = \{RTT(1), RTT(2), \dots, RTT(N)\}$ in terms of seconds. It is worth mentioning that in the following analysis we consider only a simple service class, e.g., best effort (BE) transmission container (T-CONT), to demonstrate the efficacy of the proposed algorithms under balanced traffic.

We denote processing time, $p_r$ as the processing time of each job, i.e., data packet $r^i$ on the machine, i.e., the OLT. This parameter indicates the time needed for the data packet $r$ to be completely delivered by the $i$ ONU. In essence, this process entails the transmission of packet $r$ plus the propagation time. Thus, the processing time is equal to $p_r = \frac{s_r}{9.95328 \cdot 10^9} + RTT(i)/2$, where $s_r$ symbolizes the packet size in bits, $1 \le i \le N$. Table I summarizes the adopted system notation.

### C. SPPT Policy

The SPPT policy performs a strict scheduling over the waiting data packets taking into account the ONUs' propagation delay implicitly. The absolute selection criterion is the reception time. The reception time, $rt_r$, is defined as the total time the data packet spends in the machine including the waiting time. In other words, $rt_r$ is defined as the processing time plus the waiting time onto the OLT queue. Hence, it holds that $rt_r = s_r + w_r$, where $w_r$ stands for the waiting time of data packet $r$ in the OLT queue measured in seconds. The data packet having the highest reception time is favored. The rationale behind this decision lies in the first objective as described earlier; the scheduling policy has to act in a fair manner. It treats the ONUs' requests based on their individual features. The weakest ONU, i.e., the ONU having long waiting time or/and is located far, is favored over the other ONUs in order to keep the schedule fair enough. In this way, the chance of monopolizing the flow is minimized. Furthermore, in the case that the provided bandwidth is not enough in a single downlink frame it occurs rescheduling of those data packets that either are recently arrived or are going to near destinations (inducing unequal treatment). The Algorithm SPPT describes the operation of the SPPT policy.

```
Algorithm: SPPT
Input: The capacity $C$, the set of $r^i$ data packets $R$, the vector $RTT$, the waiting time of each data packet $w_r$, and the number of ONUs $N$.
Output: The arranged set of scheduled data packets $S$.
    Calculate the reception time, $rt_r$, for each $r^i$ data packet
    While $S \neq \emptyset$ and $C > 0$
        Find the packet having the maximum reception time
        Set it as $maxr^i$
        If $C - s_{maxr} > 0$ Then
            Add $maxr^i$ to the last position of the $S$ list
            Delete $maxr^i$ from the $R$ list
            Set $C = C - s_{maxr}$
        Else
            Set $C = 0$
        EndIf
    EndWhile
    Return $S$
```

### D. SWPPT Policy

SWPPT policy incorporates the weight $W_r$ of each $r^i$ data packet. This weight is basically a priority factor, denoting the importance of data packet $r^i$. Since SWPPT policy explicitly includes the propagation delay in the calculation of the broadcast schedule, it associates $w_r$ of $r^i$ as the RTT normalized impact. Given that the ITU-T suggests a minimum of 20 km between the OLT and the nearest ONU as well as at most 40 km between the nearest and the faraway ONU, the normalization is performed as $W_r = \frac{d_r - 20}{60 - 20}$, where $d_r$ represents the ONU $i$ distance from the OLT. Following the weighted shortest processing time (WSPT) first rule [9], the decreasing order of ${W_r}/{p_r}$ maximizes the schedule efficiency as a subject of the total weighted completion time concept. According to this formula, ONUs with long RTT are prioritized. The steps of SWPPT policy are described in Algorithm SWPPT.

```
Algorithm: SWPPT
Input: The capacity $C$, the set of $r^i$ data packets $R$, the vector RTT, the number of ONUs $N$, the waiting time of each data packet $w_r$, and the distances $d_r$
Output: The arranged set of scheduled data packets $S$
    Calculate ${W_r}/{p_r}$, for each $r^i$ data packet
    While $S \neq \emptyset$ and $C > 0$
        Find the packet having the maximum ${W_r}/{p_r}$ value
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            Set it as $maxr^i$
            If $C - s_{maxr} > 0$ Then
                Add $maxr^i$ to the last position of the $S$ list
                Delete $maxr^i$ from the $R$ list
                Set $C = C - s_{maxr}$
            Else
                Set $C = 0$
            EndIf
    EndWhile
    Return $S$
```

## V. EVALUATION

### A. Evaluation Environemnt

The performance of both proposed scheduling policies is evaluated using a concise simulation environment in Matlab. The performance metrics measured are a) the Jain’ fairness index [10], b) the average downlink packet delay in terms of seconds, and the downlink network throughput in terms of bps. The Jain’s fairness index is defined as follows.

$$\mathrm{J}(\mathrm{t}_1, \mathrm{t}_2, \ldots, \mathrm{t}_\mathrm{N}) = \frac{(\sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{t}_\mathrm{i})^2}{\mathrm{n} \sum_{\mathrm{i}=1}^{\mathrm{N}} t_i^2}$$

In the aforementioned equation the parameter $t_i$ denotes the utilization of each ONU. Bearing in mind that the downlink scheduling effectiveness is inspected, the utilization represents the average packet delay per ONU. In other words, $t_i$ expresses the portion of the summation of the delay samples of each data packet destined to each specific ONU divided by the number of the samples. It is clear that the optimal $J$ value is equal to 1.

SPPT and SWPPT policies are compared against the FCFS policy, which performs a strict scheduling based on the arriving time. The data packet having the earliest arriving time is favored. Similarly to SPPT and SWPPT, the FCFS policy postpones the schedule of data packets that fail to be accommodated due to resource constraints, i.e., the total downlink capacity is exhausted, to the following downlink frame, i.e., after 125 μsec.

The simulation environment has been designed in accordance with the XG-PON standard specifications. Independent RTTs are considered which are randomly generated according to a uniform distribution corresponding to 20 - 60 km distances between ONUs and OLT [4]. The traffic traces used are synthetic exhibiting the properties of self-similarity and long-range dependence (LRD). More specifically, the self-similar traffic is used as an aggregation of multiple sources each consisting of alternating Pareto-distributed ON/OFF periods with shape parameter $a = 1.4$. This traffic generation corresponds to the traffic originated from the backbone network, i.e., the Internet, destined to the ONUs. It is assumed that this traffic flow is temporarily buffered within the OLT. The OLT buffer length is set large enough so as to avoid data packet drop, e.g., 100Mbytes. The number of PLOAMd messages included within the XGTC field is randomly produced between 0 – 10 messages per downstream frame.

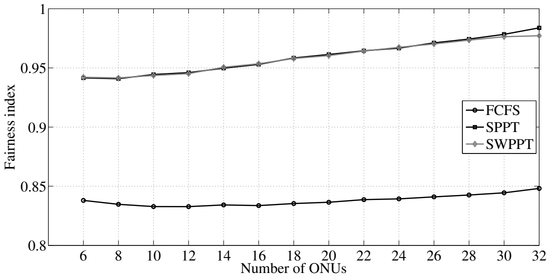

Fig. 1. *The fairness index as the number of ONUs varies.*

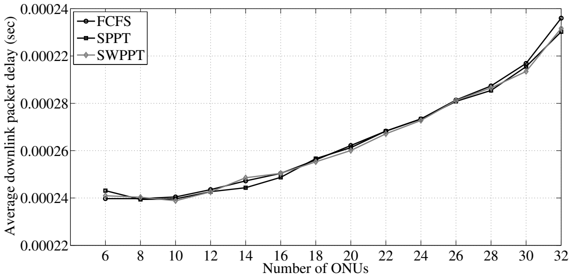

Fig. 2. *The average downlink packet delay as the number of ONUs varies.*

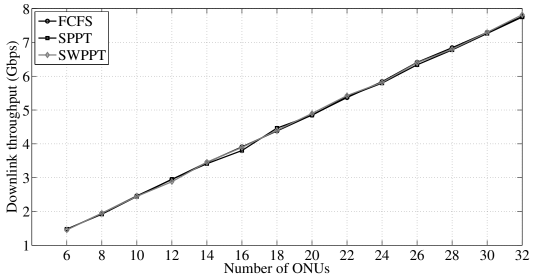

Fig. 3. *The downlink throughput as the number of ONUs varies.*

### B. Numerical Results

The evaluation of the proposed policies is structured in two scenarios. First, the performance of the three policies is examined as the number of ONUs connected to the network increases. In particular, the number of ONUs begins with 6 and increases by two until reaching 32 ONUs. The downlink traffic load is stable and equal to 240 Mbps per each ONU. Second, the number of ONUs remains fixed and equal to 32, while the downlink requested traffic varies. To be more specific, the traffic load varies from 60 to 260 Mbps per ONU.

Fig. 1 depicts the fairness index as the number of ONUs increases. It is clear that the first objective is accomplished, since both policies succeed a fairness index larger than 0.94. The FCFS policy fail to attain a fairness index larger than 0.85. The critical improvement on handling the downlink traffic

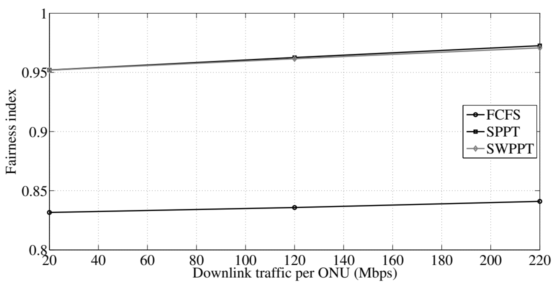

Fig. 4. *The fairness index as the downlink traffic load per ONU varies.*

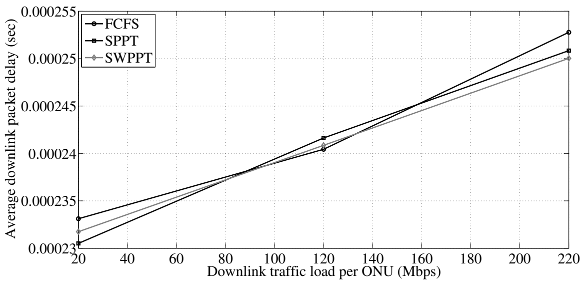

Fig. 5. *The average downlink packet delay as the downlink traffuc load varies.*

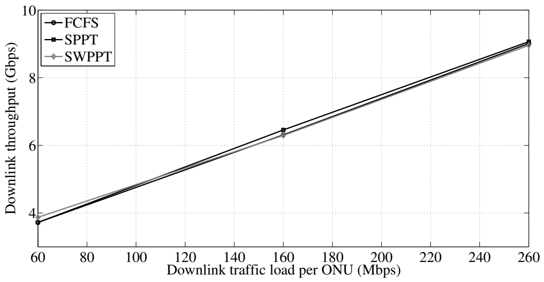

Fig. 6. *The downlink throughput as the downlink traffic load varies.*

requests is retained regardless of the number of ONUs. The reason behind this improvement lies in the module of each proposed policy. In other words, the ability of handling each downlink data packet in accordance with the heterogeneity of the destined ONU, offers a quite fair schedule. Fig. 2 shows the average downlink packet delay of the ONUs as the number of connected ONUs increases. The figure reveals that all algorithms reach almost the same delay levels at average. This means that the function of the proposed policies leaves the network performance intact in terms of average delay. Hence, the tradeoff between the fairness and the average delay becomes advantageous. Fig. 3 illustrates the downlink throughput. Again, all policies offer the same downlink throughput. The obtained remarks from Figs. 1 and 2 indicate the same conclusion: the proposed policies apply a fair schedule without harming the network performance. Fig. 4 depicts the fairness index versus the downlink traffic load. The proposed policies achieve a fairness index of at least 0.95, whereas the FCFS policy shrinks the index below 0.85. Thus, the applied scheduling technique of treating the downlink requests based on the subtle features of each ONU offers notable improvements. Figs. 5 and 6 show the average delay and downlink throughput as the requested traffic load in the downlink direction increases. Once more, it is clear that the network performance remains untouched, while a fair downlink assignment is active.

In a nutshell, both proposed policies succeed almost the same merits independently of the connected ONUs and the offered downlink load. Either in an explicit or in an implicit way both policies achieve a fair downlink bandwidth distribution without overshadowing the system performance.

## VI. CONCLUSIONS

Two novel scheduling policies were presented in this paper. The innovation behind the policies' logic lies in the fact that subtle characteristics such as the propagation delay of the connected ONUs is engaged. Thus, the proposed policies are able to fairly meet the requirements of the XG-PON system in the downlink direction. Indeed, the fairness assurance is accompanied with network efficacy, since the network performance remains in high levels. In a nutshell, the adopted policies could maintain the fairness index over 0.95, whereas conventional scheduling policies such as the FCFS scheme reduce the index below 0.85.

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