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A hybrid dynamic bandwidth allocation scheme operating with IACG and cooperative DBA for converged fronthaul networks

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ABSTRACT

The time-division multiplexed passive optical network is seen as a candidate for converged fronthaul networks in 5G, which requires low latency and high capacity. In this paper, a hybrid dynamic bandwidth allocation (DBA) scheme for converged fronthaul that combines a status reporting DBA and a cooperative DBA is proposed. Different deployment scenarios and operating conditions in a 10-Gigabit-capable PON (XGS-PON) system are investigated using the OMNeT++ network simulator. The performance of the proposed hybrid DBA is evaluated in terms of average upstream delay and percentage of frame loss meeting a 140 μs queuing delay requirement for fronthaul traffic. Simulation results show a zero-frame loss for fronthaul traffic in all scenarios using the proposed hybrid DBA which is not achievable using only the status reporting DBA, confirming the advantages of the proposed hybrid DBA.

1. Introduction

The introduction of a new generation of mobile networks (5G and beyond) has been driven by applications with a high demand in data traffic defined by three service types – enhanced mobile broadband (eMBB), ultra-reliable low-latency communications (URLLC) and massive machine-type communications (mMTC) service types [1]. These future mobile networks will require a dynamic and flexible converged network architecture that supports diverse requirements such as latency (delay), bandwidth and reliability. The advent of the cloud radio access network (C-RAN), which began with the idea of baseband pooling [2], and virtualized RAN (vRAN) architectures, has firstly addressed these requirements. The use of the Common Public Radio Interface (CPRI) protocol has been most commonly used for the transport of traffic in a C-RAN [3]. However, CPRI is a constant bitrate interface with very high bitrates that will not meet the transport requirements of a 5G network which requires a higher number of antenna elements and increased carrier bandwidths [4,5]. In order to meet the 5G requirements, the 3rd Generation Partnership Project (3GPP) standards organization introduced several functional split options [6] in the C-RAN architecture. In addition, an enhanced version of the CPRI protocol, known as eCPRI, was introduced to provide support for 5G fronthaul use cases using packet-based Ethernet, thereby enabling statistical multiplexing gains in the network [7].

In the 5G RAN architecture, the functions previously performed by the Baseband Unit (BBU) in a 4G/LTE RAN are now disaggregated and distributed among three units – the Central Unit (CU), Distributed Unit (DU) and Remote Unit (RU). The traditional backhaul transport segment connects the 5G core (5GC) to the CU. Two new transport segments were introduced to connect the CU with the DU (known as midhaul) and connect the DU with the RU (known as fronthaul [8]. Collectively, the three transport network segments are referred to as an xHaul network [9]. Each transport segment has different traffic requirements in terms of latency and capacity. Meeting these different requirements within the same physical network poses a challenge in the 5G RAN.

Passive optical networks (PONs), which are widely deployed for fiber to the home (FTTH) broadband services, are essential to the rollout of 5G mobile and next-generation fixed networks [10,11]. The convergence of the fixed and mobile networks – fixed mobile convergence [12] – will require PONs to meet the latency requirements for fixed residential and business users as well as mobile traffic. In order to satisfy the latency-sensitive requirement in a converged fronthaul, a new dynamic bandwidth allocation (DBA) method known as the cooperative DBA (CO-DBA) was proposed in [13] and recognized by the International

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Telecommunication Union Telecommunication Standardization Sector (ITU-T) [14]. In the CO-DBA, the mobile scheduler (in the CU/DU) shares the scheduling information with the PON scheduler (in the optical line terminal, OLT). A corresponding bidirectional interface is needed by the CO-DBA to facilitate the scheduling so an open interface known as the cooperative transport interface (CTI) was specified by the O-RAN Alliance and ITU-T [14,15]. The CTI is used to receive user equipment (UE) scheduling information from the mobile scheduler and pass it to the PON scheduler.

This paper proposes a hybrid DBA scheme that combines a status reporting DBA (SR-DBA) and a CO-DBA for low latency in a fronthaul network. It expands on our paper in [16] by integrating the Immediate Allocation with Colorless Grant (IACG) DBA [17], which is a SR-DBA, with a CO-DBA.

The remainder of the paper is organized as follows: Section 2 discusses the related work regarding existing DBA schemes for 5G fronthaul while Section 3 describes the proposed hybrid DBA scheme. The system model is described in Section 4. Section 5 presents the simulation results and performance evaluation. Finally, Section 6 concludes the paper.

2. Related work

This section discusses the on-going research on DBA schemes used in time-division multiplexed passive optical networks (TDM-PONs). In a SR-DBA scheme, each optical network unit (ONU) reports its buffer status to the OLT. Each ONU may have several transmission containers (T-CONTs), each with its own traffic class. The OLT computes the upstream bandwidth allocations for each T-CONT of an ONU based on the received buffer status report. The ITU-T defines five types of T-CONTs, each with a specific bandwidth and quality of service. These are T-CONT 1 (supports fixed bandwidth), T-CONT 2 (supports assured bandwidth), T-CONT 3 (supports non-assured or surplus bandwidth), T-CONT 4 (supports best-effort bandwidth) and T-CONT 5, a combination of one or more of the other four T-CONT types [18,19]. T-CONT 1 has the highest priority with T-CONT 4 having the lowest. Each T-CONT type has two service parameters, a service interval (SI) and an allocation byte (AB), which are used to allocate the available bandwidth. The SI determines how often the T-CONT gets served, while the AB determines how many bytes on the upstream frame can be assigned to the T-CONT. The SI is expressed in multiples of the frame duration (i.e., 125 μs) and the AB is expressed in bytes. The allocated bandwidth is thus calculated as the number of AB divided by the SI.

A number of DBA algorithms based on the ITU-T PON standard have been studied for use in the fronthaul. These include the Round Robin DBA (RR-DBA) [20], Group Assured GIANT (gGIANT) DBA [21], Optimized-Round Robin (Optimized-RR) DBA [22], Fixed-Elastic (FE-DBA) [23] and the Self-adjusting DBA [24]. In [20], a fixed maximum allocation bytes limit is used in its grant allocation which leads to inefficient utilization of the XG-PON upstream bandwidth [22]. The gGIANT DBA [21], which is a variation of the well-known GigaPON Access NeTwork (GIANT) [25,26], is focused on transporting latency tolerant mobile backhaul traffic and uses an XG-PON with a 2.5 Gbit/s upstream line rate which is below the recommended minimum upstream rate of 10 Gbit/s required to support fronthaul traffic [15]. In [22], a dynamic maximum allocation bytes limit is used to improve the performance of the RR-DBA, whereby the unused bandwidth of lightly-loaded T-CONTs is redistributed equally to heavily-loaded T-CONTs. The authors in [22] only simulated traffic for the optimized RR-DBA using the delay requirement for the latency tolerant high layer functional split point. Eugui and Hernández [23] use a fixed bandwidth type for fronthaul traffic and other bandwidth types (assured, non-assured and best-effort) for backhaul and FTTH traffic on the same PON to achieve sub-250 μs delay values for eCPRI functional split fronthaul traffic. A self-adjusting DBA algorithm for the support of 5G fronthaul over next generation PON networks was proposed in [24]; it dynamically adjusts the allocation intervals to the current required fronthaul throughput based on the requests reported from the ONUs to guarantee the maximum delay of 250 μs. However, all the ONUs suffer from high packet delays at the beginning of each 5G fronthaul connection. The authors in [22], [23] and [24], all rely on a status reporting DBA to handle fronthaul traffic which leads to longer delays.

Tashiro et al. [13] proposed the first CO-DBA scheme for TDM-PONs known as mobile-DBA (M-DBA), which was based on the interleaved polling with adaptive cycle time (IPACT) algorithm [27]. In this scheme (M-DBA), the OLT receives the scheduling information from the centralized baseband unit (BBU) and allocates time slots according to the received information. Uzawa et al. [28] proposed a practical mobile-DBA scheme that properly allocates time slots by estimating the arrival period of the data from the scheduling information. Also, Uzawa et al. [29,30] proposed a DBA scheme that combines fixed bandwidth allocation (FBA) with CO-DBA to converge mobile fronthaul and Internet of Things (IoT) networks on a single TDM-PON. The latter DBA scheme for converged TDM-PON allocates bandwidth differently for each subnetwork. However, using an FBA scheme cannot satisfy the demands of varying traffic in a 5G mobile fronthaul and has the disadvantage of low bandwidth allocation efficiency. Zhou et al. [31,32] proposed a mobile fronthaul architecture based on a PHY functional split with a unified mobile and PON scheduler known as Mobile-PON. The use of the unified Mobile-PON scheduler eliminates the need for additional scheduling delay at the PON by combining the PHY functional split and Mobile-PON mapping scheme. Hisano and Nakayama [33] proposed the introduction of a forwarding order control in CO-DBA to maximize the number of ONUs that can transmit fronthaul streams within the requirement and the bandwidth usage efficiency in a fronthaul link. Although the proposed algorithm increases the number of ONUs, it may increase the latency within the fronthaul requirement. Hatta et al. [34] proposed a DBA scheme that automatically adjusts the DBA cycle length according to the traffic load in order to achieve low latency. Nomura et al. [35] proposed a DBA scheme that combines both a status-reporting DBA and CO-DBA and implemented using NG-PON2, an ITU-T time and wavelength division multiplexed (TWDM) PON standard [14]. This scheme is implemented using an NG-PON2 system that only uses three ONUs with two ONUs for fronthaul and one ONU for midhaul traffic.

The DBA schemes mentioned above are mainly focused on the IEEE PON standards (e.g., EPON and 10G-EPON) with a few performing studies on ITU-T PON standards (e.g., GPON, XG-PON, XGS-PON, NG-PON2), such as the papers in [24,33,35]. Thus, this paper focuses on a hybrid DBA based on XGS-PON. The proposed hybrid DBA enables a mix of different traffic types to be transmitted on the same PON while satisfying the strict latency requirement for fronthaul traffic. The latency-sensitive fronthaul traffic is handled by the CO-DBA while the latency tolerant non-fronthaul traffic (midhaul, backhaul and fixed access traffic) is handled by the IACG DBA. By combining the CO-DBA with the IACG DBA, the hybrid DBA reduces the time during which the ONUs waits for their bandwidth allocation from the OLT. This reduction in time leads to a reduction in latency and increases the bandwidth utilization of frames in a converged fronthaul. In addition, the hybrid DBA achieves upstream bandwidth allocation that takes into account the priorities of the various T-CONT types to meet the latency requirements of the different traffic types in a converged fronthaul.

3. Proposed hybrid DBA scheme for converged fronthaul

In a PON-based transport network that uses a SR-DBA (e.g., IACG DBA), the CU/DU sends the mobile scheduling information to the UE(s), as shown in Fig. 1. We assume that the UE(s) mobile scheduling request for upstream bandwidth is already at the CU/DU. The UE(s) use this information to transmit its data in the upstream to the RU, which arrives at the ONU. The ONU makes a request to the OLT for bandwidth using the information of the data received from the RU. Meanwhile, the upstream data from the RU waits in the ONU until the OLT allocates bandwidth and sends a grant to the ONU. Using the grant from the OLT,

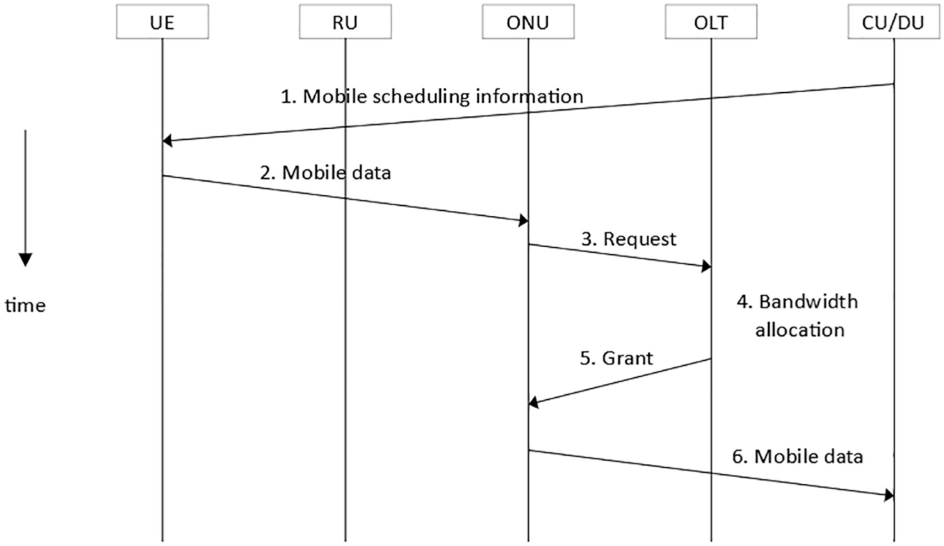


Fig. 1. Timing diagram for a SR-DBA in a PON-based transport network.

the ONU can finally begin transmission of the data to the CU/DU.

The proposed hybrid DBA scheme combines a SR-DBA, in this case the IACG DBA with a CO-DBA, in order to reduce the upstream latency in a converged fronthaul network. Fig. 2 shows the timing diagram of the CO-DBA. Again, we assume that the UE(s) mobile scheduling request is at the CU/DU. Since the OLT and CU/DU share a common interface (CTI), the OLT can access and read the scheduling information of the UE (s) at the same time it is being sent by the CU/DU. This enables the OLT to allocate upstream bandwidth before the arrival of the uplink mobile data from the RU at the ONU. Using the mobile scheduling information, the OLT makes available the bandwidth allocation as close as possible to the estimated upstream mobile data arrival time. This process allows the CO-DBA to avoid waiting for the ONU buffer report after the mobile data arrives at the ONU before allocating bandwidth.

The proposed hybrid DBA differs from a SR-DBA in that a SR-DBA allocates upstream bandwidth based on the amount of traffic buffered in each ONU queue. This requires a buffer status report from the ONUs to be sent to the OLT leading to increased latency in the upstream. However, in the hybrid DBA, which combines a SR-DBA with a CO-DBA, the CO-DBA portion functions without the need for a buffer status report from the ONUs to the OLT, thereby reducing latency in the upstream.

The whole process of the proposed hybrid DBA scheme is described as follows:

(1) The OLT allocates bandwidth to the ONUs carrying fronthaul traffic using the CO-DBA portion of the proposed hybrid DBA. The bandwidth is allocated based on the scheduling information provided by the CU/DU to the OLT without the need for a buffer status report from the ONU. This leads to a reduction in latency in the upstream.

(2) The IACG DBA portion of the proposed hybrid DBA in the OLT allocates bandwidth to the ONUs carrying non-fronthaul traffic (midhaul, backhaul and fixed access) in order of priority based on the buffer status report from each ONU. The bandwidth scheduling mechanism of the IACG DBA consists of three phases – the guaranteed phase allocation (GPA), surplus phase allocation (SPA) and the colorless grant (CG) phase. The GPA is executed first, followed by the SPA then the CG phase. In the GPA phase, bandwidth is allocated to T-CONT 3 while in the SPA phase, bandwidth is allocated to T-CONT 4. Any unallocated bandwidth at the end of the GPA and SPA phases is distributed equally to all ONUs in the CG phase using T-CONT 5. This ensures a high bandwidth utilization efficiency.

3.1. CO-DBA algorithm

The CO-DBA algorithm handles the latency sensitive fronthaul

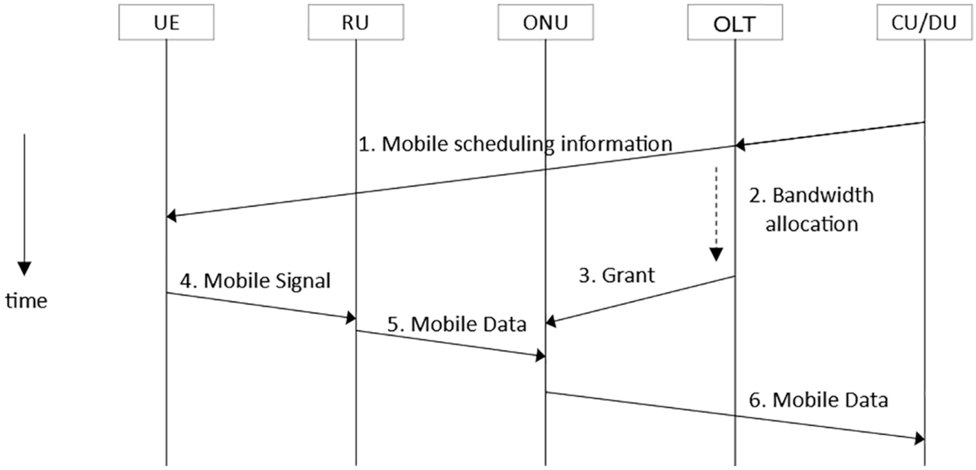


Fig. 2. Timing diagram for the CO-DBA in a PON-based transport network.

traffic. In a scenario with 16 ONUs, this upstream traffic is carried by T-CONT 2 which only uses 9 ONUs (ONU 0 to 8) while the remaining 7 ONUs is handled by the IACG DBA algorithm. The variables used in the algorithm are: T_{RU} denotes the upstream traffic load per RU from mobile scheduler in CU/DU and BW_{map} is the upstream bandwidth allocation map. The process of the CO-DBA bandwidth allocation algorithm is described as follows:

(1) If upstream traffic is from ONU 0 to 8, allocate bandwidth to T-CONT 2, according to the mobile scheduling information provided by the CU/DU.

The pseudo-code for the algorithm is described in Algorithm 1.

Algorithm 1. CO-DBA algorithm.

```
Input: $T_{RU}$
Output: $BW_{map}$
if upstream traffic from ONU = 0 to 8, then
    allocate bandwidth to T-CONT 2 according to the mobile scheduling information of CU/DU;
end
Output $BW_{map}$
```

3.2. IACG DBA algorithm

Since the latency tolerant non-fronthaul traffic is handled by the IACG DBA algorithm, the remaining 7 ONUs will be distributed such that the upstream midhaul traffic is carried by T-CONT 3 which only uses ONU 9 to 12 and the upstream backhaul and fixed access traffic is carried by T-CONT 4 which only uses ONU 13 to 15. The variables used in this algorithm are: BW_R denotes the bandwidth request of the ONU, BW_A is the total bandwidth allocated to ONUs, BW_U is the unallocated remaining bandwidth and BW_{map} is the upstream bandwidth allocation map. The process of the IACG DBA bandwidth allocation algorithm is described as follows:

(1) If upstream traffic is from ONU 9 to 12 and $BW_R \le BW_A$, allocate bandwidth to T-CONT 3, according to the bandwidth request.
(2) If upstream traffic is from ONU 13 to 15 and $BW_R \le BW_A$, allocate bandwidth to T-CONT 4, according to the bandwidth request.
(3) If $BW_U > 0$, allocate bandwidth to T-CONT 5, which is equally divided among ONU 9 to 15.

The pseudo-code for the algorithm is described in Algorithm 2.

Algorithm 2. IACG DBA algorithm.

```
Input: $BW_R$, $BW_A$
Output: $BW_{map}$
if upstream traffic from ONU = 9 to 12 and $BW_R \le BW_A$, then
    allocate bandwidth to T-CONT 3 according to the bandwidth request;
else
    if upstream traffic from ONU = 13 to 15 and $BW_R \le BW_A$ then
        allocate bandwidth to T-CONT 4 according to the bandwidth request;
    else
        if $BW_U > 0$, then
            allocate bandwidth to T-CONT 5 of ONU 9 to 15 equally;
end
Output $BW_{map}$
```

4. System model

A PON based transport network architecture, as illustrated in Fig. 3, is used to test the proposed hybrid DBA algorithm. Various functional split scenarios (fronthaul, midhaul, backhaul) are represented in the network in order to provide for different types of traffic such as mobile fronthaul, residential and business broadband on the same PON. Other functions such as massive MIMO, coordinated multipoint (CoMP) and intercell interference management can also be provided using this PON architecture [11,36].

In the system model, there are four sets of ONUs at the customer premises to accommodate the following types of traffic: (1) fronthaul, (2) midhaul, (3) backhaul, and (4) fixed access (FTTx), as illustrated in Fig. 3. It also includes an OLT at a central office (CO) and an optical distribution network (ODN) that includes a passive optical splitter/combiner.

5. Simulation results and discussion

5.1. Experimental setup

A ten-gigabit symmetric PON (XGS-PON) system [37] consisting of 16 ONUs, each at a distance of 10 km from the OLT, is implemented in OMNeT++, an open-source discrete event network simulator [38]. The downstream and upstream line rates are set at 10 Gbit/s. The simulation model is depicted in Fig. 4, and shows the different modules in the simulation. The User module acts as the upstream traffic generator and a

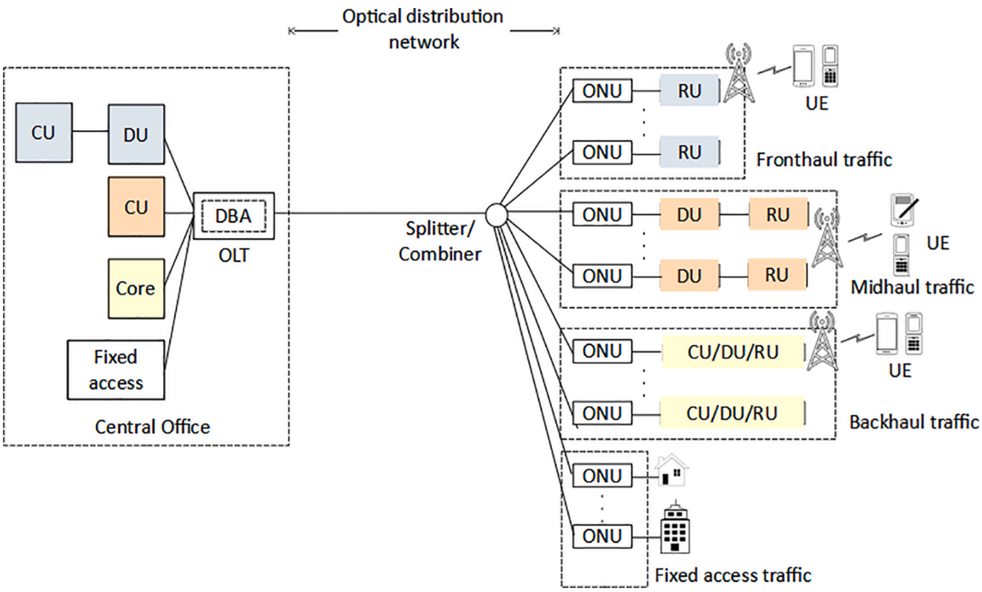


Fig. 3. PON-based transport architecture.

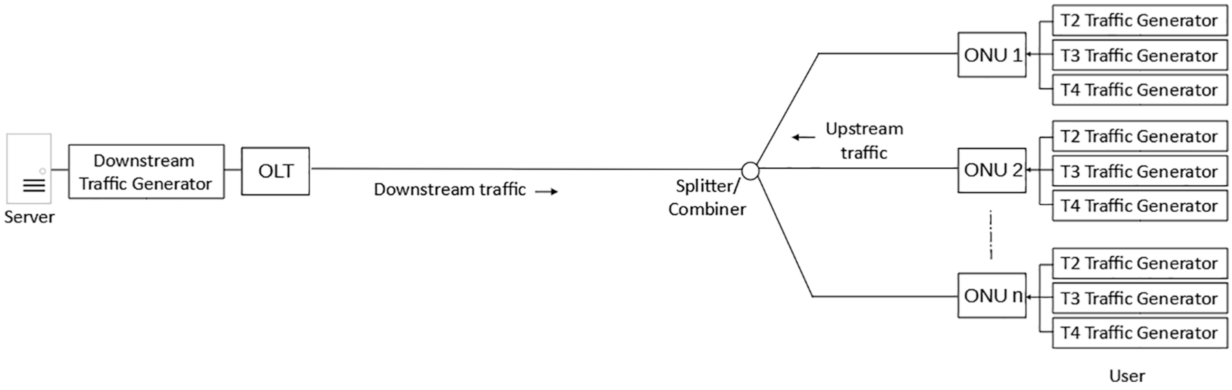


Fig. 4. Simulation setup in OMNeT++.

sink for downstream traffic. There are traffic generators for each T-CONT type (T-CONTs 2, 3 and 4) of an ONU and this ensures random frame generation of traffic in every ONU. The traffic generated was in the form of fixed frame sizes of 1500 bytes and the inter-arrival time of the frames follow a Poisson distribution, as the traffic load is varied from 0.1 to 0.9. The OLT is connected to the Server module which acts as a downstream traffic generator and upstream sink. The buffer size for each of the T-CONT queues in the ONU is set to 1 MB [17].

T-CONT 1 is not considered in the simulation since it is mainly suited for constant bit-rate traffic, and would result in inefficient bandwidth utilization in a network with varying user traffic. T-CONT 5 supports a combination of one or more of the other four T-CONT types and does not generate its own traffic so it doesn't require a traffic generator [18,19].

Several delay components determine the overall upstream delay of the frames. These include the propagation delay (fixed value), serialization delay (fixed value, for a specific frame length and line rate interface) and queuing delay (variable value). As the only variable delay component, the queuing delay is the focus of this paper. To obtain a new queuing delay threshold, several delay values are subtracted from the 250 μs one-way delay requirement for 5G fronthaul traffic defined by 3GPP [6]. The delay values deducted from 250 μs are the propagation delay of a 10 km optical fiber link (50 μs), DBA processing time (≈ 40 μs), optical-electrical-optical (OEO) conversion delay (≈ 15 μs) and FEC coding/decoding (≈ 5 μs) [39,40]. The resulting queuing delay threshold is 140 μs. To simplify the analysis of the queuing delay, the Ethernet frames are given a 1500-byte fixed length.

Two simulation scenarios were used to evaluate the IACG DBA and the proposed hybrid DBA schemes. The performance metrics used in the simulation were: queuing delay, average ONU upstream delay and percentage of frame loss. Table 1 summarizes the simulation parameters for the experimental setup.

Scenario 1 (T2 as fronthaul) – T-CONT 2 (T2) carries fronthaul traffic using 9 ONUs, T-CONT 3 (T3) carries midhaul traffic using 4 ONUs and T-CONT 4 (T4) carries backhaul & fixed access traffic using 3 ONUs.

Scenario 2 (T2 and T3 as fronthaul) – Fronthaul traffic uses 9 ONUs, with T2 carrying control and signaling while T3 carries user data in the ratio 22:78 (T2:T3). T4 carries midhaul traffic using 7 ONUs.

For both scenarios, three experiments are conducted. In the first experiment (Bandwidth allocation proportional to maximum load), the total available bandwidth in the upstream is shared in proportion to the number of ONUs carrying T2, T3 and T4 traffic, as follows: 350 Mbit/s to T2, 155 Mbit/s to T3 and 116 Mbit/s to T4, as shown in Table 2. The bandwidth is totally allocated independent of the actual load. In the second experiment (Bandwidth allocation proportional to actual load), the bandwidth in the upstream is allocated proportionally to the specific traffic load. In the third experiment, bandwidth overallocation for the fronthaul traffic (T2) is used, in order to reduce the delay and improve the performance for meeting the 140 μs queuing delay requirement at all traffic loads. Some results of the third experiment, where the 16 ONUs transmit all three T-CONT types (T2, T3 and T4), have been reported in [16].

For scenarios 1 and 2 in the proposed hybrid DBA, the same three experiments above are conducted but with different parameters for the T2, T3 and T4 bandwidth allocation. The fronthaul traffic, i.e., T2 (in scenarios 1 and 2) and T3 (in scenario 2), in the proposed hybrid DBA does not require the use of the IACG DBA process so its bandwidth allocation is zero. The performance of the hybrid DBA is evaluated in terms of the average ONU upstream delay and the percentage of frame loss meeting the 140 μs queuing delay requirement and compared with the IACG DBA.

5.2. Performance evaluation

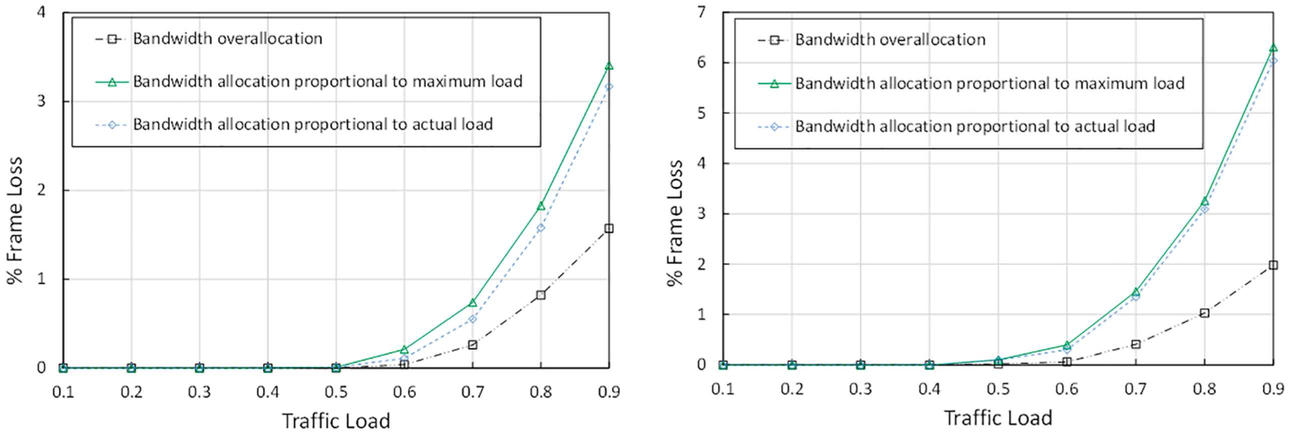
Fig. 5 shows the percentage of frame loss for the three experiments in scenarios 1 and 2 for the IACG DBA at various traffic loads. It can be

Table 1
Simulation parameters.

Parameter	Value
OLT	1
Total number of ONUs	16
Upstream line rate	10 Gbit/s
Downstream line rate	10 Gbit/s
Users to ONU line rate	200 Mbit/s
Buffer size	1 MB
Ethernet frame size	1500 bytes
T-CONT types	2, 3 and 4
Distance between ONU and OLT	10 km
Propagation delay	5 μs/km

Table 2
Bandwidth allocation for scenario 1 (T2 as fronthaul) experiments in IACG DBA.

Experiment	T-CONT type	Traffic type	Bandwidth allocation per ONU	ONU
Bandwidth allocation proportional to maximum load	T2	Fronthaul	350 Mbit/s	0 – 8
	T3	Midhaul	156 Mbit/s	9 – 12
	T4	Backhaul/ Fixed access	116 Mbit/s	13 – 15
Bandwidth allocation proportional to actual load (at 90 % traffic load)	T2	Fronthaul	315 Mbit/s	0 – 8
	T3	Midhaul	140 Mbit/s	9 – 12
	T4	Backhaul/ Fixed access	104 Mbit/s	13 – 15
Bandwidth overallocation	T2	Fronthaul	560 Mbit/s	0 – 8
	T3	Midhaul	40 Mbit/s	9 – 12
	T4	Backhaul/ Fixed access	20 Mbit/s	13 – 15



(a)

(b)

Fig. 5. Percentage of frame loss vs traffic load in IACG DBA. (a) T2 in scenario 1 (T2 as fronthaul) (b) T3 in scenario 2 (T2 and T3 as fronthaul).

observed that where there is bandwidth overallocation to T2, the frame loss is the smallest. This is also the case for the T3 frame loss in scenario 2, which carries user data (fronthaul) traffic, as shown in Fig. 5 (b). In scenario 2, the frame loss for T2, which carries control and signaling (fronthaul) traffic, is zero. This is due to the smaller amount of T2 traffic being transmitted and T2 having a higher priority over T3 in bandwidth allocation.

Fig. 6 shows the results for the percentage of frame loss for bandwidth overallocation in the IACG DBA and proposed hybrid DBA. It can be clearly seen that the proposed hybrid DBA performs better than the IACG DBA and provides zero frame loss for T2 (in scenarios 1 and 2) and T3 (in scenario 2) at all traffic loads. The reason for this is that in the proposed hybrid DBA, there is no bandwidth waste at the ONU, as the OLT knows the amount of bandwidth to allocate to T2 before the arrival of the frames at the ONU buffer in the upstream.

Tables 3 and 4 show the comparison of the average ONU upstream delay between the IACG DBA and hybrid DBA for scenarios 1 and 2. In scenario 1 (T2 as fronthaul), the average ONU upstream delay for fronthaul traffic (T2) at 90 % traffic load in the IACG DBA is the lowest (approximately 68 μs) when there is bandwidth overallocation, as shown in Table 3. For the hybrid DBA, the average ONU upstream delay for T2 is lower and remains the same at approximately 64 μs for all three experiments.

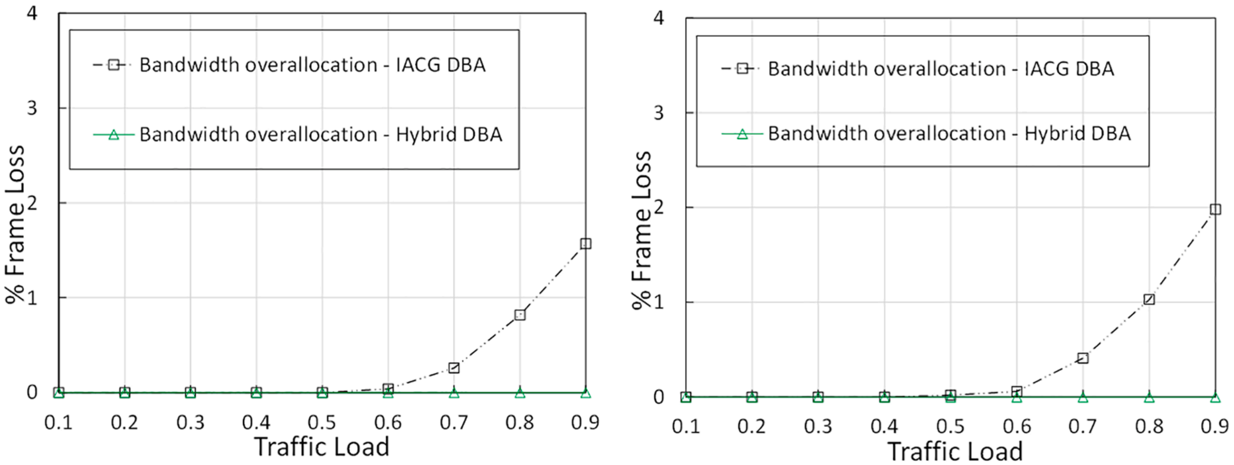
Table 3
Comparison of T2 average ONU upstream delay in IACG DBA and Hybrid DBA for scenario 1 (T2 as fronthaul) at 90% traffic load.

Experiment	IACG DBA	Hybrid DBA
Bandwidth allocation proportional to maximum load	71 μs	64 μs
Bandwidth allocation proportional to actual load	71 μs	64 μs
Bandwidth overallocation	68 μs	64 μs

Table 4
Comparison of T3 average ONU upstream delay in IACG DBA and Hybrid DBA for scenario 2 (T2 and T3 as fronthaul) at 90% traffic load.

Experiment	IACG DBA	Hybrid DBA
Bandwidth allocation proportional to maximum load	76 μs	64 μs
Bandwidth allocation proportional to actual load	75 μs	64 μs
Bandwidth overallocation	68 μs	64 μs

In scenario 2 (T2 and T3 as fronthaul), the average ONU upstream delay at 90 % traffic load for T2 (control and signaling – fronthaul traffic) in the IACG DBA remains at approximately 64 μs for the three experiments, while it is approximately 64 μs in the hybrid DBA. As shown in Table 4, the average ONU upstream delay at 90 % traffic load



(a)

(b)

Fig. 6. Percentage of frame loss vs traffic load for bandwidth overallocation in IACG DBA and hybrid DBA. (a) T2 in scenario 1 (T2 as fronthaul) (b) T3 in scenario 2 (T2 and T3 as fronthaul).

for T3 (user data – fronthaul traffic) for the hybrid DBA remains constant at 64 µs in the three experiments and this value is lower than the smallest value for the IACG DBA, obtained for the bandwidth overallocation experiment.

In order to further test the performance of the proposed hybrid DBA, we consider a fourth experiment in which the number of ONUs carrying fronthaul traffic for scenarios 1 and 2 is increased from 9 to 15 ONUs with only 1 ONU carrying midhaul traffic in scenario 2 or both midhaul and backhaul/fixed access traffic in scenario 1. Scenario 1 uses one ONU, with T3 carrying midhaul traffic and T4 carrying backhaul/fixed access traffic in the ratio 57:43 (T3:T4). The number of ONUs used by fronthaul traffic is increased in order to show that overallocation of bandwidth to T2 can be avoided while obtaining improved results using the proposed hybrid DBA at the same time.

In scenario 1 (T2 as fronthaul), 15 ONUs carry fronthaul traffic (T2) instead of 9 ONUs, while 1 ONU carries both midhaul (T3) and backhaul (T4) traffic. The bandwidth in the upstream is shared proportionally to the number of ONUs carrying T2, T3 and T4 traffic. In scenario 2 (T2 and T3 as fronthaul), the number of ONUs carrying fronthaul traffic (T2 and T3) is also increased from 9 to 15 with 1 ONU carrying midhaul traffic (T4).

Tables 5 and 6 show the frame loss at 90 % traffic load in the IACG DBA and hybrid DBA for scenarios 1 and 2. In the IACG DBA, with the increased number of ONUs (from 9 to 15) for fronthaul traffic, it is observed that there is a higher frame loss in scenario 1. In scenario 2, the frame loss for fronthaul traffic – control and signaling (T2) remains the same at 0 % while it increased significantly for fronthaul traffic – user data (T3). In the hybrid DBA, for both scenarios 1 and 2, the frame loss of the fronthaul traffic (T2) remains at 0 %.

Tables 7 and 8 show the average ONU upstream delay at 90 % traffic load in the IACG DBA and hybrid DBA for scenarios 1 and 2. In scenario 1, it can be observed that there is a decrease in the average ONU upstream delay for midhaul and a significant increase for backhaul traffic in the IACG DBA. This is due to only one ONU being used for both midhaul and backhaul traffic with a larger proportion of traffic generated going to midhaul traffic and the backhaul traffic having a lower priority in bandwidth allocation. The midhaul traffic (T4) also has a large increase in average ONU upstream delay. This is due to only one ONU (previously 7 ONUs) carrying T4 traffic and the T4 traffic class having the lowest priority.

In the hybrid DBA, for both scenarios 1 and 2, the average ONU upstream delay remains unchanged at approximately 64 µs when using either 9 or 15 ONUs for transmission. The average ONU upstream delay for midhaul traffic (T3) in scenario 1, which originally transmitted using only one ONU, decreases slightly when 4 ONUs were used for transmission. There is also a similar slight decrease in the average ONU upstream delay for backhaul traffic (T4) when the number of ONUs is decreased from three to one. In scenario 2, the average ONU upstream delay for midhaul traffic (T4) remains the same at 66 µs.

Increasing the number of ONUs for fronthaul traffic in the proposed hybrid DBA shows that the performance for frame loss and average ONU upstream delay remains unchanged in both scenarios. However, for non-fronthaul traffic (midhaul, backhaul and fixed access), there is a slight improvement in the average ONU upstream delay.

Table 5
Frame loss in IACG DBA for scenarios 1 (T2 as fronthaul) and 2 (T2 and T3 as fronthaul) at 90% traffic load.

Scenario	Traffic type	Frame loss	Frame loss
Scenario 1 (T2 as fronthaul)	Fronthaul traffic (T2)	1.57 % (with 9 ONUs)	4.51 % (with 15 ONUs)
Scenario 2 (T2 and T3 as fronthaul)	Fronthaul traffic – control and signaling (T2)	0 % (with 9 ONUs)	0 % (with 15 ONUs)
Scenario 2 (T2 and T3 as fronthaul)	Fronthaul traffic – user data (T3)	1.98 % (with 9 ONUs)	5.87 % (with 15 ONUs)

Table 6
Frame loss in hybrid DBA for scenarios 1 (T2 as fronthaul) and 2 (T2 and T3 as fronthaul) at 90% traffic load.

Scenario	Traffic type	Frame loss	Frame loss
Scenario 1 (T2 as fronthaul)	Fronthaul traffic (T2)	0 % (with 9 ONUs)	0 % (with 15 ONUs)
Scenario 2 (T2 and T3 as fronthaul)	Fronthaul traffic (T2)	0 % (with 9 ONUs)	0 % (with 15 ONUs)

Table 7
Average ONU upstream delay in IACG DBA for scenarios 1 (T2 as fronthaul) and 2 (T2 and T3 as fronthaul) at 90% traffic load.

Scenario	Traffic type	Frame loss	Frame loss
Scenario 1 (T2 as fronthaul)	Midhaul traffic (T3)	81 µs (with 7 ONUs)	67 µs (with 1 ONU)
Scenario 1 (T2 as fronthaul)	Backhaul traffic (T4)	82 µs (with 7 ONUs)	164 µs (with 1 ONU)
Scenario 2 (T2 and T3 as fronthaul)	Midhaul traffic (T4)	82 µs (with 7 ONUs)	207 µs (with 1 ONU)

Table 8
Average ONU upstream delay in hybrid DBA for scenarios 1 (T2 as fronthaul) and 2 (T2 and T3 as fronthaul) at 90% traffic load.

Scenario	Traffic type	Frame loss	Frame loss
Scenario 1 (T2 as fronthaul)	Midhaul traffic (T3)	66 µs (with 4 ONUs)	63 µs (with 1 ONU)
Scenario 1 (T2 as fronthaul)	Backhaul traffic (T4)	66 µs (with 3 ONUs)	64 µs (with 1 ONU)
Scenario 2 (T2 and T3 as fronthaul)	Midhaul traffic (T4)	66 µs (with 7 ONUs)	66 µs (with 1 ONU)

6. Conclusion

In this work, a hybrid DBA scheme operating with the IACG and CO-DBA for a converged fronthaul based on the ITU-T PON standard is proposed. The scheme uses a XGS-PON system model implemented using the OMNeT++ discrete event network simulator. The CO-DBA transmitted fronthaul traffic while the IACG DBA, using its colorless grant phase, transmitted non-fronthaul traffic.

The performance of the proposed hybrid DBA was evaluated using four simulation experiments in two deployment scenarios. The hybrid DBA was shown to give enhanced performance over the IACG DBA for the percentage of frame loss meeting a 140 µs queuing delay requirement for fronthaul traffic and the average ONU upstream delay. It also showed that T3 frames relies less on the colorless grant. When the number of ONUs carrying fronthaul traffic is increased, the IACG DBA shows an increased frame loss and average ONU upstream delay while the hybrid DBA is able to maintain a zero-frame loss.

CRediT authorship contribution statement

Samuel O. Edeagu: Conceptualization, Methodology, Software, Investigation, Writing – original draft, Writing – review & editing. **Rizwan A. Butt:** Software. **Sevia M. Idrus:** Supervision. **Nathan J. Gomes:** Supervision, Project administration, Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors are unable or have chosen not to specify which data has been used.

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