# Self-adjusting DBA algorithm for Next Generation PONs (NG-PONs) to support 5G fronthaul and data services

Aziza Zaouga, Amaro de Sousa, Monia Najjar, and Paulo Monteiro

***Abstract*—In this paper, we propose a novel Dynamic Bandwidth Allocation (DBA) algorithm for NG-PON networks to jointly support 5G fronthaul and best-effort data services in the same PON channel. The proposed Self-adjusting DBA adjusts dynamically the allocation intervals to the current required fronthaul throughput based on the requests reported from the ONUs. It is suitable for dynamic 5G scenarios where, for energy efficiency reasons, the fronthaul connections are dynamically set up and torn down over time: when a new 5G fronthaul connection is set up, the maximum latency of the current connections is guaranteed while when a current 5G fronthaul connection is torn down, the freed transmission resources become available for data services. The only requirement is that the capacity of the channel in the NG-PON network is enough to support the throughput of all 5G fronthaul connections supported by the channel. In this way, the proposed Self-adjusting DBA algorithm has the advantage of reducing to a minimum the management coordination between the 5G infrastructure and the NG-PON infrastructure, that is usually required when the throughput of the 5G fronthaul connections is supported as a guaranteed service.**

***Index Terms*—DBA, NG-PON, channel bonding, 5G fronthaul, latency.**

## I. Introduction

OVER the last years, traffic demand has dramatically increased and is predicted to continuously grow due to new multimedia streaming services, Internet of Things and machine-to-machine communications [1]. Therefore, new technologies related to wireless and wireline networks have emerged. In wireless, the increase of mobile traffic combined with the variable load of baseband units during the day cycle has lead the 3rd Generation Partnership Project (3GPP) to propose new Radio Access Network (RAN) architectures [2].

These architectures based on Next Generation Radio Access Network (NG-RAN), allow the sharing of resources between different base stations. This not only reduces operation costs, but also allows for greater densification of base stations, by splitting the traditional base station into smaller units of the 5G RAN: Centralized Unit (CU), Distributed Unit (DU) and Remote Unit (RU). Each of these units is responsible for a specific part of the protocol stack, being the CU responsible for the higher layers, the DU for the lower layers and the RU for the final digital and analog radio frequency layer (RF) [3].

In Centralized RAN (C-RAN) architecture, CU is centralized in the access convergence room or small access room, where DU and RU, (can be up to 20 km far away) are connected together by an optical transmission network based on the Radio-over-Fiber (RoF) technology called mobile fronthaul (MFH) [4]. Different initiatives and alliances of equipment manufacturers, operators and academy have been proposing different transmission and control management protocols for MFH, such as Open Base Station Architecture Initiative (OBSAI) [5], Open Radio Interface (ORI) [6] and Common Public Radio Interface (CPRI) [7] protocol. CPRI is the typical and widespread MFH interface at 4G/LTE radio access technology. But since it is hungry in term of fronthaul throughput, it gave place to the emergence of a new version called enhanced-CPRI (eCPRI) [8] suitable for 5G technology and based on new functional splits of the radio stack. More recently, the WG4 (The Open Fronthaul Interfaces Workgroup) of the O-RAN Alliance has been working on truly open fronthaul interfaces for 5G, in which multi-vendor DU-RRU interoperability can be realized [9].

The 5G technology has improved the throughput, the latency and the number of connections, in addition to the new application features and the new network architectures [10], [11]. This has created the conditions for a convergence between mobile and fixed infrastructure. In other words, this has enabled the fixed access infrastructures to support mobile services, in one hand, and the mobile infrastructures to be extended to support fixed service, in the other hand [11], [12]. In contrast, it has imposed new requirements to the transport network such as low latency, synchronization and high transmission bandwidth, as performance aspects, and cost-savings as operational aspect.

One of the most promising solutions to support 5G MFH is Passive Optical Networks (PONs) since it is a widely deployed Fibre-To-The-Premise (FTTP) technology and available in many urban areas. It has also the lowest FTTP deployment cost compared to fibre point-to-point and perfectly suited to bursty traffic services [13]. PONs also benefit from the fact of their inherently centralized system architecture which makes them suitable for MFH in a C-RAN architecture.

There are three major PON options, Wavelength Division Multiplexing (WDM), Time Division Multiplexing (TDM) or an hybrid solution called Time- and Wavelength-Division Multiplexing (TWDM-PON). The general PON architecture consists of an Optical Line Terminal (OLT) located in a central

A. Zaouga, A. de Sousa and P. Monteiro are with the Instituto de Telecomunicações, Departamento de Eletrónica, Telecomunicações e Informática, Universidade de Aveiro.

A. Zaouga and M. Najjar are with Communication Systems Laboratory (SysCom), National Engineering School of Tunis (ENIT), University of Tunis El Manar (UTM), Tunisia.

office (CO) connected via an Optical Distribution Network (ODN) to multiple Optical Network Units (ONUs) located in the subscriber's premises and it is able to fully support both fixed and mobile traffic. Figure 1 illustrates the architecture of a PON based fronthaul: an OLT is located in a central office and connected with a CU and/ or DU while ONUs are located nearby antenna sites and linked with RUs.

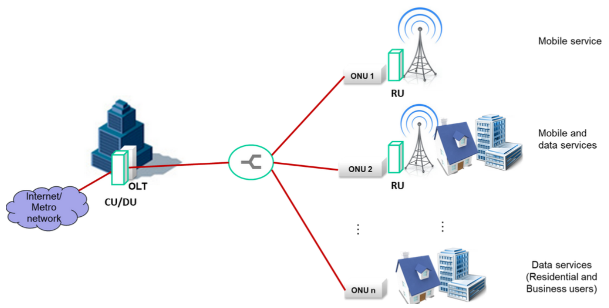



Fig. 1: General PON architecture

Supporting multiple wavelength channels (up to 8) in Downstream (DS) and Upstream (US) directions makes NG-PONs based on TWDM-PON technology, a very high-capacity fiber access system able to support different services including residential, business, mobile and Internet of Things. In fact, NG-PON2 has been normalized to support up to 40 Gbps (4 $\times$ 10 Gbps) of PON capacity and can go up to 80 Gbps (8 $\times$ 10 Gbps) [14]–[16]. According to the latest updates of the physical media dependent (PMD) layer standard (G.989.2), several enhancement options for the NG-PON2 have begun to be discussed to reach a 100 Gbps capacity PON (4 $\times$ 25 Gbps), based on what IEEE 100G-EPON Task force targets in [17] and [18] and what IEEE Std. 802.3ca-2020 standard specifies in [19]. These options include the increase in per-channel line rates from 10 Gbps to 25 Gbps [18] and the use of wavelength channel bonding [17]. Channel bonding consists on enabling an ONU to operate simultaneously on multiple channels, achieving in this way a higher aggregated data rate [20], [21] to further accommodate the eventual increase of customers and bandwidth demand. These enhancements leverage a high capacity PON and flexible bandwidth sharing.

In each wavelength in the US direction, the NG-PON uses time division multiplexing to schedule the transmission opportunities between ONUs and avoid collisions while transmitting data to the OLT. Therefore, a packet scheduling algorithm, commonly named a Dynamic Bandwidth Allocation (DBA) algorithm, is needed to manage the bandwidth among all ONUs operating at each single wavelength. In fact, allocating and scheduling optimally the US bandwidth to satisfy the fronthaul low-latency requirement has been a hot research topic for PON based fronthaul [15], [22], [23]. Since the major constraint of fronthaul is the maximum latency, in this work, we investigate the time domain of a single channel in the NG-PON in order to resolve the 5G fronthaul latency requirements.

To reduce the throughput of the 5G fronthaul between the distributed unit (DU) and the remote unit (RU), 7 different functional split options (from 2 to 8) have been proposed for the base station, including, the option 7 with its variants 7.1, 7.2 and 7.3, depicted in Figure 2 [24], that are candidates to be used for 5G (the traditional 4G/LTE fronthaul given by CPRI protocol corresponds to split option 8). Split options 8 and 7.1 require a constant bitrate transport regardless of the presence of user traffic. In the other split options, the required bitrate becomes lower and bursty but at the cost of not providing many advanced features useful in practice as cooperative multipoint (CoMP) and enhanced inter-cell interference coordination (eICIC) [25]–[27]. So, in this work, we consider that the 5G fronthaul connections operate in split option 7.1, as it requires a lower throughput than split option 8 and maintains all advanced features.

As specified in [24] and [28] for split options higher than 5, the maximum allowed one-way latency (DS or US delay) cannot exceed 250 $\mu$s, including the propagation delay and the processing delays. In order to use NG-PON for mobile fronthaul traffic toward 5G networks and ensure that the 5G latency requirements are met, it is crucial to design a proper DBA algorithm taking into account the fixed mobile convergence scenarios.

To achieve such aim, we have previously proposed in [29] and [30] a DBA algorithm for NG-PON2 that supports both 5G fronthaul and best-effort data services on a single PON channel. The DBA algorithm proposed on those works is different from the classical DBA in terms of the number and the structure of the allocated time slots at each upstream frame and it was shown that it minimizes the US 5G fronthaul delays and also maximizes the data services throughput among all active ONUs connected to PON channel. In these previous works, the 5G fronthaul service was treated as a guaranteed service. Such proposal might be not suitable for dynamic 5G scenarios where, for energy efficiency reasons, the fronthaul connections can be dynamically set up and torn down over time. In such case, a tight management coordination between the 5G infrastructure and the NG-PON infrastructure is required so that the throughput value of each new 5G fronthaul must be first set in the new DBA settings and the throughput of each torn down 5G fronthaul connection must be freed (or, otherwise, it will remain reserved preventing the network to use it for data services). Similarly to [29] and [30], the DBA proposed here assumes that a single allocation interval is assigned to both services and each ONU uses its allocation interval to transmit the packets of both services giving higher priority to 5G fronthaul packets.

In this paper, we propose a Self-adjusting DBA algorithm for NG-PON networks to jointly support 5G fronthaul and best-effort data services in the same PON channel such that the 5G fronthaul service is not treated as a guaranteed service. The Self-adjusting DBA algorithm is suitable for 5G dynamic scenarios by dynamically adjusting the allocation intervals to the current throughput required by the 5G fronthaul connections solely based on the requests reported from the ONUs. The only requirement is that the capacity of the PON channel in the NG-PON network is enough to support the throughput of all 5G fronthaul connections supported by the channel. In this way, the proposed DBA algorithm reduces to a minimum the management coordination between the 5G infrastructure and the NG-PON infrastructure, that is usually required when

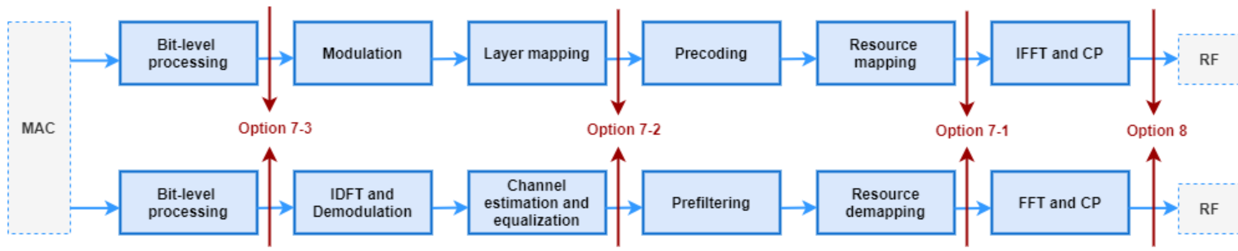



Fig. 2: Different split options for the lower-layer processing [27].

the throughput of the 5G fronthaul connections is supported as a guaranteed service.

This paper is organized as follows. Section 2 provides a brief overview of related work. Section 3 describes the proposed DBA algorithm, together with its considered variants. Section 4 presents and analyses the results obtained by a simulator developed for this aim. Finally, Section 5 offers closing remarks.

## II. Related work

NG-PON2 is a PON technology evolution, inherited from GPON and XG-PON, standardized under the ITU-T G.989.x standards. A NG-PON2 may accommodate a set of point-to-point wavelength division multiplexing (PtP-WDM) channels, or a set of time and wavelength division multiplexing (TWDM) channels, or both [31]. By dint of TWDM, a NG-PON2 system supports multiple wavelength channels and is able to add more capacity as the demand grows. Very recently, a critical mass of operators, vendors and a research institute (18 co-signers) proposed a new project to support 25G PON [32]. Our goal is to study novel DBA algorithms for 5G fronthauling considering next-generation PON systems.

NG-PON2 was developed to provide optical access for residential, business mobile backhaul services and to support mobile fronthaul applications, up to CPRI option 8, over the overlay point-to-point wavelengths [31]. Moreover, it is able to co-exist with previously deployed PON networks, such as GPON and XG-PON1, on the same infrastructure as illustrated in Figure 3. This advantage makes easier the migration of existing subscribers to the new technology without disturbing services for customers on the legacy PON systems.

In a given TWDM channel in NG-PON2, all ONUs operating on the channel are sharing the US path contrary to the DS in which a broadcasting mechanism is used to transmit traffic. Thus, a process to allocate the upstream transmission opportunities to ONUs is needed, which is commonly referred to as the Dynamic Bandwidth Allocation (DBA) mechanism. The DBA decision is made based on the dynamic indications in the US direction from all connected ONUs, which includes the current US buffer occupation. The buffer occupation reporting can be based on one of the following methods: (i) a Status Reporting (SR) method which is based on explicit reports; (ii) a Traffic Monitoring (TM) method through the observations of the idle XG-PON Encapsulation Method (XGEM) frames during the upstream transmission opportunities; or (iii) both [28]. Generally, in a PON system, assigning dynamically the

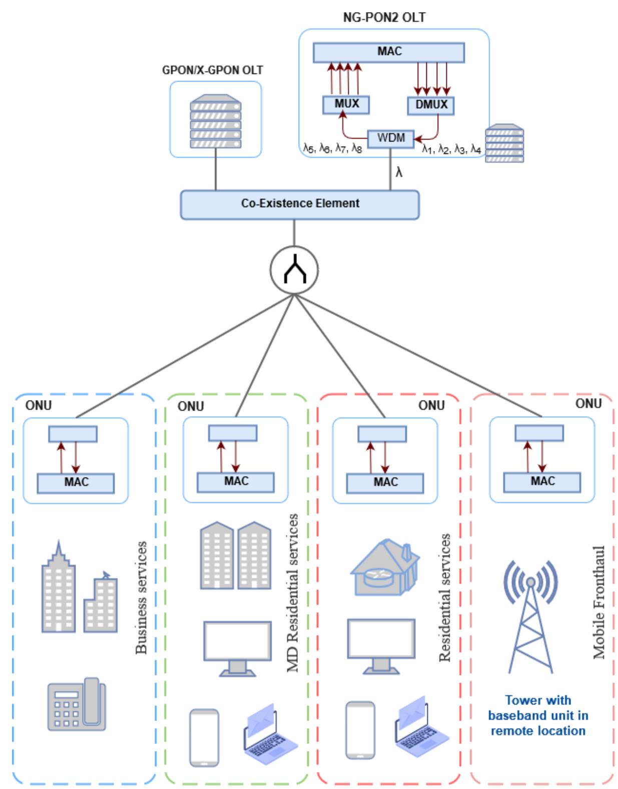



Fig. 3: NG-PON2 architecture.

bandwidth improves the upstream bandwidth utilisation and enables operators to include more subscribers in the access network.

In the US direction, each traffic-bearing entity is represented by an allocation ID (Alloc-ID). These Alloc-IDs are considered by the OLT as logical buffers and the traffic aggregate associated with each subtending Alloc-ID is modelled as a single logical buffer [14]. Hence, it is mandatory to avoid collisions by scheduling the transmission of ONUs including their associated Alloc-IDs in the US direction. This is the role of the DBA mechanism where the bandwidth allocation to different Alloc-IDs are multiplexed in time for a given TWDM channel.

In the DBA mechanism, the DBA algorithm in the OLT starts by collecting information about the ONUs' buffers occupation using one of the methods mentioned above. In the case of SR DBA, in-band status reports are sent by ONUs in the beginning of their US transmission opportunity through a flag called dynamic bandwidth report (DBRu). Based to the received indications, the DBA algorithm determines the bandwidth allocation for every traffic-bearing entity of every ONU and generates a bandwidth map (BWmap) specifying the start and the end time instants of the US opportunities of every Alloc-ID (named in the remaining of this paper as allocation intervals). BWmap is broadcasted to the ONUs at the beginning of every DS frame. Thus, every ONU is allocated with a time slot composed by multiple allocation intervals, in which each one corresponds to an associated Alloc-ID as depicted in Figure 4 [33]. The bandwidth calculation and allocation are handled by the DBA algorithm run in the OLT every 125 $\mu s$ since both US and DS frames have a fixed size of 125 $\mu s$ [14].

Generally, with TWDM-PON, managing the time domain of each wavelength is a key challenge. This is more challenging when supporting a mix of data services and 5G fronthaul services since the latter ones require to guarantee a latency of less than 250 $\mu s$, including the propagation delay due to the fiber with a length that can reach 20 km. Indeed, managing and controlling the time domain is the main issue for TDM and TWDM PON based fronthauls and the DBA has been an important research topic in PON systems.

To improve the US delay performance in TDM and TWDM PON, several DBA algorithms have been proposed. Most of the proposals were for Ethernet PON (EPON).

In [34], a DBA based on Fuzzy logic was proposed, which consists of the application of DBA both on the OLT and the ONU side and the bandwidth allocation to each ONU is based on Interleaved Polling with Adaptive Cycle Time (IPACT) [35]. The bandwidth is allocated to each type of traffic in the ONU using a fuzzy logic regulator. The results showed that the average packet delay is low compared to previous proposals in addition to the high bandwidth utilization.

In [36], the authors propose the Universal-DBA (UDBA) in which it allocates, at first, a minimum bandwidth and, then, it allocates the remaining bandwidth according to the excessive and the shortage bandwidth of the under-loaded queues and the over-loaded queues, respectively. The UDBA algorithm grants giving priority to the under-loaded queues over the over-loaded queues. The experimental results showed that this algorithm improves packet delays and bandwidth utilization.

In [37], Tashiro, Takayoshi et al. have proposed a novel DBA algorithm for EPON based fronthaul (M-DBA) that assumes the cooperation between the mobile and the optical networks and the bandwidth allocation is associated with the processing of the mobile scheduling to guarantee the latency requirement of the mobile fronthaul.

Moreover, in [38], Hatta, Nobuyuk and Takeshi have developed a low latency DBA method to address the priority scheduling in mobile fronthaul. The DBA cycle in this method depends on the traffic load, it is shortened in the case of a light traffic load and thus it reduces the latency and improves the bandwidth efficiency. In [39], the same authors propose a new idea of a DBA, based on the DBA proposed previously in [38], to further improve the bandwidth efficiency of the algorithm.

Concerning TDM-PON, a recent scheme has been proposed in [40] for network-slicing. This scheme is based on the cooperative dynamic bandwidth allocation scheme proposed in [41] that allocates time slots by estimating data arrival period from mobile scheduling information. The proposal incorporates bandwidth allocations for guaranteed bandwidth given by the allocation for MFH and IoT Slices and for the discovery window in the auto-discovery process given by the allocation for control slice. Using this algorithm, the US latency on MFH slice is minimized.

Concerning TWDM-PONs, several dynamic wavelength and bandwidth allocation (DWBA) algorithms have been recently proposed for MFH in TWDM-PON systems including NG-PON2 and NG-EPON, such as the proposals in [42] and [43] that allocate the wavelength and the bandwidth based on the characteristics of TDD (Time-Division duplex) fronthaul traffic. The proposal in [44] consists on allocating multiple time slots in multiple wavelengths to each ONU. The main purpose of these algorithms is to minimize the number of active wavelength channels in order to improve the energy efficiency and to connect the maximum number of accommodated Radio Units (RUs), in addition to satisfying the strict delay requirement of mobile fronthaul.

Furthermore, there has been some research for adapting the DBA algorithms proposed for TDM-PON and deployed in NG-PON2 system, focusing on improving the transmission packet delay of fronthaul segment and the bandwidth utilization efficiency, like the proposal in [26] that applies the M-DBA in every TDM-PON corresponding to a single wavelength and the proposal in [45] that consists of combining SR-DBA (status-report DBA) and CO-DBA (cooperative DBA).

Note that some of these previous proposals do not address the specific latency requirements of mobile fronthaul. Moreover, all DBA proposals for the support of 5G fronthaul over PON networks require a tight coordination between the 5G infrastructure and the PON infrastructure, which, in practice, assume that the 5G operator deploys the mobile fronthaul over its own PON infrastructure. In this work, we focus on appropriate DBA algorithms for fixed mobile convergence scenarios where the operators of already deployed PONs aim also to support the 5G fronthaul connections that 5G operators need between their central office locations and their site locations. Such scenarios require solutions with minimal management coordination between the 2 operators.

## III. Proposed Self-adjusting DBA algorithm

In this section, we describe our proposed Self-adjusting DBA algorithm, the reporting variants and the time slot calculation methods for NG-PON. The aim is to minimize the 5G fronthaul delay and to provide a maximum data service throughput as fair as possible among the different active ONUs.

### A. Proposed Reports variants

In the conventional DBA mechanism of TWDM-PON, a report is sent by each ONU at the beginning of its allocation interval and the reporting information is the occupation of each of its queues (in number of bytes) at the moment of the report upstream transmission (i.e., at the beginning of the allocation interval). This has been shown to be adequate for best-effort

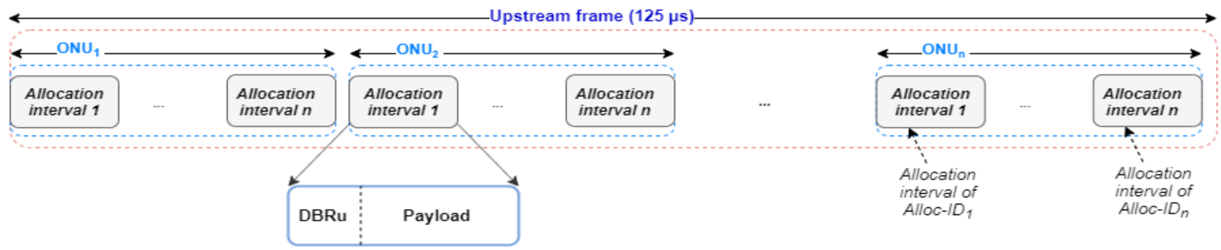



Fig. 4: Conventional DBA scheme.

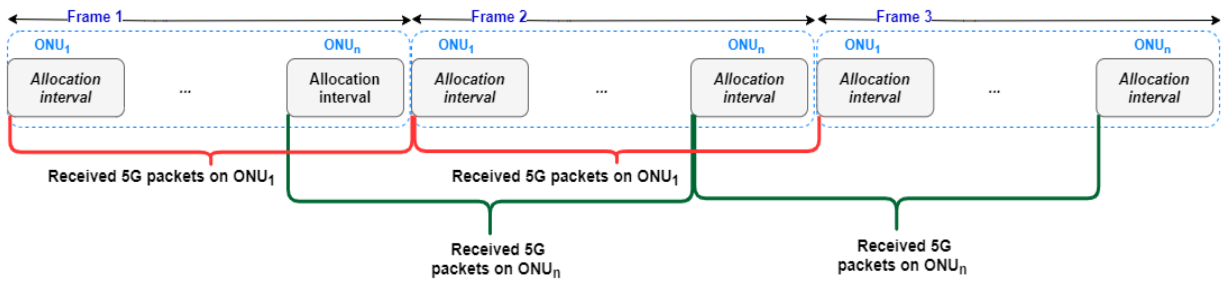



Fig. 5: Proposed reporting scheme.

services and, in our proposal, it is the adopted solution for reporting the data services.

For reporting the 5G fronthaul services, besides the standard variant, we investigate two alternatives methods. Since the 5G fronthaul has a constant bit rate, for splitting ratios from 6 to 8, the reporting must allow the DBA algorithm (running on the OLT) to have a better estimation on the current throughput of each 5G fronthaul connection. So, the first alternative method is that the reporting information is the total number of bytes received in the 5G queue from the beginning of the previous allocation interval until the beginning of the current allocation interval, as illustrated in Figure 5. In this reporting variant, the ONU starts a counter at the beginning of each allocation interval which is used to compute the total number of bytes received in the 5G queue (both during the present allocation interval and during the elapsed time until the beginning of the next allocation interval). At the beginning of the next allocation interval, the reporting information is the value of the counter which is then reset to start counting the received bytes for the next period.

The previous alternative enables the DBA to have a correct estimation of the required throughput of the 5G traffic received at each ONU when it is in its steady state. However, in its initial state when a new 5G fronthaul connection starts, an additional amount of resources is required to accommodate the initial queued packets. To enable the DBA to take into consideration this fact, the second investigated alternative is that the reporting information is the sum of two values: (i) the total number of bytes received in the 5G queue from the beginning of the previous allocation interval until the beginning of the current allocation interval (similar to the previous alternative) and (ii) the 5G queue occupation at the end of the previous allocation interval.

Note that, in the steady state, the queue occupation of the 5G queue at the end of an allocation interval should be zero as the amount of resources should be enough to transmit all 5G traffic. When the 5G queue occupation is higher than zero at the end of the allocation interval, it means that the throughput of the 5G flow is rising and extra resources are required to transmit the still queued data.

In the remaining of the paper, we name the conventional method, the first alternative variant and the second alternative variant as C, V1 and V2 reporting variants, respectively.

### B. Proposed allocation interval calculation methods

The overall DBA algorithm runs one of 3 algorithms, depending on the 5G requests that have been received. The variables used in the DBA algorithm description are shown in Table I.

TABLE I: Variables

| Variable | Definition |
|---|---|
| $T$ = 125 $\mu s$ | Frame duration |
| $N$ | Number of ONUs |
| $i = 1...N$ | ONU identifier |
| $f$ | Current frame identifier |
| $t_i$ | Time slot allocated to ONU $i$ (seconds) |
| $X$ | Remaining time in the frame (seconds) |
| $AvgData_i$ | Data request of ONU $i$ |
| $Avg5G_{fi}$ | 5G request of ONU $i$ on frame $f$ |
| $Avg5G_{(f-1)i}$ | 5G request of ONU $i$ on frame $(f-1)$ |
| $Avg5G_{(f-2)i}$ | 5G request of ONU $i$ on frame $(f-2)$ |
| $\delta 1_i$ | Difference between $Avg5G_{fi}$ and $Avg5G_{(f-1)i}$ |
| $\delta 2_i$ | Difference between $Avg5G_{(f-1)i}$ and $Avg5G_{(f-2)i}$ |

The first algorithm (Algorithm 1) is run when the reports received from all ONUs report null requests concerning the 5G queues (i.e., $\sum_{i=1...N} Avg5G_{fi} = 0$ in line 1). If the total data request is not null ($\sum_{i=1...N} AvgData_i > 0$ in line 2), the DBA algorithm allocates to each ONU $i$ an allocation interval with a duration proportional to the data request $AvgData_i$ of each ONU $i$ (lines 3–5). Otherwise, the total time $T$ is equally divided among all ONUs (lines 7–9).

**Algorithm 1** Time slot calculation algorithm with no 5G traffic

1: **if** $\sum_{i=1...N} Avg5G_{fi} = 0$ **then**
2:     **if** $\sum_{i=1...N} AvgData_i > 0$ **then**
3:         **for** $i$ = 1 to $N$ **do**
4:             $t_i = \frac{AvgData_i}{\sum_{j=1...N} AvgData_j} \times T$
5:         **end for**
6:     **else**
7:         **for** $i$ = 1 to $N$ **do**
8:             $t_i = \frac{T}{N}$
9:         **end for**
10:     **end if**
11: **end if**

When $\sum_{i=1...N} Avg5G_{fi} > 0$, we distinguish two cases: the under-loaded case and the over-loaded case. The under-loaded case is when the sum of the 5G requests can be fully assigned within the wavelength capacity (i.e., $\sum_{i=1...N} Avg5G_{fi} \leq T$). In this case, Algorithm 2 is run, which starts by assigning each allocation interval of each ONU with the time duration given by the 5G requests (lines 2–6) and, then, runs algorithm 1 to assign the remaining time based on the data requests (line 7).

**Algorithm 2** Time slot calculation algorithm in the under-loaded case

1: **if** $\sum_{i=1...N} Avg5G_{fi} \leq T$ **then**
2:     $X = T$
3:     **for** $i$ = 1 to $N$ **do**
4:         $t_i = Avg5G_{fi}$
5:         $X = X - t_i$
6:     **end for**
7:       Algorithm 1 starting from line 2
8: **end if**

The over-loaded case is when the sum of all 5G requests cannot be fully assigned (i.e., $\sum_{i=1...N} Avg5G_{fi} > T$). The over-loaded case can happen when a new 5G fronthaul connection starts. In this case, we have considered 2 algorithmic alternatives.

The first one, described in Algorithm 3a, is to apply the same method that is used for data services in Algorithm 1, i.e., to allocate the total time $T$ proportionally to the 5G request $Avg5G_{fi}$ of every ONU $i$. The second proposal, described in Algorithm 3b, makes a distinction between 5G fronthaul connections which are in their steady-state and the new 5G connections (i.e., whose throughput is changing to a higher value). The aim is that the DBA algorithm first fulfils the requests of the steady-state 5G connections and the remaining time is proportionally divided by the new 5G connections. By doing so, the maximum delay of the steady-state 5G connections will not be penalized by the new 5G connections. The identification of the two types of fronthaul connections is based on the average 5G requests $Avg5G_{fi}$ of the current frame $f$ and of the two last frames: requests $Avg5G_{(f-1)i}$ of frame $f-1$ and $Avg5G_{(f-2)i}$ of frame $f-2$. With this information, Algorithm 3b starts by calculating (in lines 3–5) the values $\delta 1_i$ and $\delta 2_i$ for all ONUs $i$ as:

$$\delta 1_i = Avg5G_{fi} - Avg5G_{(f-1)i} \tag{1a}$$

$$\delta 2_i = Avg5G_{(f-1)i} - Avg5G_{(f-2)i} \tag{1b}$$

Then, for each ONU $i$, DBA assumes that the throughput of the 5G flow on ONU $i$ has increased if both values are positive, or is in the steady-state, otherwise. For the ONUs whose 5G flow is in steady-state, Algorithm 3b assigns (in lines 6–14) to each ONU a duration $t_i$ which is the maximum among the three 5G requests (i.e., $max(Avg5G_{fi}, Avg5G_{(f-1)i}, Avg5G_{(f-2)i})$). Then, Algorithm 3b assigns (in lines 15–19) the remaining time proportionally to the 5G request $Avg5G_{fi}$ of the other ONUs. In this case, since the time is not enough to fulfil all 5G requests, no time is left for data flows.

**Algorithm 3a** Time slot calculation algorithm in the over-loaded case (option 1)

1: **if** $\sum_{i=1...N} Avg5G_{fi} > T_s$ **then**
2:     **for** $i$ = 1 to $N$ **do**
3:         $t_i = \frac{Avg5G_{fi}}{\sum_{j=1...N} Avg5G_{fj}} \times T$
4:     **end for**
5: **end if**

**Algorithm 3b** Time slot calculation algorithm in the over-loaded case (option 2)

1: **if** $\sum_{i=1...N} Avg5G_{fi} > T_s$ **then**
2:     $X = T$
3:     **for** $i$ = 1 to $N$ **do**
4:         Determine $\delta 1_i$ and $\delta 2_i$ according to (1a) and (1b)
5:     **end for**
6:     **for** $i$ = 1 to $N$ **do**
7:         **if** $\delta 1_i \leq 0$ **or** $\delta 2_i \leq 0$ **then**
8:             $t_i = max(Avg5G_{fi}, Avg5G_{(f-1)i}, Avg5G_{(f-2)i})$
9:             $X = X - t_i$
10:             $a_i =$ TRUE
11:         **else**
12:             $a_i =$ FALSE
13:         **end if**
14:     **end for**
15:     **for** $i$ = 1 to $N$ **do**
16:         **if** $a_i$ is FALSE **then**
17:             $t_i = \frac{Avg5G_{fi}}{\sum_{j=1...N} Avg5G_{fj}} \times X$
18:         **end if**
19:     **end for**
20: **end if**

## IV. Simulation results

To evaluate the different variants of the proposed DBA, we have implemented an event-driven simulator of a NG-PON system, developed in Matlab and customized to our needs and our study requirements. We consider a NG-PON with $N$ = 4 or 8 ONUs operating on a channel of 50 Gbps assuming 2 bonded wavelengths with a data rate of 25 Gbps each. We set the distance between ONUs and the OLT to 5 and 20 km. The 20 km represents a worst case scenario since it is the maximum distance that a PON can reach while the 5 km represents a more realistic urban scenario. First, we have considered the following 2 simulation scenarios:

**Scenario 1** – Some ONUs provide 5G fronthaul services and all ONUs provide data services (including the ONUs that provide 5G fronthaul services).

**Scenario 2** – Each ONU provides either data services or 5G fronthaul services.

In both scenarios, we consider that the two first ONUs (ONU1 and ONU2) provide 5G fronthaul services to a single sector cell site and to a two sectors cell site, respectively. The total US 5G throughput is 13.3 Gbps and 26.6 Gbps (= 2 × 13.3 Gbps) for ONU1 and ONU2, respectively. The throughput value of 13.3 Gbps per sector considers a 5G spectrum bandwidth of 100 MHz, a 4x4 MIMO antenna and 15 bits per sample in the uplink and calculated based on the 3GPP TR 38.816, Release 15 [46]. Note that the 26.6 Gbps fronthaul connection requires the bonding of at least 2 wavelengths and, then, there is enough capacity to accommodate also the 13.3 Gbps fronthaul connection in the 50 Gbps created channel.

The data throughput is defined as the total channel capacity equally divided between the ONUs providing data services (for example, $50/4 = 12.5$ Gbps for each ONU when the number of ONUs providing data services is 4). The aim is to analyse the ability of the DBA algorithm to cope with the 5G fronthaul latency requirements in worst-case scenarios with over-loaded traffic, i.e., where the throughput generated by all services is higher than the PON channel capacity.

Regarding packets size, we consider a fixed size of 1518 bytes for 5G fronthaul packets and random sizes between 64 and 1518 bytes for data packets. Data packet sizes are generated with the following probabilities: 10% for 64 bytes, 30% for 1518 bytes and all other values with equal probability. Regarding packet inter-arrival times, the time between 5G packets arrival is constant and the time between data packet arrivals is an exponentially distributed random variable.

We set up the simulations with data packet arrivals starting at the beginning of the simulation, 5G packets starting at frame 30 for ONU1 and at frame 60 for ONU2. The aim is to evaluate the dynamic set up of different 5G fronthaul connections in the system. All simulation results were obtained with 5 runs to determine proper 95% confidence intervals and considering a DBA processing latency equal to 40 $\mu s$ (i.e., the OLT runs the DBA algorithm with the requests received from the ONUs up to 40 $\mu s$ before the beginning of each DS frame). The parameters used in the simulations are summarized in Table II.

TABLE II: Simulation parameters

| Parameter | Value |
|---|---|
| Functional split option | 7.1 |
| Throughput of a single sector cell site (Gbps) | 13.3 |
| Guard time ($\mu s$) | 1.216 |
| 5G packet size (bytes) | 1518 |
| Data packet size (bytes) | [64 - 1518] |
| DBA processing latency $\mu s$ | 40 |
| Distance ONU-OLT (km) | 5 and 20 |
| Number of simulation runs | 5 |
| Number of frames of each simulation run | 1000 |

Let us first consider the results obtained with the DBA Algorithm 3b and with the the 3 reporting variants as described in section III-A. The average US delay of 5G fronthaul packets obtained with C, V1 and V2 and with a distance of 5 km and 20 km is shown in Figure 6 for scenario 1 and in Figure 7 for scenario 2.

Concerning scenario 1, the results show that the average US delays achieved by C, V1 and V2 do not exceed the delay threshold of 250 $\mu s$ (including the fiber propagation delay that is equal to 25 $\mu s$ and to 100 $\mu s$ corresponding to the 5 km and 20 km fiber length, respectively). When comparing the different reporting variants, V1 and V2 exhibit almost the same average US delays which are better than the C reporting variant. Moreover, the results show that the number of ONUs affects very slightly the average US delays as, in all cases, the delays with $N$ = 8 ONUs are slightly higher than the delays with $N$ = 4 ONUs. Finally, the ONU-OLT distance significantly affects average delays as the US delays with a distance of 20 km are higher than the delays obtained with 5 km (easily explained by the higher propagation delay over longer fiber links).

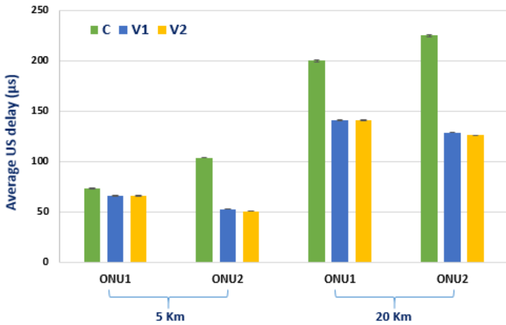
Concerning the results of scenario 2, V2 is the reporting variant providing the smallest average US delays. Moreover, we can check in Figure 7 that the average US delays exceed 250 $\mu s$ in scenario 2 for reporting variant V1 with both distances 5 km and 20 km. This is due to the fact that reporting only 5G data received between the beginning of 2 consecutive allocation intervals on an ONU (variant V1) does not allow the DBA to have enough information on the current ONU needs. In V1 variant, the queue occupation at the end of the allocation interval is ignored and the ONU is prevented from transmitting the newly received packets and the queued packets altogether. This drawback is not observed in scenario 1 because, in this case, ONU1 and ONU2 are also supporting data services and the allocated time for data requests enables the ONU to immediately use it for sending the queued 5G packets.

Note that in all cases of both scenarios with the V2 reporting variant, ONU2 has a lower average US delay than ONU1. This is because ONU2 requires a higher throughput and, consequently, is assigned with a longer allocation interval. Longer allocation intervals result in shorter waiting times between intervals and, consequently, shorter average US delays.

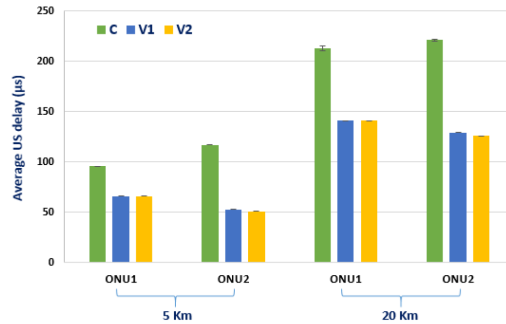
So, we can clearly conclude that, in terms of 5G average US delays, the DBA algorithm with V2 reporting variant is the best among all variants. Now, let us address the delays suffered by each 5G packet when each 5G connection starts.

For this analysis, we focus on the simulation results with the ONU-OLT distance of 20 km, as it corresponds to the worst-case scenario in terms of delays. Figure 8 shows the US delay of each 5G packet sent by ONU1 and ONU2 on the first 200 frames of a single simulation run. Figure 8 shows 3 plots, considering the 3 reporting variants (C, V1 and V2) with scenario 1 and $N$ = 4.

These results show that the behaviour of C is different from the behaviour of V1 and V2 variants. From Figure 8a, we can

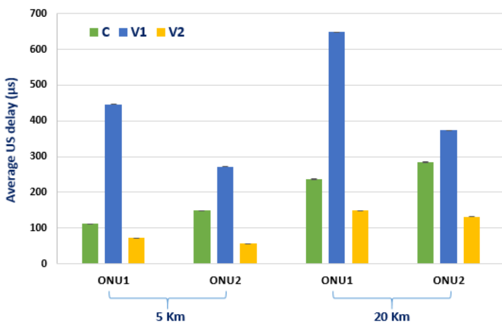



(a) $N$ = 4

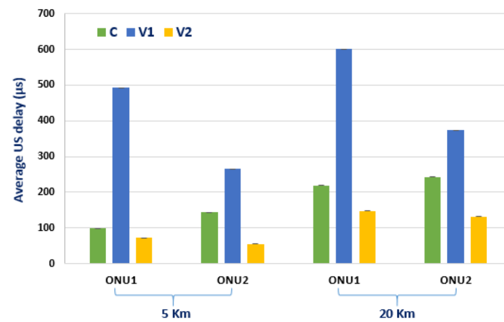



(b) $N$ = 8

Fig. 6: Average US delay of 5G fronthaul packets in scenario 1.




(a) $N$ = 4




(b) $N$ = 8

Fig. 7: Average US delay of 5G fronthaul packets in scenario 2.

observe that, when the second 5G connection starts in ONU2, none of the 5G connections of ONU1 and ONU2 stabilize and the US delays suffered by the packets of both flows keep oscillating over time. This oscillation is the result of solely reporting the queue occupation at the beginning the time slot: the ONUs keep oscillating between an empty queue and an occupied queue which results in an imbalance in requests sent by the ONUs (and, consequently, in the duration of the allocation intervals). The reporting variant V1 and V2 were able to eliminate this oscillating behaviour as observed in Figure 8b and Figure 8c.

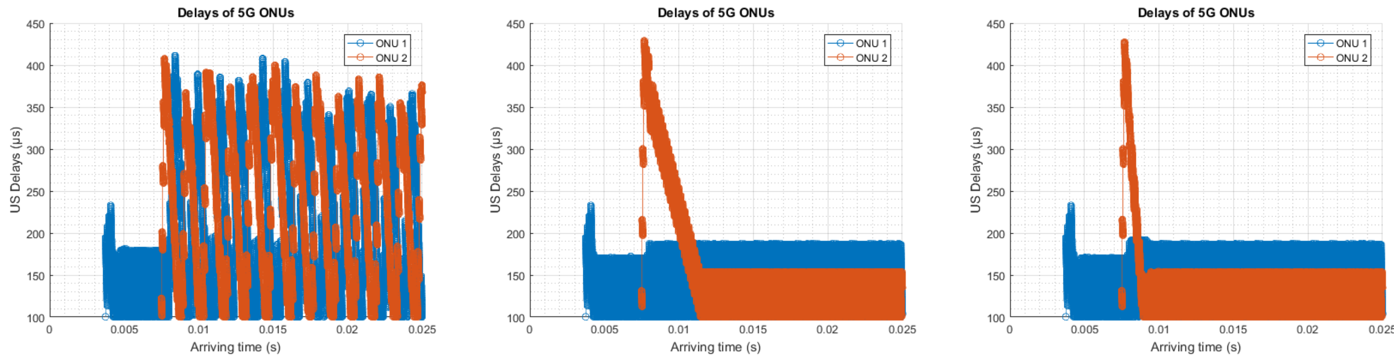
Note that by using the V2 reporting variant (Figure 8c), the 5G connection started in ONU2 recovers in a shorter time to a maximum packet delay below 250 $\mu s$ than using the V1 reporting variant (Figure 8b). With V2, the 5G connection on ONU2 takes around 8 frames to recover since it starts generating packets at frame 60 (corresponding to time instance 0.0075 seconds) and it gets its steady-state behaviour around 0.0085 seconds (corresponds to frame 68).

The results in figure 8 show that the 5G connection on ONU1 (the first one to start) does not suffer from very high US delays at its beginning in any reporting variants compared to ONU2. Recall that, in the first 30 frames, data traffic is being generated requesting the same resources among all ONUs (following Algorithm 1). So, at frame 30, ONU1 has been assigned 12.5 Gbps (= 50/4) for data traffic and when the 5G traffic starts at frame 30, ONU1 immediately uses the assigned allocation interval to transmit the 5G packets. This is not the case of the 5G connection in ONU2, which needs 26.6 Gbps, a much higher value than the one assigned to its data traffic at frame 60 (the reason why the first 5G packets of ONU2 always suffer a much higher US delay).

So far, we have shown that the reporting variant V2 is the best among all 3 reporting variants in scenario 1. The next results show the performance of this reporting variant in the more demanding case of scenario 2. Recall that in this scenario, ONU1 and ONU2 are not supporting any data service. So, when the 5G flows start on ONU1 and ONU2, their allocation intervals are only enough to transmit their DBRu field (i.e., no space to transmit packets).

Figure 9 shows the 200 frames of a single simulation run with scenario 2 for V2 reporting variant. In this case, both ONU1 and ONU2 suffer from high delays in the beginning but the maximum delays quickly recover in very short times to maximum packet delays below 250 $\mu s$. Moreover, when the second 5G connection starts in ONU2, the maximum packet delay of the 5G flow in ONU1 maintains its steady-state behaviour (recall that the second 5G connection is the 5G connection requiring the highest throughput).

All results presented so far were obtained with DBA using Algorithm 3b, which is, in practice, more complex than Algorithm 3a. In order to highlight the need for Algorithm 3b, Figure 10 shows the results obtained by using Algorithm 3a with the V2 reporting variant for $N$ = 4 and for the two scenarios. These results show that when the 5G fronthaul service starts in ONU2, the 5G packets of the ongoing 5G fronthaul service in ONU1 suffer (in both cases) a US delay




(a) C (b) V1 (c) V2

Fig. 8: A single simulation run in scenario 1 for $N$ = 4 ONUs.

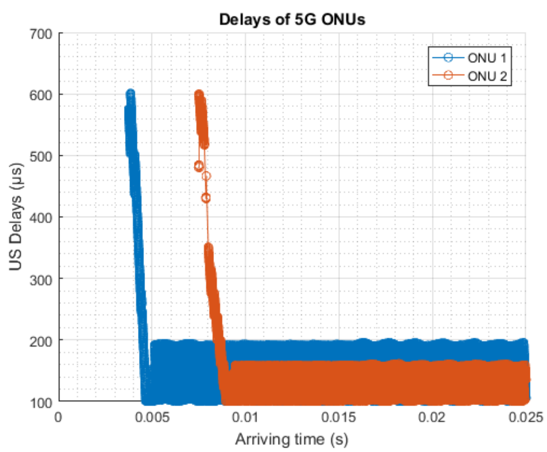



Fig. 9: A single simulation run in scenario 2 for $N$ = 4 ONUs with V2.

much higher than the required 250 $\mu s$ delay, an unacceptable performance as it can disrupt (i.e., turning it out-of-sync) the ongoing 5G fronthaul connection. This behaviour is not observed when the DBA uses Algorithm 3b, as already seen in Figures 8c and 9.

In order to further test the performance of the best DBA alternative (which is using Algorithm 3b with the V2 reporting variant), we have considered two additional scenarios:

**Scenario 3** – ONU1, ONU2 and ONU3 provide 5G fronthaul services (each one to a single sector cell site with a throughput of 13.3 Gbps each) and ONU 4 provides data services.

**Scenario 4** – ONU1 and ONU2 provide 5G fronthaul services (ONU1 to a double sector cell site with a throughput of 26.6 Gbps and ONU2 to a single sector cell site with a throughput of 13.3 Gbps) and ONU3 and ONU4 provide data services.

In the simulations of these scenarios, we again consider that the 5G fronthaul connections start 30 frames apart between ONUs, i.e., we consider that the 5G fronthaul connection starts at frame 30 in ONU1, frame 60 in ONU2 (and frame 90 in ONU3, in the case of scenario 3). Figure 11 shows the obtained results. Like in the previous scenario 2, also in these cases, all ONUs suffer from high delays in the beginning of the 5G fronthaul connections but the maximum delays quickly recover in very short times to maximum packet delays below 250 $\mu s$. Moreover, the US delays of the 5G packets of the ongoing 5G fronthaul connections never suffer any delay penalties when each new 5G fronthaul connection starts.

In conclusion, the DBA using Algorithm 3b with the V2 reporting variant is successful in guaranteeing the maximum delay in the lifetime of a 5G connection except in its initial transient state, which is very short, as the simulation results show. Note that, when a new 5G connection starts, the connection must be first setup over the PON between the DU and the RU before the air interface is initialized. So, the initial transient will only delay in a few milliseconds the connection setup over the PON (the connection is established as soon as the delay becomes steadily below the required maximum delay).

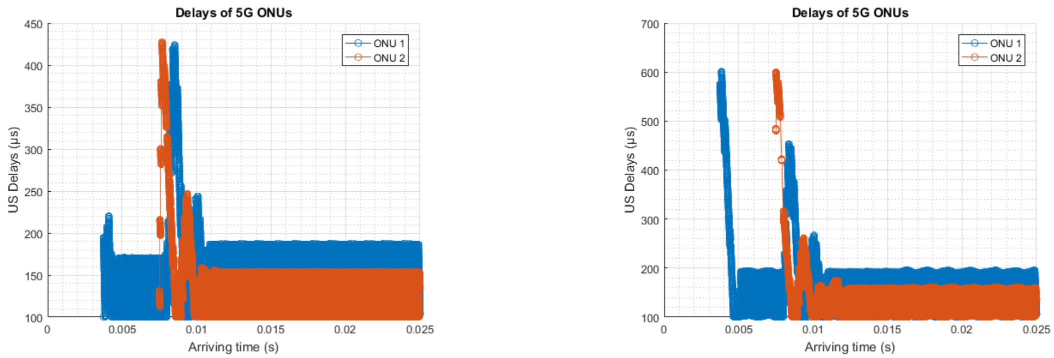
Concerning data services, recall that all simulations consider the same average traffic in all ONUs supporting data services. In the simulations, we have also computed the average data service throughput provided at each ONU.

In scenario 1, ONU1 and ONU2 are providing simultaneously both 5G fronthaul and data services. The data throughput of each ONU for $N$ = 4 and $N$ = 8 is shown in Figure 12a and Figure 12b, respectively, with C, V1 and V2 reporting variants. These results show that, concerning data service fairness, the V1 and V2 reporting variants are better than the C as they provide (almost) the same throughput among all ONUs. On the other hand, the C reporting variant is quite unfair as the data throughput differences between different ONUs are quite large.

In scenarios 2, 3 and 4, each ONU is either proving the 5G fronthaul service or providing the data service but there is no ONU providing simultaneously both services. In these cases, the simulation results (which are not shown) show that the average data throughput is the same for all ONUs supporting data services whatever reporting variant is used. This means that in such cases, the DBA is fair among all ONUs providing data services.

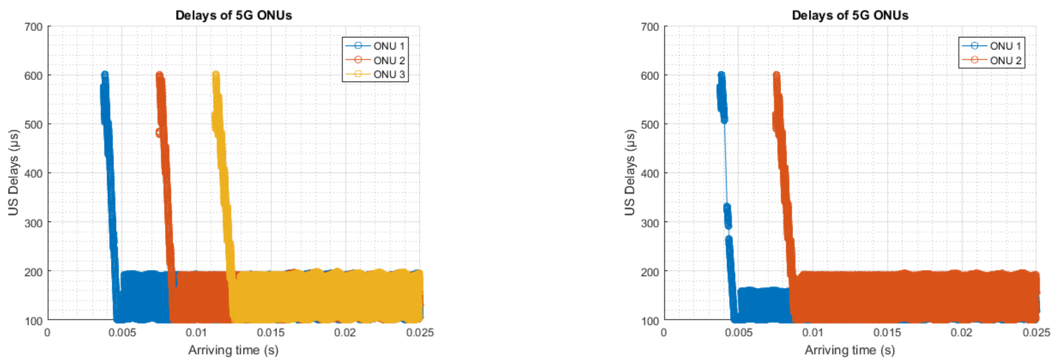
## V. Conclusion

In this paper, we have proposed a novel DBA algorithm for NG-PON networks to jointly support 5G fronthaul and best-



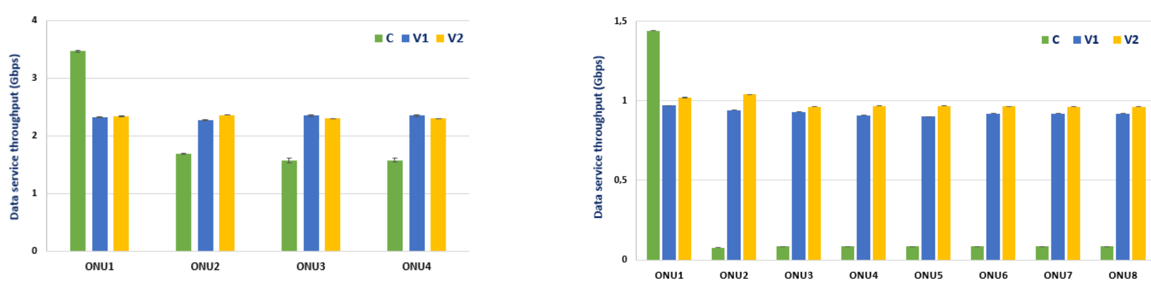

(a) Scenario 1 (b) Scenario 2

Fig. 10: A single simulation run with algorithm 3a and $N$ = 4 ONUs.




(a) Scenario 3 (b) Scenario 4

Fig. 11: A single simulation run for Scenario 3 and Scenario 4.




(a) $N$ = 4 (b) $N$ = 8

Fig. 12: Data service throughput provided at each ONU with scenario 1.

effort data services in the same PON channel. The proposed DBA assumes that a single allocation interval is assigned to both services for each ONU and each ONU uses its allocation interval to transmit the packets of both services giving higher priority to 5G packets.

We have shown through simulation that the proposed Self-adjusting DBA algorithm is suitable for 5G scenarios where the 5G fronthaul connections are dynamically set up and torn down over time. This is achieved by dynamically adjusting the allocation intervals to the current required fronthaul throughput based on the requests reported from the ONUs. These achievements come at the cost of high packet delays at the beginning of each 5G fronthaul connection. However, the initial transient state of the 5G connections are shown by simulation to be very short and, shortly after, the maximum latency delays required by the 5G fronthaul service can be guaranteed for the remaining lifetime of the connections.

Previous known DBA proposals for the support of 5G fronthaul over PON networks require a tight coordination between the 5G infrastructure and the PON infrastructure. In this work, we focus on appropriate DBA algorithms for fixed mobile convergence scenarios where the operators of already deployed PONs aim also to support the 5G fronthaul connections that 5G operators need between their central office locations and their site locations. Such scenarios require solutions with minimal management coordination between the 2 operators. The proposed Self-adjusting DBA algorithm is suitable for such scenarios as it reduces to a minimum the management coordination between the 5G infrastructure and the NG-PON infrastructure (the only requirement is that the capacity of the PON channel in the NG-PON network is enough to support the throughput of all 5G connections supported by the channel).

## ACKNOWLEDGMENTS

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