Adaptive Protocol with Weights for Fair Distribution of Resources in Healthcare-Oriented PONs

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***Abstract*—The rapid growth of the demand for high-throughput wideband networks with increased security, ease of expansion and cost-efficient architecture has led to a growing interest for new network technologies. Along similar lines, the healthcare sector driven by the need for higher levels of efficient hospitalization, requires in addition, networking technologies that could serve the various hospital application flows in a fair way. A promising candidate that fulfills all the above requirements is the Ethernet-based Passive Optical Network (EPON). The main aim of this paper is to propose a dynamic bandwidth allocation (DBA) scheme specifically for modern healthcare environments that ensures high levels of fairness. Modern healthcare environments are based on a form of ubiquitous computing facilitating continuous and timely monitoring of the patients along with the support of the infrastructure of the hospital area. The algorithm incorporates Quality of Service (QoS) through weighted flows (supports a max-min fairness) and takes into consideration the different requirements that should be met due to the complexity of a hospital environment. The analysis and simulation results show that the proposed scheme ensures fairness while maintaining high levels of performance.**

***Index Terms*—dynamic bandwidth allocation, optical passive networks, healthcare, max min algorithm, fairness**

I. Introduction

Among the variety of access technologies that have been introduced in the last mile access networks, EPON stands out as the most future-proof technology for bringing both narrowband and broadband services to the end-user on any scale, offering high data capacity and reliability. Such an integrated optical access network that can support both wired and wireless last-mile solutions would be ideal for a diverse number of environments like a university, a healthcare campus or a business center. The healthcare sector has become a key player concerning the development of Passive Optical Network (PON), as requirements for low interference generation and tolerance (people should not be exposed to considerable levels of Radio Frequency (RF) radiation from wireless networks), spectrum congestion and energy efficiency were addressed efficiently in this kind of networks.

The role of IT technology in shaping the future of the healthcare sector is major as it can reform traditional tasks towards the hospital of the Future (HoF) [1], a concept that attracts more and more popularity among researchers as it combines a series of different ideas and theories. Real time healthcare monitoring, remote control of medical devices and exchange of information inside the hospital campus, Fig (1), are data demanding processes that require the most from the underlying network infrastructure as hospital institutions are increasingly concerned about ensuring quality care for their clients.

In its general form, a PON is a typical passive optical fiber network. It as a point-to-multipoint optical access network that comprises an Optical Line Terminal (OLT) at the Central Office (CO) which is connected to a number of Optical Network Units (ONUs) at remote ends, using optical fiber and passive splitters. Each ONU is interconnected with the Access Points of the users, either wireless (like pagers and smartphones) or wired (like medical machinery and life-critical devices). The PON technology has also become the prominent technology for Local Area Networks (LAN) with its scalability and ease of administration. It also provides high throughput under a cost effective way with increased security due to its inherent characteristics (light propagation).

Over the years, various PON standards have been developed: EPON, GPON and 10G-PON. GPON will be more suitable for customers with high bandwidth, multi-service, QoS and security requirements and ATM technology as the backbone. EPON is the rival activity to GPON which uses Ethernet packets instead of ATM cells. 10G-PON (also known as XG-PON) enables new capabilities of delivering shared Internet access rates up to 10 Gbit/s (gigabits per second) over existing dark fiber. The research model in this work is not bounded in EPON only but can be applied slightly modified in GPON and XG-PON without affecting the results as their main difference is the higher bit rate (physical level differences do not affect directly the concept of fairness for different generation optical networks).

Driven by the significant growth in application data that need to be transferred among different departments in today's

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healthcare ecosystem, healthcare concerns are looking for next-generation network technologies to support the increasing bandwidth demand in a cost effective way. To address this challenge, healthcare providers are adopting more and more the EPON paradigm to ensure that their critical life-supporting data is delivered with minimum delay and ease in escalation. The addition of internet connected devices that track patients vitals and other diagnostics, created the Internet of Medical Things (IoMT). All the aforementioned devices and needs are part of a realtime connected healthcare system (RTHS). Taking into the equation the different types of network traffic based on differences in the requirements for data transmissions between different clinical departments, the cornerstone of an RTHS is the connectivity among the central infrastructure and the patients and their devices. Better connectivity, scalability security and control can be realized through an enterprise private optical network (PON).

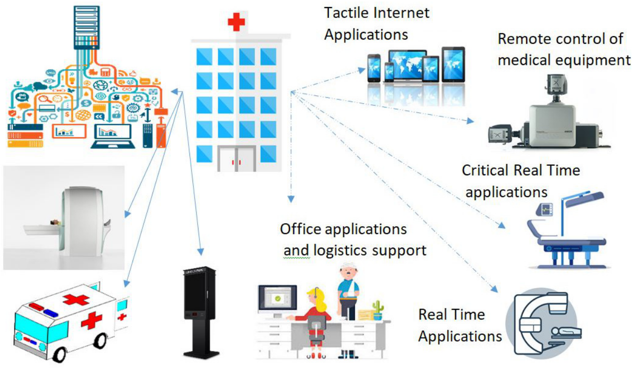

Fig. 1. A novel healthcare environment with the infrastructure (left) and the different types of application flows (right)

In this work, the well-established model in the literature named IPACT [2] is amended accordingly with a fairness scheme so as to be suitable for contemporary healthcare systems supporting various types of application flows. The proposed scheme supports max-min fairness that intuitively allocates the bandwidth primarily to flows with light demand and distributes the remaining resources to more data-demanding flows. This sharing policy seems to fit perfectly to a healthcare environment where hospitalization units and Emergency Room (ER), route almost one third of all the incidents in a healthcare system [3]. By delving into the segmentation of a health care system, one can easily extract that in the aforementioned units, the need for data is based on devices that send light data traffic contrary to other medical departments like the medical imaging devices and the remote surgery equipment. The max-min algorithm selection is fully justified from the fact that according to [4] only a small number of medical issues (on average only $1,55\%$ of errors) related to IT are classified as network transfer problems. Computerized prescriber order entry in hospitals is responsible for almost 75% of the IT related errors meaning that the majority of the healthcare information traffic is assigned to applications with limited data needs realized by small data chunks. Hence, the need for reliably handling these types of traffic is fully covered from a service priority algorithm that maximizes the light data flows serving.

The remainder of this paper is organized as follows. In Section 2 the work related to fairness in PONs is presented while in Section 3 we visualize the relation between performance and fairness. The proposed scheme along with simulation results are provided in Section 4 with aim of verifying that the algorithm presented does not overshadow the system performance. Finally, Section 5 concludes this paper.

II. Related Work

As the IEEE 802.3ah standard for the EPON does not mandate any specific approach concerning the assigning of the channel bandwidth across different users, there is a substantial number of Dynamic Bandwidth Allocation (DBA) algorithms for allocating bandwidth in the upstream channel from ONUs to OLT. One of the first, and admittedly, the most well-known is IPACT. It goes without saying that, the number of protocols that incorporate fairness is a small portion of the proposed in the literature DBA algorithms, as fairness has received relatively little attention. In [5], the authors explored bandwidth allocation among heterogeneous flows coupled with router queue management schemes. In [6], the authors proposed a queue management system called Approximate Fair Dropping under a sufficiently large buffer. Even though they considered different buffer sizes, they did not take into consideration the effect of buffer sizing in fairness behavior. That last detail was investigated by [7].

In [8], various buffer allocation strategies were explored when heterogeneous traffic is multiplexed at an optical router with very small buffers. The effect of the heterogeneity of different TCP flows in fairness was studied in [9] showing that the queue management schemes and buffer sizes have a direct effect in the overall fairness of the system. In [10], the authors discussed the fairness of the Limited Allocation with Excess Redistribution (LAER) using fixed weights in an absolute sense rather than based on a more dynamic sense. Thus there is a need for an adaptive algorithm tailored to the needs of a contemporary hospital campus.

III. Fairness and Performance Consideration in a Healthcare System

Healthcare communication system network should enable prioritization and ensure fairness of data transmissions. Nevertheless, in networks that reward heavy flows in order to maximize network utilization and performance the problem of starvation may appear. In this case, the channel resources are not equally available to all the flows resulting in resource starvation for these flows. The proposed algorithm was designed in order to provide a fair resource allocation in an optical network especially in healthcare environments but also do limit the occurrence of starvation. The fairness of bandwidth allocation of an algorithm can be characterized, either by quantitative or by qualitative indexes. The most common quantitative fairness indices are the Jain's Index, the statistical entropy of the system and the Tian Lan's model. Qualitative fairness measures include the max-min fairness along with the proportional fairness [11].

Even though prioritization and fairness are complementary concepts, fairness and performance have a more complex relation as the throughput performance remains robust as long as bandwidth sharing is reasonably fair [12]. Fig 2 shows the sweet spot that a fair algorithm tries to attain. The dashed line represents the optimal network resources distribution between two flows $f1$ and $f2$ ($f1 + f2 = C$, where C is the capacity of the connection between the flows-ONUs and the OLT). The surface above that line in the white area stands for an overuse of resources which obviously is valid only on a theoretical level, while all point in the filled area represent a solution that is not optimal. The red line is the optimal solution $(f1 = f2)$ from a fairness perspective. The point S where the two lines intersect is the optimal solution for every algorithm that tries to combine performance and fairness. In practice, during the execution of any fair algorithm the working range will be inside the dark blue area, aiming at the cross section of the red and the dashed line (green spot) .

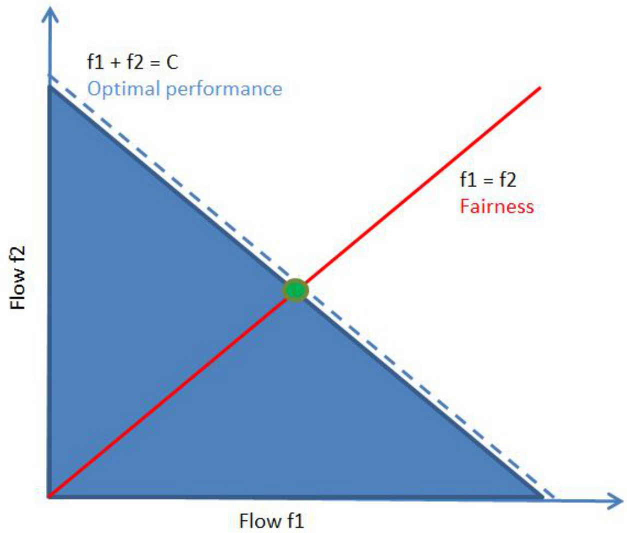

Fig. 2. Performance and Fairness interaction chart

IV. An Adaptive Weighted max-min Fairness Algorithm for Healthcare Environments

Following the system described by the seminal work in [2], OLT determines the Grant policy in this cycle (Grant is the control message that informs each ONU on the number of bytes it is permitted to send) for all the ONUs. A key point of differentiation in the proposed algorithm is the multiplexing principle that was applied. Every ONU has a finite number of queues which are served in order of their priority. In the original IPACT, the packets generated by the sources are aggregated on a single line without overlapping, applying the FCFS discipline to multiplex the packets. However, in a fully occupied ONU buffer, the higher priority packets will take the place of lower priority packets. This has a direct effect on the mean packet delay, as packets that are inside the buffer waiting to be transmitted to the OLT may be replaced by newer packets with a higher priority. Consequently, the older packets will be replaced, and as statistics are based on packet-level measurements, the packets that were dropped according to their priority inside a buffer would affect the measurements in favor of newly arrived packets, resulting in lower packet delay times.

Another reason for not applying any kind of prioritization between the different queues inside an ONU is because this could bend the fairness of the service policy of the proposed algorithm. OLT should be the main orchestrator, responsible for applying the fairness policy, without any kind of packet sieving inside the ONUs that could alter the results. The self-similarity and long-range dependence characteristics of the Pareto distribution were preserved as in the aforementioned work in order to have a direct comparison between the proposed scheme and the well-established model in the literature.

TABLE I

Traffic Type	Delay
Tactile internet	$<$1msec
Remote control of medical devices	$<$3sec
Critical real-time medical equipment	$<$300msec
Non critical real-time medical equipment	$<$10msec
Support services	$<$1sec

We considered 5 different categories for the traffic of a healthcare ecosystem as shown in Table I. These categories were based on a healthcare system special characteristics and needs for network resources and servicing. The Tactile internet applications do not tolerate neither packet losses nor delays. Remote control of medical application traffic that support the operation of medical devices like the injection pumps that control the medicine portions injected to the patients cannot tolerate unpredictable delays or losses. This traffic type does not need high bandwidth but is almost 0 packet-loss tolerant. Life-critical real-time applications include devices that monitor critical functions and support of Triage systems [13], [14]. They require low packet loss rates and high service rates. Medical imaging and medical teleconference applications can stand packet losses but they are sensitive to variations of packet arriving times (jitter). Finally, health care support services including office applications and infostations are less demanding as they can handle medium delays and packet losses.

The aim of the algorithm is twofold:

1) To restrain aggressive behaviors from resources wanting to monopolize the optical medium and assign in a more targeted manner the available bandwidth
2) To categorize the data packets and serve them according to their priorities. Priorities are assigned from a weight mechanism in order to offer a fine granularity QoS.

Inspired from previously proposed congestion control mechanisms, the scheme is based on a weighted max-min fairness algorithm, applying an adaptive logic so as to ensure performance for the most critical flows of a healthcare system. Each flow is ranked based on the type of application data. This is implemented by the different weights they have been assigned. ER departments have the maximum priority while support devices have the lowest and this is directly translated to different weight coefficients for each group of ONUs. The weight assignment coefficient is introduced so as to describe the dispersion of the assigned weight values of the flows.

A. The Healthcare-oriented Fair (HoF) Algorithm

By evaluating each ONU buffer occupancy, the system amends the assigned weights in order to release the pressure from the heavily fulfilled ONUs maintaining the packet loss probability as low as possible. The Jain index calculation, is used as a tool to visualize fairness and spot the differences in fairness when different weights assignment ratios are used.

We assume that there are N ONUs. Every ONU transmits data with a rate of r_i, $i \epsilon 1, ..N$. Every source is assigned a weight w_i based on its application traffic and the channel bandwidth is C. The Gated scheduling service discipline is used (does not impose any limitation on the granted window) as long as the demand from ONUs does not exceed the channel bandwidth capacity. As shown in [2], this service has the best performance concerning delay and average queue size among the others.

At the beginning of a new service cycle, the OLT sums up the requested bandwidth and in the case of $\sum r_i > C$, calculates the fair share portion of C as $c_i = \frac{w_i}{\sum w_i} C$.

For the resources where $r_i > c_i$, the bandwidth surplus $c_i - r_i$ is being prorated among the other sources. This procedure continues until there is no bandwidth surplus. With the aim of providing fairness, the algorithm supervises the ONUs buffer occupancy and in case this exceeds 50%, then the assigned weight of the flow is updated by adding $0,25$ units for every 10% of increase. By adding units, apart from the obvious result of increasing the bandwidth share for the specific ONU, the probability of a packet loss due to buffer occupancy also decreases. The threshold was specifically selected because around that buffer size, the Gated service has the steeper buffer occupancy increase, related to offered load.

Algorithm 1 Adaptive max-min weighted fairness algorithm

Inputs: i Number of ONUs, r_i Requested bandwidth from $\mathrm{ONU_i}$, w_i Weight of $\mathrm{ONU_i}$

Outputs: Bandwidth distribution for every ONU

ONUs: Receive data and, Send Report messages to OLT

OLT:

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1: Calculate ∑ r_i for all ONUs that remain without a fair
   share.
   IF ∑ r_i > C
2:   then IF buffer size of ONU > buffer/2
3:        then For every 10% of total increase w_i = +0.25
          and For every 10% of total decrease w_i = −0.25
          ENDIF
4:   Normalize all weights
5:   Find the minimum guaranteed bandwidth Z = (w_i / ∑ w_i) C
     for all the remaining ONUs.
      IF Z > r_i
6:     then calculate ∑ Z − r_i. Update the list of remaining
       ONUs. Distribute to the remaining ONUs the ∑ Z − r_i
       according to their weights.
       ENDIF
   ENDIF
```

The Jain index is calculated from the following formula:

$$J(X_1, X_2, ...X_n) = \frac{(\sum_{i=1}^{n} x_i)^2}{(n \sum_{i=1}^{n} x_i^2)} \quad (1)$$

The relation (1) calculates how fair is the measured bandwidth distribution according to the criterion for fair throughput, the max-min optimality with weights.

B. Simulation Results

A simulation framework was developed for verifying the operation of the model. A series of simulations have been conducted in measuring the mean packet delay and the Jain index of fairness for various weight assignments. Our simulator tool was developed on the Anylogic multimethod simulator platform [15]. There are two main conceptual components implemented in Java: the OLT component and the ONU component. Each component encompasses all of the parameters related to their specific operation. OLT includes parameters like the number of active ONUs, data structures for storing the incoming messages, timers and weight information. ONUs on the other hand, have a buffer structure for storing the incoming messages and the traffic generator component that ensures the unique traffic characteristics injected into the system. For every ONU there are 32 streams sending data. The resulting traffic is an aggregation of these streams, each one consisting of alternating Pareto-distributed ON/OFF periods. The ONUs send their Report messages one after the other. The OLT component, having all the Report messages from the ONUs, runs the algorithm and calculates the final bandwidth distribution in the beginning of every cycle. The parameters that were used are described in Table II.

TABLE II
SIMULATION PARAMETERS

Paremeter	Value
Number of ONUs	16
Upload bandwidth from ONU to OLT	1000Mbps
Input bandwidth from each source to ONU	100Mbps
Number of sources for each ONU	32
Traffic generator characteristics	Pareto
Packet interval size	160bit
Guard Time	5µs
ONU buffer size	10MB
Weight distribution schemes	1_1_1_1_1, 1_5_1_5_1, 10_10_1_1_1, 1_1_1_10_10, 1_1.3_1.6_1.8_7

1) Fairness Algorithm vs IPACT: Fig 3 depicts the mean packet delay as a function of an ONU's aggregated load. There are three different algorithms presented in this figure. The blue line represents the original IPACT model results, using the Gated grand scheduling service. The green line represents the mean packet delay from the proposed algorithm where all the ONUs have the same weight. This is a model without any distinctive QoS and is related to IPACT with a modification in the aggregation of sources in each ONU. Otherwise stated, green line is the IPACT gated model without any type of priority. This specific result establishes the claim stated before, where the applied priorities in the queue aggregation of IPACT result in lower packet delay.

The third line in Fig 3, shows the average servicing time for the healthcare system, having 5 different flow types with different priorities (weights). In low loads ($< 30\%$), the system has comparable delay times with a system without QoS. However, as the load increases until it reaches about 60%, there is a decrease in the service speed for the proposed algorithm as the system tries to serve first the small flows (like ER) and holds up the heavier flows. This service delay affects the packet delay times. Above 60% of load the three systems have comparable delays reinstating the fairness algorithm as a balance option for these types of networks.

A noteworthy point in Fig 3 is the phase transition observed around 60% of load. This is explained by the following rationale:

- As there are 16 ONUs and $C = 1000Mbps$, the total bandwidth in case of equal transmission demands from each ONU should be:

$$\frac{1000\ Mbps}{16} = \frac{125000000\ bytes/sec}{16} = 7812500 bytes/sec \tag{2}$$

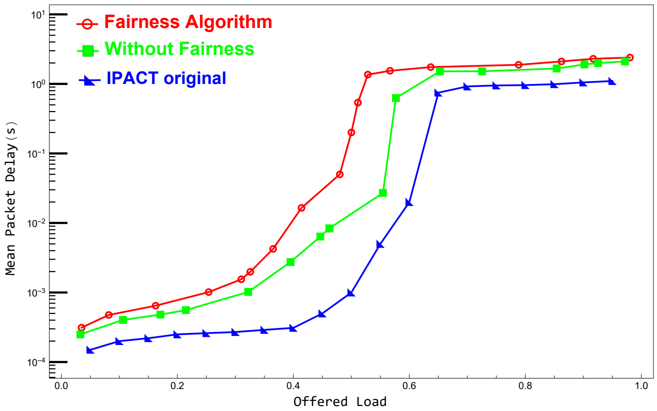

Fig. 3. The Mean Packet Delay of the model using the Adaptive Fair algorithm with different weights, without weights and IPACT model

- Taking into consideration that the ONU to OLT line is 100Mbps, the load from equation (2) is equal to

$$\frac{7812500\ bytes/sec}{100\ Mbps} = \frac{7812500\ bytes/sec}{12500000\ bytes/sec} = 0,625 \tag{3}$$

The result from (3) represents the percentage of offered load above which the system will face significant delays because the OLT would not be able to serve the request in one cycle. This will eventually result in packet losses, as in the next cycles new packets will arrive in ONUs having almost fully occupied buffers. Evidently, this is the point where the system undergoes a phase transition concerning the packet delay.

2) Different Weight Assignments: Contributing to the substantiation of the proposed model, the specific simulation scenario shows the effects of different weight assignments. Fig 4 presents the calculated Jain index for the weighted algorithm. The red line practically reveals the fairness of the algorithm for the case where all the ONUs have the same priority. As there is no type of QoS, all ONUs receive a max-min portion of the bandwidth so the calculated index reaches almost 0,98. However as it can be extracted from the other graphs of Fig 4, the weight distribution plays a key role in the calculated fairness. The weight coefficient for the four weight distributions $1, 1.3, 1.6, 1.8, 7/1, 5, 1, 5, 1/10, 10, 1, 1, 1/1, 1, 1, 10$ is 0.8844, 0.7537,0.95, 0.95 respectively. Hence, regarding the weight coefficient, there is no direct correlation to the fairness. However taking a deeper look at the results reveals something interesting. As the OLT serves the ONUs on a cycle basis, it creates a type of linearity in serving regarding the weights. As the OLT calculates the Gated messages for each ONU based on the proposed algorithm, after every iteration the OLT tries to serve first the ONUs having the higher weights based on a sequential order. By this token, the weight distributions that puts large weights in the first positions of the weight distribution array tend to have lower Jain indexes as they create inequalities in the way the OLT serves the ONUs.

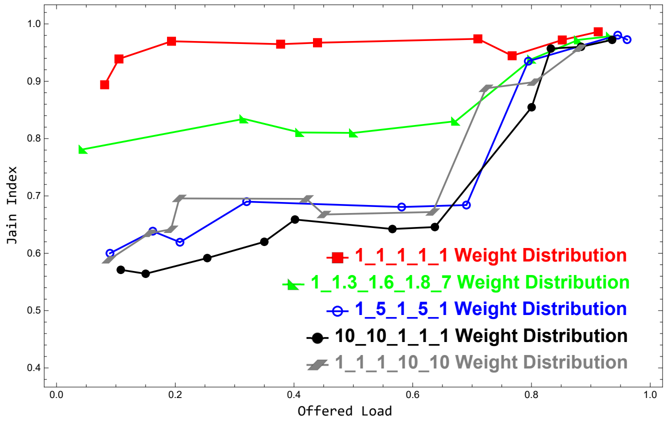

Fig. 4. Jain index for different weight assignments

Based on Fig 4, it should be also mentioned that lower loads have smaller values of the Jain index. Contradicting though it may be, the result is fully explained by the fact that in lower system loads, there are only a few packet burst but with a huge number of packets relative to the system load, that cause the system to give almost all the available bandwidth to these flows. However, as the load increases, almost all the flows experience these bursts so the previous inequality is being diminished.

V. Conclusions

As the emergence of modern healthcare facilities has become another potential domain for the EPON, the fairness aspect gains popularity. To this end, a novel fairness algorithm has been developed based on the special characteristics of a healthcare system and a number of simulation scenarios have been devised. This study revealed that despite conceptual differences between performance and fairness, existing DBA algorithms can be enhanced with QoS characteristics in order to serve the multifarious hospital environments. The weight distribution between the nodes of a PON directly affects the notion of fairness and should be selected based on the specific needs of each application area. Future work should investigate the existence of optimal weight distributions based on the perceived QoS (the newly established Quality of Experience-QoE) and even insert a form of prediction in order to minimize the mean packet delay.

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