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PARNIAN: A TWO-STAGE NESTED-AUCTION FOR DYNAMIC BANDWIDTH ALLOCATION IN ETHERNET PASSIVE OPTICAL NETWORKS*

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Abstract– One of the key challenges in next generation access networks based on Ethernet Passive Optical Network (EPON) technology is Dynamic Bandwidth Allocation (DBA) process. In this paper we have proposed 'Parnian', a two-stage nested-auction for dynamic bandwidth allocation management in Ethernet Passive Optical Networks. In the proposed 'Parnian' method, by running nested auction, based on EPON architecture, the Optical Network Units locally optimize the users' bandwidth requests by first stage auction and then the Optical Line Terminal runs the second stage auction for allocating the requested bandwidths dynamically and effectively. Simulation results show that 'Parnian', in comparison with the Fair Sharing with Dual Service Level Agreement (FSD-SLA) and limited service Interleaved polling with adaptive cycle time (IPACT) experiences more delay, but regarding other quality of service parameters such as execution time, packet loss ratio, line utilization, and throughput, it has a better performance.

Keywords– Dynamic bandwidth allocation (DBA), ethernet passive optical network (EPON), auction theory, quality of service (QoS)

1. INTRODUCTION

As a result of the significant increase in the number of network users and their requests for receiving various types of networking services, it is essential to exploit the next generation access networks [1]. One of the major technologies on the wired platform in the development of next generation networking is the Ethernet Passive Optical Network (EPON) technology (Fig. 1) [2]. EPON is a network that consists of an Optical Line Terminal (OLT), as an operating centre, and several Optical Network Units (ONUs), which are the users whose requests are going to be dealt with. In this network architecture, the downstream line from the OLT to the ONUs is a point to multipoint network and the upstream line from the ONUs to the OLT is a multipoint to point network, where there is a channel shared between the ONUs for sending the frames based on the MAC layers [1].

The advantages of EPON over the older methods include a high capacity for configuration, large scale compatibility, and lower cost of bandwidth allocation to the users [3]. Therefore, development of EPON technology has been the center of attention of many researchers as one of the best and most suitable ways for creating the next generation access networks [4].

The recognition of bandwidth bottleneck is important not only for research reliability, but also for the successful implementation of access networks that will be designed for the survival of communications and keeping the next generation access network active on the "last mile" communication network areas [5].

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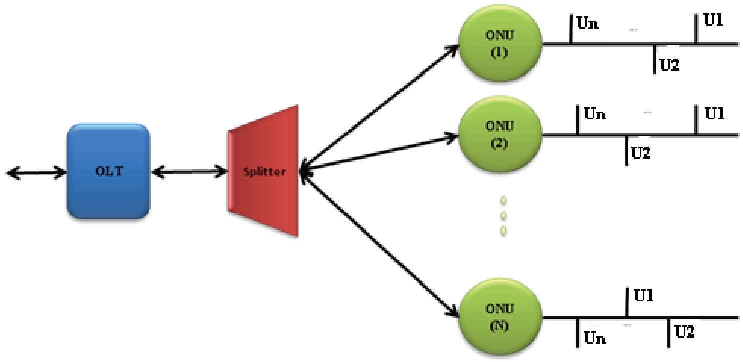


Fig. 1. EPON's architecture

The dynamic allocation of bandwidth and the efficient time management for sending the ONUs requested frames are two essential issues that the EPON technology has developed in order to prevent data interference and queuing up the members at any time. All the current methods based on the EPON architecture are designed as either dynamic or static [6].

In this paper, a new dynamic bandwidth allocation method is proposed based on two-stage nested-auction [7] mechanism. Bandwidth auctioning methods have been proposed before in which bandwidth is assigned to a node/port based on the bids that are submitted by all the nodes/ports in the network. The node that submits the highest bid is the allocated bandwidth. To ensure the success of such a method, the bidding is done ahead in time and is also arbitrated through a central authority. In this approach, two stages of auction [8] are conducted between the users and the ONUs separately. The bandwidth allocation is performed by running auction in two stages, one for the ONUs under the OLT Control and another for the users under the ONUs' administration. In the Proposed method Dynamic bandwidth allocation automatically occurs in Inter-ONU and Intra-ONU levels of EPON technology.

The rest of this paper is organized as follows: In section 2, some important DBA methods will be briefly analysed based on EPON architecture. Section 3 covers the Parnian method in detail. Section 4 presents simulation results and discussion. Finally, the conclusion will be in section 5.

2. RELATED WORK

Currently, various methods are designed based on the EPON technology and can be classified into static bandwidth allocation and dynamic bandwidth allocation methods [9].

In static bandwidth allocation methods each ONU is allocated a time slot with a fixed length that requires no bandwidth negotiation and is due to the bursting nature of the network traffic [9]. This, however, may result in a situation in which some timeslots are overflowed even under very light loads, causing packets to be delayed for several timeslots, while other timeslots are not fully used, even under very heavy traffic, leading to an under-utilized upstream bandwidth. Thus, the static allocation is not preferred [10].

In dynamic bandwidth allocation methods used to increase the bandwidth utilization, the OLT must dynamically allocate a variable timeslot to each ONU based on the instantaneous bandwidth requests of the ONUs. Given that Quality of Service (QoS) is the main concern in EPONs, these methods are classified into DBA without QoS support and DBA with QoS support [11].

In order to dynamically allocate bandwidth without QoS support, several algorithms have been developed based on 'polling' which are centered around the OLT. One of these algorithms is interleaved polling with adaptive cycle time (IPACT) which dynamically responds to the ONUs' requests through the OLT's polling function. Three types of services are offered by the IPACT method including constant service, gate service, and limited service [10]. This method has been extended and improved within the following algorithms: IPACT with Smallest Available Report First (SARF) [12], interleaved polling with adaptive cycle time and grant estimation (IPACT-GE), and Estimation-based dynamic bandwidth allocation [13].

Another DBA without QoS support method is the Bandwidth guaranteed polling (BGP) algorithm which has been developed to guarantee the bandwidth allocation in the EPON architecture [14]. In this method, all of the ONUs are divided into either ONUs with a guaranteed bandwidth or ONUs without a guaranteed bandwidth. However, OLT is still responsible for bandwidth allocation based on the polling function, where all of the ONUs are given a constant polling time and are then assigned a constant bandwidth according to the service level agreement [15]. This method causes a reduction in the delay, although more guard time is needed inbetween the allocations which will eventually result in reduced line utilization. Therefore, all the current methods are suitable for the best effort traffic [11].

In the EPON system only some of the received data traffic types are based on the best effort and the rest are spontaneous types of traffic such as sound, video, etc. which might face limited bandwidth, delay in packet transfer, and delay jitter. Therefore, to tackle these challenges, the DBA approaches with QoS support are needed. One of the major methods in this category is Fair Sharing with Dual Service Level Agreement (FSD-SLA) where all of the ONUs that require lower bandwidth are given a higher priority and bandwidth allocation occurs in a time period within the upstream level. On the other hand, the ONUs with greater bandwidth requests are given a lower priority. This method is based on the service level agreement, although the major issue in this approach is starvation, which is inevitable during the second level of the service level agreement. Thus, to overcome this issue Min-Max algorithm is exploited to allocate the bandwidth in a more justified manner [15].

Another method under the DBA with QoS support is Limited sharing with traffic prediction (LSTP) which uses adapted mechanisms to allocate the bandwidth in a more effective way. This method can predict the traffic based on the waiting period for receiving a bandwidth, or in other words, the bandwidth allocation can be calculated based on the previous time periods of the traffic. Therefore, the ONU's requests for bandwidth allocation are comprised of an estimated queue length which can then be used by the OLT in order to allocate a share of an upstream bandwidth for data transfer. Consequently, the delay and the packet loss ratio will be reduced [16].

Other algorithms classified as DBA with QoS service include Class-of-Service-oriented Packet Scheduling (COPS) [17], Hybrid Granting Protocol (HGP) [18], Dynamic Bandwidth Allocation with Multiple services (DBAM) [19], Two-layer bandwidth allocation [20], Limited allocation with excess distribution [21], Queue-based dynamic bandwidth allocation [22], QoS-aware dynamic bandwidth allocation [23], Intra-ONU bandwidth scheduling [24], Intra-ONU bandwidth allocation [25], Fine scheduling [26], Priority-based dynamic bandwidth allocation for emergency handling [27], Admission control for QoS protection [28], and Fair bandwidth allocation using effective multicast traffic share [29].

3. THE PROPOSED PARNIAN METHOD

The Parnian dynamic bandwidth allocation method (Fig. 2) is based on two-stage nested-auction under the EPON network. The bandwidth allocation is performed by running auction in two stages, one for the ONUs under the OLT management and another one for the users under the ONUs' control.

The proposed method organizes the auction in two stages by the OLT and the ONUs. Therefore, in order to further describe this method, each stage will be explained separately:

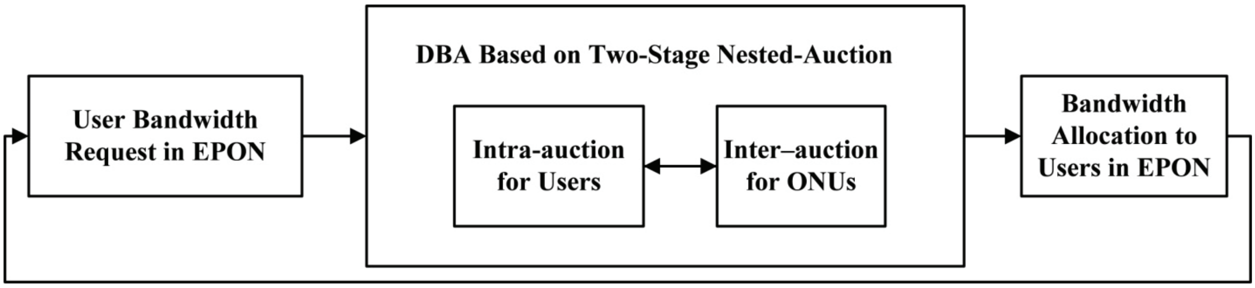


Fig. 2. Overall design of the proposed Parnian method

a) First stage

The first stage auction is performed by the ONUs. Overall, the main steps of the first stage in the Parnian method (Fig. 3) are listed as follows:

- *First step:* Announcing the auction by the ONUs for receiving the bandwidth allocation requests from the users and submitting the initial conditions to them.
- *Second step:* Analyzing the initial auction conditions by the users and announcing the bandwidth requests parameters to ONUs in order to run the first stage auction for users.
- *Third step:* Evaluating the received requests from the users, running auction, and selecting the winners followed by producing a list of ONUs with winner users for the second stage of the nested-auction.
- *Fourth step:* Forwarding the relevant ONUs in the third step to the second stage of auction and generate the users' list which did not win in the first stage of the auction.

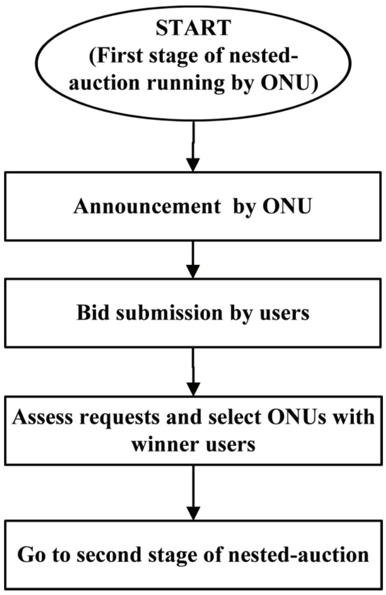


Fig. 3. Overall design of nested-auction's first stage in the proposed Parnian method

In the first step of the first stage in nested auction, ONUs submit the conditions of the auction to all the users, including the allocated time slot to each user in order to send their requests for participating in the first step of nested-auction, the maximum buffer available for the ONU, and the time required for ONU to respond to users.

In the second step of the first stage in nested-auction, the users send their requests, which are parametric bid values, to the ONUs after evaluating the first step conditions. The bid value is comprised of three parameters including the user's cost function, requested bandwidth, and priority, which are illustrated in Eq. (1-3).

$$Bid_{ij}^{User}(t) = \alpha(\pi_{ij}^{User}(t), BW_{ij}^{\mathrm{Re}q}(t), \Pr_{ij}^{User}(t)) \tag{1}$$

In Eq. (1), $\pi_{ij}^{User}(t)$ is the cost function that the j[th] user from ONU_i announces for the requested bandwidth and $BW_{ij}^{\mathrm{Req}}(t)$ is the requested bandwidth of the j[th] user from ONU_i at time *t*. Eq. (2) shows the value of $\pi_{ij}^{User}(t)$, where the $\Pr_{ij}^{user}(t)$ is the priority of the j[th] user from ONU_i which has requested a bandwidth through the ONU_i.

$$\pi_{ij}^{User}(t) = \frac{\Pr_{ij}^{User}(t)}{BW_{ij}^{\mathrm{Re}q}(t) \times D_{ij}^{User}(t)} \tag{2}$$

In Eq. (2), $BW_{ij}^{\mathrm{Req}}(t)$ shows the requested bandwidth of the j[th] user from ONU_i and D_{ij}^{User} is the maximum delay that ONU_i can expect to receive the requested service or, in other words, the time length that is required for the j[th] user from ONU_i to receive a response.

Moreover, in this method, for a more effective simulation, four levels of traffic priority have been proposed which are critical, high, medium, and low. One of the major advantages of this method is that the increased levels of traffic priority will not affect the function of the algorithm and, therefore, different priority levels can be maintained. Furthermore, all of the ONUs are given a similar level of priority. Table 1 illustrates these priority levels.

Table 1. User's priority

Priority	*Value*
Critical	4
High	3
Medium	2
Low	1

Finally, in Eq. (2) $BW_{ij}^{\mathrm{Req}}(t)$ is equal to:

$$BW_{ij}^{\mathrm{Req}}(t) = m_{ij}^{Frame} \times L_{ij}^{Frame} \tag{3}$$

Where the m_{ij}^{Frame} shows the number of requested frames of the j[th] user from ONU_i and L_{ij}^{Frame} is the length of the frames sent by the j[th] user of ONU_i.

In the third step of the first stage in nested auction, ONU calculates users' bids regarding the received requests, runs the first stage in nested auction, and evaluates each user based on the first-price auction theory. Finally, the users who have the greatest value of not more than the maximum buffer capacity of the *ONU* are selected.

In the fourth step of the first stage in nested auction, to increase the success rate for the users who were not successful in this stage and prevent their starvation, a credit-based mechanism is developed to calculate and store this type of users' new cost function. To achieve this, the cost function is calculated for this type of user and the new received requests within the next time period (Eq. (4)).

$$\pi_{ij}^{User}(t) = [1+\lambda] \times \pi_{ij}^{User}(t-1) \tag{4}$$

Where λ equals

$$\lambda = thre_{w}^{User}[\pi_{ij}^{User}(t-1)] - \pi_{ij}^{User}(t-1) \tag{5}$$

In Eq. (5), $thre_{w}^{User}$ is the lowest bid of winner users who have won in the previous step.

The requested bandwidths are not allocated to the users at this stage and the winner's requests will be stored in a separate buffer. However, the bandwidth will be allocated in the second stage of nested auction to the winner users. Figures 4 and 5 show the pseudo code and overall execution of the first stage of nested auction in Parnian.

```
START /* First stage of nested-auction  process */
:STEP  I
    Run (Auction process by ONU)  /*Auction process running by ONUs*/
    Send (Announce signal from ONUs to users)
:STEP  II
      For j=1 to l Do
           If (User_j has a req.?)
             Then
                  Compute (Parametric bid )
                  Submit (Optimal bid ) /*Send parametric bid from users to OLT by ONU*/
             Else
                  Send (Auction_out_msg)/*Send exit message from auction and wait until receive
new req.*/
          End If
       End For

:STEP III
      For j=1 to n Do
          Bid_computation(non busy user_j)
      End For
      For L=1 to n Do
          Select (winners) /*Select winner users by ONUs  based  on first price sealed bid auction*/
      End For
      Publish List 1. /*List 1 consists of all user's request*/
      Publish List 2. /*List 2 consists of (list 1.)-(winner users by ONUs)*/

:STEP IV
       Do Parallel:
         1- K ONUs with winner users go to second stage of nested-auction

         2-For j=1 to m Do
                 Bid-computation (Users from list 2) /*New bid computation with threshold of  bid*/
          End For
          Publish remaining users list with new bids to be able to participate them in next round of
first-stage auction
```

Fig. 4. Pseudo code for first stage of nested-auction in Parnian

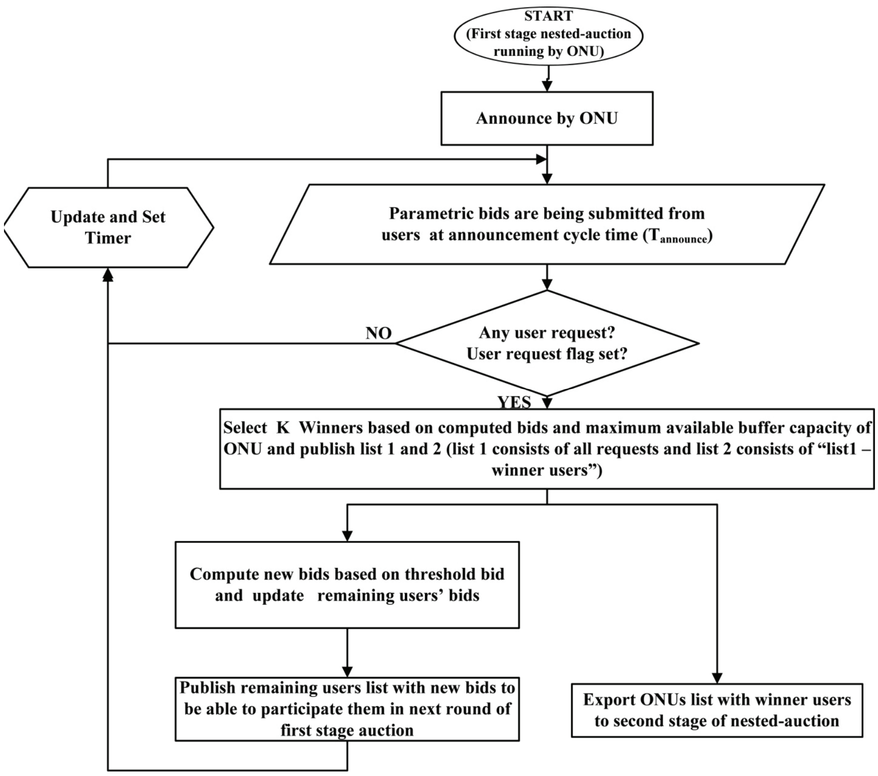


Fig. 5. Overall execution process in the first stage of nested-auction

b) Second stage

The second stage in nested-auction is performed by the OLT. In this stage, auction is being managed by the OLT which responds to the bandwidth requests of the ONUs relative to their priority and the maximum time they can wait to receive the requested bandwidths. Overall, the main steps in the second stage of nested-auction in the Parnian method (Fig. 6) are listed as follows:

- *First step:* Announcing the auction by the OLT for the allocation of ONUs requested bandwidths and submitting the second stage auction conditions to the ONUs.
- *Second step*: Analyzing the initial auction conditions by ONUs and announcing the bandwidth requests' parameters from ONUs to the OLT. These parameters are the maximum waiting time of an ONU to receive a service, the requested bandwidth of an ONU, and the ONU's priority.
- *Third step:* Evaluating the received requests from the ONUs, running auction, and selecting the winner ONUs followed by producing a sub-list from winners of the second stage in the two-level nested-auction process.
- *Fourth step:* Allocation of the requested bandwidths to the winner ONUs and monitoring the bandwidth under use.
- *Fifth step:* Repeat first stage of nested-auction.

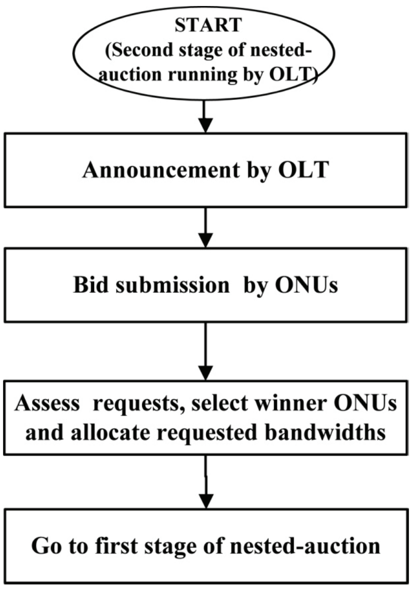


Fig. 6. Overall design of the second stage of nested-auction in the proposed Parnian method

The second stage of the algorithm in the proposed Parnian method is discussed in more detail here. In the first step of the second stage in nested-auction, OLT submits the conditions of the auction to all the ONUs, including the allocated time slot that each ONU is given in order to send it's requests, the maximum bandwidth available from the OLT, and the time required for the OLT to respond to the received requests.

In the second step of the second stage in nested-auction, the ONUs send their requests to the OLT as parametric bid values after evaluating the conditions of the auction. The relationship between various parameters and the final bid value is demonstrated in Eq. (6), (7) and (8).

$$Bid_i(t) = \beta(\pi_i^{ONU}(t), BW_{ONU_i}^{\mathrm{Req}}(t)) \tag{6}$$

In Eq. 6, $\pi_i^{ONU}(t)$ is the cost that ONU_i announces for the requested bandwidth and $BW_{ONU_i}^{\mathrm{Req}}(t)$ is the requested bandwidth of ONU_i at time *t*.

$$\pi_i^{ONU}(t) = \frac{\Pr_i^{ONU}(t)}{BW_{ONU_i}^{\mathrm{Req}}(t) * D_i^{ONU}(t)} \tag{7}$$

Equation (7) shows the value of $\pi_i^{ONU}(t)$, where $\Pr_i^{ONU}(t)$ is the average priority of the users who have sent their bandwidth requests to the ONU_i. In order to simplify the calculations and load reduction, the priority of users is determined based on the type of their requested traffic which provides a fair and equal situation. Eq. (8) shows the priority of ONU_i

$$\Pr_i^{ONU}(t) = \frac{\sum_{j=1}^{k} \Pr_{ij}^{User}}{k} \tag{8}$$

Additionally, in Eq. (7) $BW_{ONU_i}^{\mathrm{Req}}(t)$ is equal to the maximum requested bandwidth that has been announced to the ONUs by the users dependent on their type usage. It has also been assumed that the ONU_i buffer has a limited capacity for receiving the submitted requests from the users. Eq. (9) shows the requested bandwidth of ONU_i.

$$BW_{ONU_i}^{\mathrm{Req}}(t) = \sum_{j=1}^{m} BW_{ij}^{\mathrm{Req}}(t) \tag{9}$$

Finally, in Eq. (7), the $D_i^{ONU}(t)$ value is the maximum delay that ONU_i can expect to receive the requested service or, in other words, the maximum time length that the ONU_i can use to respond to the users' requests (Eq. (10)).

$$D_i^{ONU}(t) = \min_{i=1 \to j}\left[D_{ij}^{User}(t)\right] \tag{10}$$

Here, it is necessary to explain the minimum $D_{ij}^{user}(t)$ in Eq. (10), since the minimum latency used to receive the requested service has to employ the maximum or average service desperation time that exists between users will cause users to lower this limit. Waiting time has never received the requested bandwidth and we can see starvation in this method.

In the third step of the second stage in nested-auction, OLT evaluates the requests received from the ONUs. This evaluation is mediated by initially confirming whether at least one ONU submitted a request or not. If the above was confirmed, a list of all the ONUs who have requested to participate in the auction is generated, with the assumption that they are currently idle. Their bid values are then calculated and examined with the first price auction theory. At this step, K' number of ONUs are selected as the winners of the second stage in nested-auction and then, in the fourth step of the second stage in nested-auction, the bandwidth is allocated with the only condition that the total requested bandwidth of the winners should be less than or equal to the maximum available bandwidth offered by the OLT. This has been further illustrated in Eq. (11).

$$ABW_{OLT}(t) \geq \sum_{W=1}^{k} BW_{ONUw}^{\mathrm{Req}}(t) \tag{11}$$

In Eq. (11), $ABW_{OLT}(t)$ is the bandwidth available to the OLT and $BW_{ONUw}^{\mathrm{Req}}(t)$ is the requested bandwidth of the winner ONUs.

Furthermore, in order to increase the efficiency of line utilization and robustness in the proposed method, if there was more bandwidth available than the total allocated bandwidth to the winners, there would be another round of auction between the ONUs who could not win earlier. The remaining bandwidth is then allocated to the second round winners of the second stage in nested-auction. However, there could be no winners.

In the fourth step of the second stage in nested-auction, OLT also monitors the bandwidth under use. This part of the fourth step from the second stage is called service time level in the Parnian method, where OLT stands by until a part of the earlier allocated bandwidth becomes free and can be offered by the OLT in another round of nested-auctioning. The minimum level of bandwidth required for reinitiating the nested-auction is defined as the bandwidth threshold (Eq. (12)).

$$A_{threshold} = \begin{cases} 1 & ABW_{OLT}(t) \geq \dfrac{\left[TBW_{OLT}^{Allocated}(t-1)\right]}{3} \\ 0 & Otherwise \end{cases} \quad (12)$$

In Eq. (12), $A_{threshold}$ defines the time of reinitiating the nested-auction, which is a Boolean value and $TBW_{OLT}^{Allocated}$ is the total allocated bandwidth to the ONUs in the previous round of auction. Figures 7 and 8 show the pseudo code and the overall execution process for the second stage of nested-auction in the Parnian method.

```
START /* Second  stage of nested-auction  process */
:STEP I
      Run (Auction process by OLT)  /*Auction process running by OLT*/
      Send (Announce signal from OLT to ONUs)
:STEP II
      For i=1 to n Do
           If (ONUi has a Req.?)
                 Then
                    Submit (Parametric bid ) /*Send parametric bid from ONUs to OLT*/
                 Else
                   Send (Auction_out_msg)/*Send exit message from auction and wait until
receive new Req.*/
           End If
      End For
:STEP  III
      For j=1 to n Do
          Bid_computation (non-busy ONUj)
      End For
          Select (winners) /*select k winners by OLT based on first price sealed bid auction*/
      If (ABWOLT>Min(BWj,...,BWn)
        Then
        {
           For j=1 to m Do
             Bid_computation (non-winner ONUs)
           End For
             Select (new winners if possible)
                 }
        Else
           Send (Auction_out_msg)
      End If
:STEP  IV
      Until (ABWOLT >  BW THRESHOLD )  Do
        Allocate (Bandwidths to winner ONUs)
        Wait (Service_Time)
      End Until
:STEP V
     Goto first stage of nested-auction
END /* Second stage of nested-auction  process */
```

Fig. 7. Pseudo code for second stage of nested-auction in Parnian

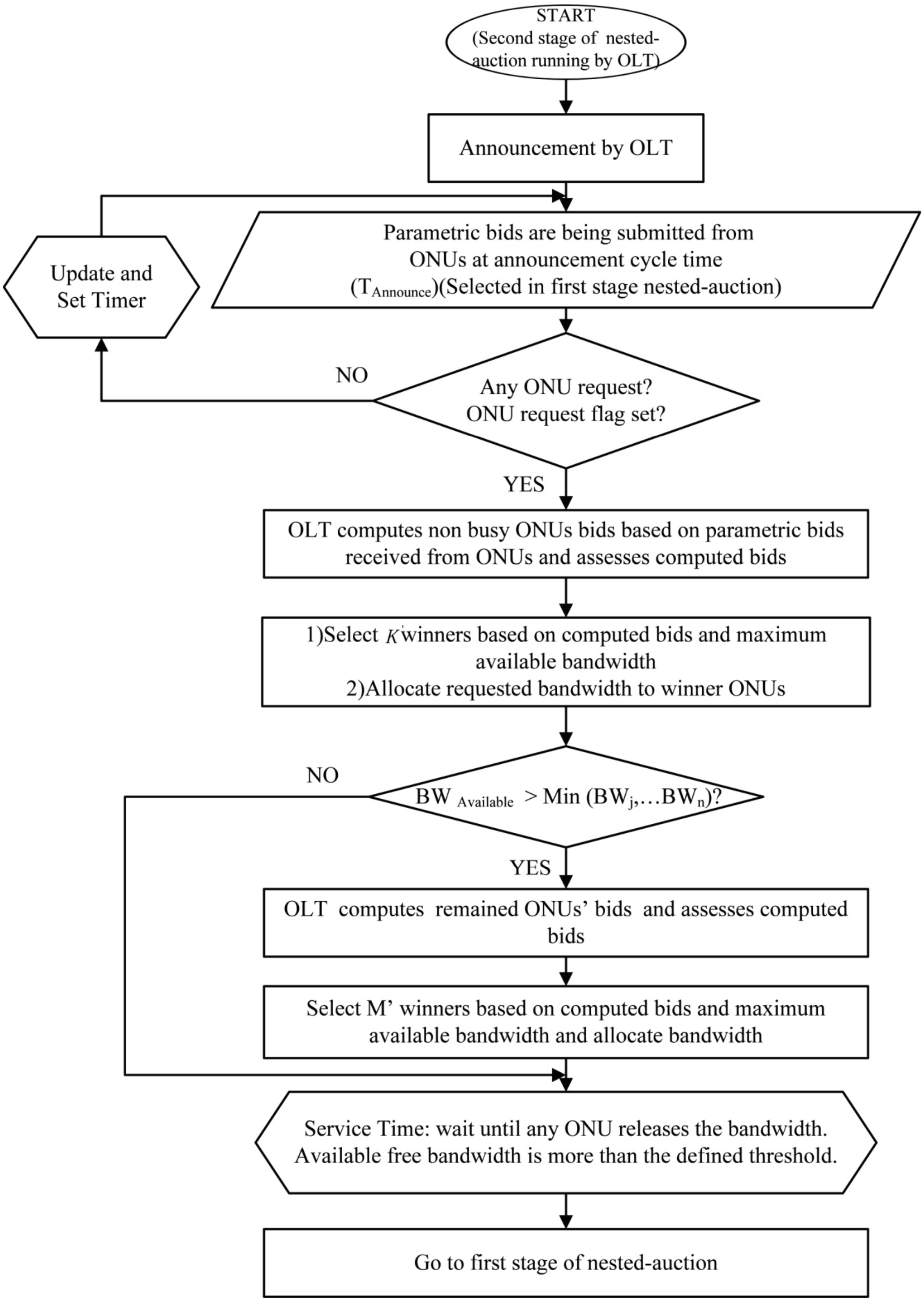


Fig. 8. Overall execution process in the second stage of nested-auction

The assessment of Fairness index in the Parnian method is most difficult when most of bandwidth requests are from the users with the highest priority level or when the users' waiting time to receive bandwidth is very limited.

4. SIMULATION RESULTS

In order to compare the performance of Parnian with other dynamic bandwidth allocation methods, a C++-based EPON simulator is designed. In the simulation process, a multipoint to point network, based on the EPON architecture is used. Table 2 shows the simulation parameters.

Table 2. Simulation parameters

Parameters	Value
Number of ONUs	16
Amount of bit rate for `ONU to OLT` connection	5 to 57.5 Mbit/s
Two-way fiber delay	200 µs
Packet size	15000 Byte (30 Packets)
Ethernet overhead	38 Byte
Request message size	570 Bit
Upstream bandwidth	1 GBit/s
Maximum transition window	10 Packets
Guard time	5 µs
Max cycling time	2 ms
Buffer capacity	10 Mbyte
Traffic type	CBR, VBR

The proposed Parnian method has been compared to FSD-SLA and "limited service" IPACT. The comparison was done based on QoS parameters such as delay, throughput, packet loss ratio and line utilization. Besides, the execution time of this method has also been compared with other methods.

The values of the parameters that are set for the simulation of various models are the values that are used in the simulations designed in recent bandwidth allocation methods. Furthermore, in order to increase the credibility and accuracy of simulations for the Parnian method, similar parameters were chosen to those used in IPACT and FSD-SLA methods [9, 10, 15, 30 and 31].

The equations that were used to calculate the QoS parameters in Parnian model have been compared in Table 3, with the current bandwidth allocation methods such as "Limited Service" IPACT and FSD-SLA.

Table 3. Equations of QoS parameters

<table>
<tr><th>QoS parameters</th><th>Equations</th></tr>
<tr><td rowspan="3">Delay</td><td>$$D_{IPACT} = D_{Poll} + D_{Grant} + D_{Queue}$$
$\boldsymbol{D}_{\mathbf{POLL}}$ = time between packet arrival and next request sent by that ONU. On average, this delay equals one-half of the cycle time.

$\boldsymbol{D}_{\mathbf{GRANT}}$ = time interval from an ONU’s request for a transmission window until the beginning of the timeslot in which this frame is to be transmitted. This delay may span multiple cycles (i.e.,a frame may have to skip several timeslots before it reaches the head of the queue), depending on how many frames there were in the queue at the time of the new arrival.

$\boldsymbol{D}_{\mathbf{QUEUE}}$ = delay from the beginning of the timeslot till the beginning of frame transmission. On average, this delay is equal to half of a slot time and is insignificant compared to the previous two components.</td></tr>
<tr><td>$$D_{FSD-SLA} = T_{Cycle-Time} + D_{Grant} + D_{SLA}$$
$\boldsymbol{T}_{\mathbf{Cycle\text{-}Time}}$ = Maximum time cycle duration. The scheduler at the OLT may schedule bandwidth for a maximum duration of *T* in one iteration of scheduling

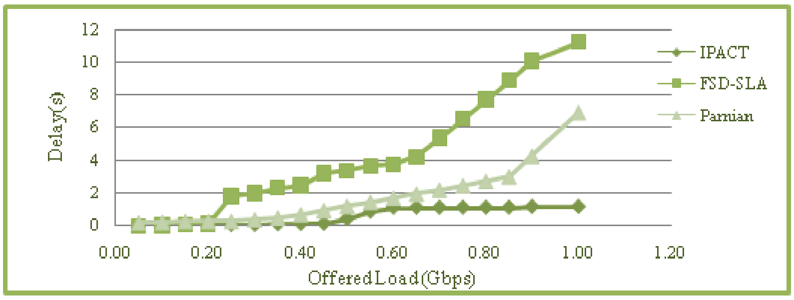
$\boldsymbol{D}_{\mathbf{GRANT}}$ = time interval from an ONU’s request for a transmission window until the beginning of the timeslot in which this frame is to be transmitted. This delay may span multiple cycles (i.e., a frame may have to skip several timeslots before it reaches the head of the queue), depending on how many frames there were in the queue at the time of the new arrival.

$\boldsymbol{D}_{\mathbf{SLA}}$ = delay for checking the Primary and secondary SLA of Requests.</td></tr>
<tr><td>$$D_{Parnian} = D_{Announce} + D_{Auction-Process} + D_{Allocation}$$
$\boldsymbol{D}_{\mathbf{Announce}}$= Time to kick off the auction and submit the bid
$\boldsymbol{D}_{\mathbf{Auction\text{-}Process}}$ = time that auction process was running.
(Assess and select winners)
$\boldsymbol{D}_{\mathbf{Allocation}}$ = Time that bandwidth was allocated to the winners</td></tr>
</table>

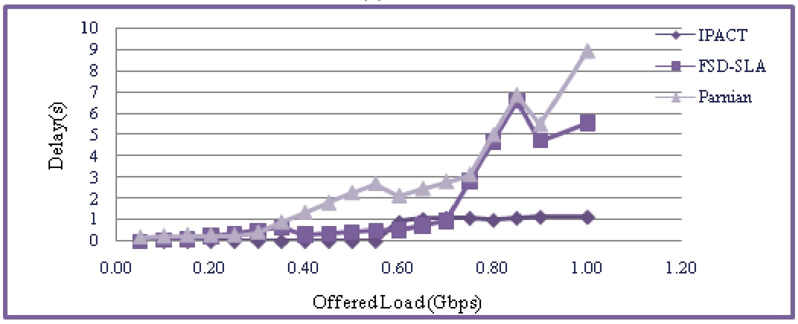
Table 3. Continued.

Packet loss ratio	$$PLR = \frac{(N_{PL})}{(N_{PL} + N_{PR})}$$ N_{PL} : Number of lost packets. N_{PR} : Number of packets received successfully.
Throughput rate	$$TR = \frac{Info_{Total-Recv}}{Time_{Take-To-Recv}}$$ $\boldsymbol{Info_{Time-Recv}}$ = the useful information that needs to be delivered between end-points. $\boldsymbol{Time_{Take-to-Recv}}$ = the time it takes to deliver it.
Line utilization	$$U_{Line} = 1 - \frac{N(B + (R / R_N)}{(t_c)}$$ ***N**:* number of ONUs ***B**:* guard time. ***R**:* remainder. $\boldsymbol{t_C}$: cycle time

Figure 9a shows the delay comparison for the methods based on CBR traffic. Over the course of running auction, due to the decrease in the number of requests, less calculation time is required and, thus, the behavior of Parnian is approximately the same as "limited service" IPACT. As the number of requests increases, more delay will be expected. As in FSD-SLA, the SLAs which request the bandwidth should be checked in each time of the bandwidth allocation process, thus it consistently has the largest delay.



(a). CBR



(b). VBR

Fig. 9. Comparison of average delay in FSD-SLA, "limited service" IPACT, and Parnian

According to the use of VBR traffic in the simulation, Fig. 9b illustrates the comparison between the delay factors of the above methods. It can be observed that there is a delay in the proposed Parnian method at the beginning of the nested-auction. This is greater since the calculation of the requested amount of bandwidth from all ONUs should be accomplished based on the first stage algorithm and optimizing the buffer size before being sent as a parametric bid. On the other hand, over the course of running the auction, due to the decrease in the number of requests, less calculation time is required and thus, the behavior of the proposed method is approximately the same as the behavior of the FSD-SLA method. By the end of the third step of the proposed method, as the number of requests increases, more delay will be expected. In this Step, however, FSD-SLA has the greatest delay consistently, which is due to the greater time required for analyzing the SLAs that are received from the requesting users. Overall, "limited service" IPACT has the minimum delay during the simulation.

Based on CBR traffic type Fig. 10a illustrates the comparison of packet loss ratio. Parnian has the least packet loss ratio because ONUs which can announce more bids in the auction can win it, and, based on their bid they will receive bandwidth, therefore, transferring their packets, whereas in FSD-SLA, analyzing the SLAs shows that the smaller packets are given higher priority and vice versa. Therefore, the larger packets with lower priority would be lost. In "limited service" IPACT, according to the rules, round robin will be sent out to the ONUs without any limitation and only in allocated time slots. So, due to the buffer overflow, "limited service" IPACT has the worst packet loss ratio in comparison.

Figure 10b demonstrates the packet loss ratio in both the IPACT and FSD-SLA methods compared with the proposed Parnian method. The Parnian method shows a lower level of packet loss ratio since all the users who submit a greater bid value can win the auction and receive a bandwidth relevant to their Bid values, which have been optimized based on the first and second stage of auctionning, and transfer their packets. However, in the FSD-SLA approach, through evaluating the SLAs the smaller packets are given higher priority and vice versa. Therefore, the VBR packets with lower priority would be lost. Moreover, in IPACT, according to the rules, round robin will be sent out to the ONUs without any limitation and only in their allocated time slot. Furthermore, as can be noticed in Fig. 10b, the packet loss ratio is significantly higher in the FSD-SLA method since in this method, based on the primary and secondray of SLA concept, the ONUs are only permitted to send small size packets at a specified time slot. Thus, many packets are lost due to over-riding the time limit of receiving the service.

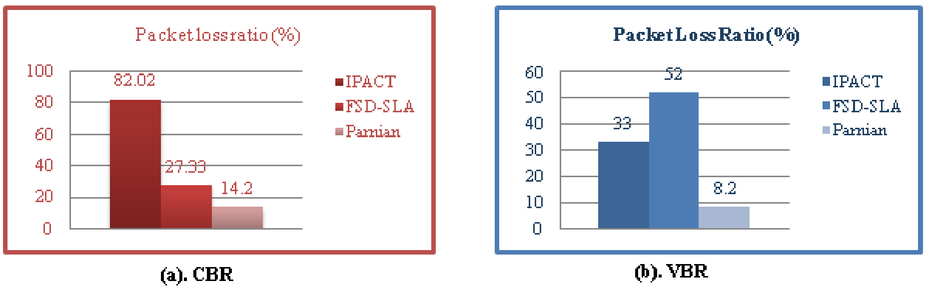
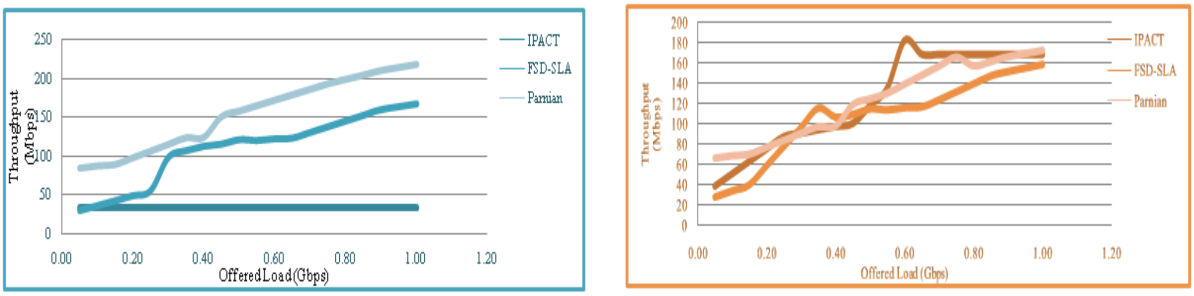


Fig. 10. Comparison of packet loss ratio in FSD-SLA, "limited service" IPACT, and Parnian

Figure 11a demonstrates the comparison between the throughput rates of the three methods based on transferring CBR packets. Just as it is noticeable in the graphs, in "limited service" IPACT, since a monotonous, stable and steady period of time has been given to all of the ONUs, the throughput rate will show similar behavior against increasing traffic load. The condition of throughput in FSD-SLA is better than "limited service" IPACT, but because the allocation priority is defined according to SLAs with a lower volume of traffic, the throughput rate is lower at the beginning and it will be improved by increasing the traffic load and using the min-max solution. Parnian has the best throughput rate in this comparison as the bandwidth is allocated in different stages based on the auction theory, thus creating a condition for the ONUs to send their requests for taking part in the auction.

Figure 11b shows the throughput rate of the VBR packets in the compared methods. As it can be observed, in IPACT, since a stable period of time is given to each ONU according to its buffer size, the throughput rate shows a similar behavior against the increased traffic load. Therefore, in IPACT, the throughput rate is lower as a result of lack of variety between the allocated bandwidth to the ONUs.

Although the condition of throughput in the FSD-SLA is better in comparison with IPACT, the allocation priority is defined according to the SLAs with a lower size of traffic load. Therefore, the throughput rate is lower at the beginning and it will improve by increasing the traffic load and using the min-max solution. On the contrary, our proposed method demonstrates a better throughput rate because the bandwidth is allocated in a more robust manner based on the first price auction theory where the designed conditions allow all the users with requests to participate in the seccond stage of nested-auction which is comprised of different steps. This observed improvement in the throughput rate is due to the bandwidth allocation to all the users through their ONUs, which is shown to be a better approach in VBR type of traffic.



(a). CBR (b). VBR

Fig. 11. Comparison of throughput in FSD-SLA, "limited service" IPACT, and Parnian

Figure 12a and b shows the comparison for line utilization. As they clearly show, the best line utilization belongs to Parnian, because all the packets are being sent in different specific times and therefore the line is being used at its best condition. As "limited service" IPACT allocates a specific period of unlimited time alternately to each ONU, and because it is possible that in the mentioned period ONUs might not have any packet to send, the line utilization is lower than Parnian. The FSD-SLA allocates a higher priority to smaller packets and vice versa, thus, it cannot have appropriate line utilization in comparison.

(a). CBR (b). VBR

Fig. 12. Comparison of line utilization in FSD-SLA, "limited service" IPACT, and Parnian

Finally, the comparison of the average execution time between IPACT, FSD-SLA and Parnian models is shown in Figure 13. Moreover, the parameters required for the calculation of average execution time for each of the above bandwidth allocation methods are summarized in Table 4.

Table 4. Execution time parameters

Number of ONUs	Iteration
4-32	10-100

As it can be noticed (Fig. 13), when the number of ONUs is either 4 or 8, the "limited service" IPACT approach has the lowest execution time amongst all, which is due to the short supervision time in this approach. However, in the Parnian method the length of execution time is the longest because of the nested auction process. By increasing the number of ONUs and consequently increasing the length time required for their requests, the simulation results show that the average execution time in the Parnian method is more than the other approaches. The reason for the above observation is due to the fact that in the Parnian method ONUs assess the bandwidth requests of the users after the first stage of nested auction and then send them to the OLT for participating in the second stage nested auction and, therefore, the time spent at this method is considered when the nested auction is running. It can also be observed that the FSD-SLA method has the longest execution time of all, which is a result of both supervising the ONUs and analyzing the SLAs and the traffic priority of the ONUs with a bandwidth request. Thus, this method has the longer execution time than the "limited service" IPACT. Totally, with the increased number of ONUs, Parnian has the best execution time amongst all.

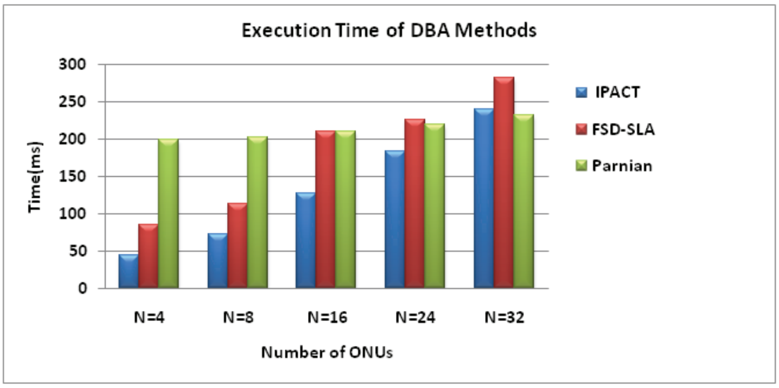


Fig. 13. Comparison of Execution Time in FSD-SLA, "limited service" IPACT and Parnian

5. CONCLUSION

Regarding the importance of dynamic bandwidth allocation in next generation access networks based on EPON technology, in this paper we have proposed Parnian, an optimal DBA method based on auction theory. In this new method, the dynamic bandwidth allocation is performed by running auction in two stages, one for the ONUs under the OLT management and another one for the users under the ONU's control. Simulation results show that Parnian, in comparison with FSD-SLA and "limited service" IPACT experiences more delay, but regarding other quality of service parameters such as packet loss ratio, line utilization, and throughput, it has better performance. On the other hand, the average execution time in Parnian method is better than the "limited service" IPACT and FSD-SLA approaches and, as a result, it works faster. The future research potential in the dynamic bandwidth allocation process in EPON networks will allow us to go further and open new research horizons by utilizing heuristics methods such as genetics algorithm, cellular automata, neural networks, and etc. instead of running auction in user level. Moreover, it would be possible to apply this new DBA method in Wi-Fi and WiMax environments and evaluate the performance.

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