Optimal criteria based Adaptive Wavelength and Bandwidth Allocation for NG-EPON

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Summary
This paper proposes a novel wavelength and bandwidth resource allocation scheme for NG-EPON, where the resource allocation is completely adaptive based on the traffic reported by each optical network unit (ONU) in the network. NG-EPON supports up to 100 Gb/s data rate with 4 wavelengths with an individual capacity of 25 Gb/s. The proposed dynamic wavelength and bandwidth allocation (DWBA) scheme is based on online gated service to assign adaptive number of wavelengths and dynamic bandwidth size on each selected wavelength. The resource assignment is done such that it not only fulfills the bandwidth needs of each ONU in the network but also utilizes all the wavelength resources in equal and effective manner. First the bandwidth is allocated on the wavelength with the least utilization and new wavelength is allocated only if its bandwidth utilization is more than the bandwidth overhead, i.e. guard time. Further, this effectiveness is evaluated with the help of a parameter named *alpha*, and its optimal value is decided based on machine learning. The proposed DWBA algorithm is evaluated in terms of average packet delay, grant utilization, and number of wavelengths used in comparison with modified-IPACT, First-Fit DWBA (FF-DBA), and water-filling algorithm based DWBA (WF-DBA) algorithms. The proposed DWBA performance is validated with the help of simulation results.
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Key words:
NG-EPON, dynamic wavelength and bandwidth allocation, average packet delay, machine learning.

1. Introduction

The existing data networks are continuously running out of data capacity, and as estimated by 2021, globally generated IP traffic will exceed 3.5 ZB [1]. Therefore, the need for high speed solutions is increasing day by day. Passive Optical Networks (PONs) [2] are becoming promising and prominent solutions for such high data required applications due to their high capacity and coverage potential [3-7]. Current EPON standards [8-11] are not able to support the future-PON applications. Therefore, IEEE standardized new technology, NG-EPON (next generation passive optical network), to come across the expectations of future access networks.

1.1 Next Generation Ethernet Passive Optical Network (NG-EPON)

NG-EPON consists of 4 wavelengths with an individual capacity of 25 Gb/s, and thus supports aggregated data rates of 100 Gb/s. In NG-EPON, every ONU is equipped with 4 fixed-wavelength transceivers and can transmit data on all wavelengths simultaneously depending upon the resource allocation scheme adopted by the service providers for an access network [12-16].

In the PON structure, the optical line terminal (OLT) assigns bandwidth resource in round robin to the ONUs by using a message called GRANT. In NG-EPON, the OLT specifies bandwidth, named as the transmission windows (TWs) on four wavelengths to the ONU through the GRANT message. The decision to assign specific size of TW on specific wavelength is decided by the dynamic wavelength and bandwidth allocation (DWBA) algorithm adopted by the OLT. Every ONU begins transmitting its frames immediately upon the reception of GRANT message from the OLT. At the end of transmission, the ONU intimates the OLT for next TW for its buffered frames through a REPORT message. To avoid data overlapping among the TWs of multiple ONUs, a guard time is placed after each TW on each assigned wavelength. Generally, this guard time is of 1 µs duration. Over a link of 25 Gb/s, it represents 3.125 KB data space [5, 11, 17-20].

1.2 Dynamic Bandwidth Allocation Algorithm

The importance of effective DBA has been increased in NG-EPON to decide flexible and optimal number of wavelengths to all ONUs in the network. If the DBA algorithm is not well designed, it may assign inappropriate number of wavelengths as well as insufficient size of the TW on each assigned wavelength. In this way, it may assign insufficient number of wavelengths to a heavily loaded ONU, and excessive number of wavelengths to an ONU with low load. In either case, the performance of the

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network will degrade. For heavily loaded ONUs, their packet delay will increase due to less assigned bandwidth. For lightly loaded ONUs, TW on each assigned wavelength could be small such that its size is equal to or even smaller than the guard time. These too many guard times for lightly loaded ONUs will waste the upstream bandwidth resource, and thus will also increase average packet delay of the network.

Therefore, this paper proposes a DWBA algorithm to improve the delay performance of NG-EPON. It is named as flexible wavelength and dynamic bandwidth allocation (FW-DBA). The main objective of FW-DBA is to assign flexible and appropriate number of wavelengths and TW on each assigned wavelength based on the grant utilization.

The rest of the paper is organized as follows: Related work is explained in section II. Section III discusses proposed DWBA algorithm. Section IV briefly discusses simulation model and results, section V concludes this paper.

2. Related Work

For PONs with one wavelength in the system, various dynamic bandwidth allocation (DBA) algorithms have been proposed [21-26]. However, none of them can be directly implemented in NG-EPON without modification to adjust with the underlying requirements of NG-EPON [27, 28].

2.1 IPACT Algorithm in NG-EPON

IPACT DBA [24] is one of the well-established and used DBAs for basic EPONs, which assigns bandwidth to ONUs in an interleaved way. For NG-EPONs, IPACT can easily be used, if we assume all 4 wavelengths as a single wavelength. We named it as modified-IPACT. Modified-IPACT will distribute the required bandwidth equally on all 4 wavelengths. Therefore, TW of equal size will be assigned on all 4 wavelengths.

In modified-IPACT, bandwidth would be wasted in two ways. Firstly, the decided TW size for each assigned wavelength may not be able to carry an integer number of Ethernet frames, as Ethernet frames are not of equal size [29]. This is called frame-size mismatching problem [19]. Therefore, bandwidth would be wasted due to this underutilization of grant due to frame size mismatch problem. Secondly, TW on every wavelength would be followed by a guard time, which is also wastage of bandwidth, specifically when the traffic reported by an ONU is low. Therefore, modified-IPACT cannot give resources to ONUs fairly.

2.2 First-Fit DWBA

First-Fit DWBA (FF-DBA) [19] is proposed for NG-EPONs. This kind of DWBA algorithms always assigns one wavelength to every ONU irrespective of the reported bandwidth request [21, 30-32]. Our previous work [19], identified frame-size mismatching and frame resequencing delay problems for NG-EPON. FF-DBA is proposed to cater frame resequencing delay problem. FF-DBA gives good performance when number of ONUs is large in the network. However, FF-DBA does not adapt with the change in offered load or with the change in number of ONUs in the network.

2.3 Water-Filling DWBA

Water-Filling DWBA [20] (WF-DBA) is based on water-filling algorithm [33]. Differing from FF-DBA, WF-DBA tries to make the wavelength usage equal while assigning bandwidth to each ONU in the network. WF-DBA assigns bandwidth first on the wavelength with earliest start time, and tries to make it equal to the start time of second wavelength in sequence. Once they become equal, it assigns bandwidth on both wavelengths equally and tries to equalize them to the start time of third wavelength in sequence. Reference [34] implemented WF-DBA as limited grant sizing offline DBA by considering mix of different capacity ONUs (i.e. 25G, 50G and 100G) in the network. Once start time of all the wavelengths become equal, WF-DBA behaves like modified-IPACT and assigns equal TW on each wavelength irrespective of the offered load. Therefore, WF-DDBA too does not have flexibility. WF-DBA works well when number of ONUs is small in the network.

Grant allocation comparison is shown in Fig. 1 for FF-DBA and WF-DBA. We assumed different number of ONUs in the network (i.e. N=16 and N-64). We also assumed different start time of all wavelengths. It can be seen that if reported bandwidth is high or the number of ONUs is low in the network, WF-DBA works well as compared to FF-DBA. However, if number of ONUs is high or reported bandwidth is low, then FF-DBA works well as compared to WF-DBA.

Figure 1 (d) shows that if reported bandwidth is small, and there is some factor which makes bandwidth start time unequal, still WF-DBA allocates wavelength resources without considering the utilization of wavelength. Therefore, a high portion of bandwidth will be wasted by the guard times

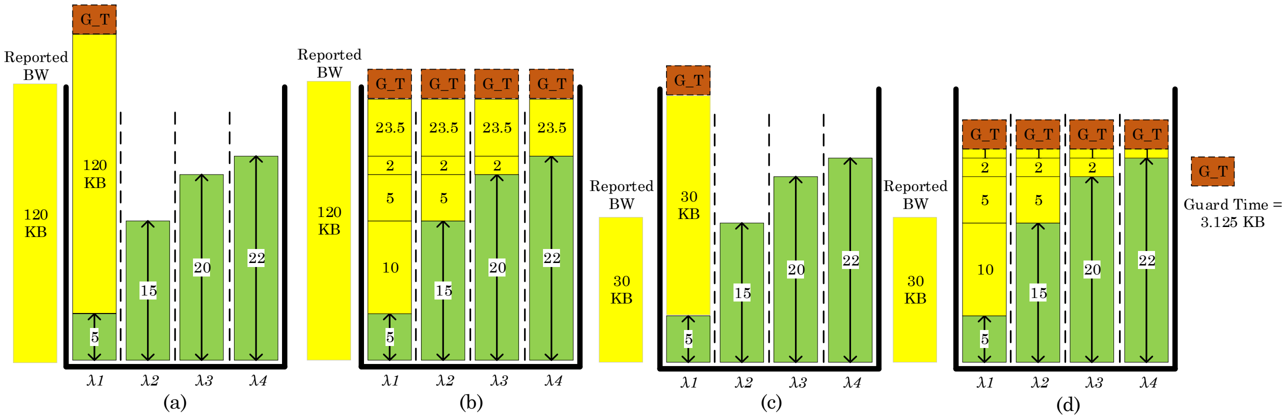


Fig. 1. Grant allocation comparison: (a) FF-DBA when N=16, (b) WF-DBA when N=16, (c) FF-DBA when N=64, (d) WF-DBA when N=64

In summary, FF-DBA and WF-DBA, both are not adaptive with respect to number of ONUs in the network and offered load by the ONUs.

3. Proposed Adaptive Wavelength and bandwidth Algorithm

We proposed a DWBA algorithm, called flexible wavelength allocation algorithm (FW-DBA) to assign number of wavelengths and bandwidth adaptively according to the offered load of ONUs and effective size of TW on each assigned wavelength. FW-DBA is previously proposed in [35]. Various algorithms too have been proposed based on FW-DBA [36-38]. However, the focus of this paper is to find the optimal value of *alpha* using machine learning. FW-DBA distributes the traffic of the ONU to different wavelengths according to their start times and grant utilization. If load by an ONU is high, larger TW would be assigned on each wavelength, and transmission delay can be reduced effectively. In such cases, FW-DBA will give similar performance as that of WF-DBA by assigning TW on all wavelengths.

If the offered load is small, FW-DBA will assign less number of wavelengths based on the grant utilization. If the reported bandwidth by an ONU is less than guard time or less than the chosen criteria of grant utilization, then in this case, FW-DBA would allocate only one wavelength. Therefore, FW-DBA will behave just like FF-DBA. However, if the required TW size on another wavelength is greater than guard time or criteria of grant utilization, then another wavelength will be assigned. Thus, FW-DBA could give grant adaptively on any number of wavelengths from 1 to 4 based on grant utilization.

3.1 Grant Utilization and Alpha Parameter

Based on reported bandwidth from every ONU, whenever a grant is given, it consists of TW for data reported and guard time. Therefore, grant utilization is defined as:

grant utilization= TW*100/(TW+guard_time) (1)

The larger the TW size, better the grant utilization will be. For example, if TW becomes equal in size to the guard time, then the grant utilization will be 50 %. Similarly, if TW becomes further smaller, the grant utilization would be further reduced. Therefore, a criterion is proposed in our work that a new wavelength is assigned to an ONU only when the TW on that wavelength is larger than guard time. This is required to improve the efficiency of the concept of giving parallel grant to an ONU on multiple wavelengths.

To achieve this goal, FW-DBA introduces a parameter *alpha*. *Alpha* controls the criterion to define effectiveness of grant utilization. If the grant utilization is higher than the defined criterion, then additional wavelength will be assigned to an ONU.

$$TW_i \geq \propto * guard\_time \qquad (2)$$

Where TW_i is the TW on *ith* wavelength. and $\propto$ is *alpha* (controlling parameter). If TW size is higher than *alpha* times guard_time, then this wavelength will be assigned, else it will not be assigned.

3.2 Working of FW-DBA

The proposed DWBA would work in 4 steps:

First Step: Initialize λ_used =1, number of wavelengths to be used for i^{th} ONU in j^{th} scheduling cycle

Second Step: Sort all the wavelengths in ascending order of their start time S_{ij}^{k}, so that the least utilized wavelength in previous grant allocation to last ONU, is considered first for new grant allocation.

Third Step: Decide number of wavelengths to be used (λ_used) based on the following condition.

$$if\left(\frac{1}{\lambda\_used+1}\left[reported-\sum_{k=1}^{\lambda\_used+1}\left(S_{i,j}^{\lambda\_used}-S_{i,j}^{k}\right)\right]>\propto * G_T\right) \quad (3)$$

then λ_used++

Fourth Step: Calculate *transmission window*, TW_k on each k^{th} selected wavelength based on decided value of λ_used .

$$TW_k=\left(S_{i,j}^{\lambda\_used}-S_{i,j}^{k}\right)+\left(\frac{1}{\lambda\_used}\left[reported-\sum_{k=1}^{\lambda\_used}\left(S_{i,j}^{\lambda\_used}-S_{i,j}^{k}\right)\right]\right) \quad (4)$$

Fifth Step: Update grant start time based on RTT_i: $S_{ij}^{k}=\max(S_{ij}^{k}, t+RTT_i)$ to avoid grant collisions among the ONUs.

Sixth Step: Update finish time on all chosen wavelengths, based on $F_{i,j}^{k}=S_{i,j}^{k}+TW_k+G\_T$

Where k is index of assigned wavelength, S_{ij}^{k} is start time of k^{th} wavelength for j^{th} scheduling of i^{th} ONU, RTT_i is round-trip time of the scheduled ONU, t is current time, $F_{i,j}^{k}$ is finish time of grant on k^{th} channel, and G_T is guard time of every given grant on each selected wavelength.

If alpha is chosen as $\propto=1$, then new wavelength will be assigned if TW size is higher than guard_time. In that case, grant utilization will be 50%. If some higher value of *alpha* is chosen, then new wavelength would only be assigned when grant utilization is further higher. Working of FW_DBA is shown in Fig. 2 with $\propto=2$, and comparison of FW-DBA with WF-DBA is shown in Fig. 3 with $\propto=1$. It can be seen that FW-DBA is completely adaptive with respect to the reported bandwidth by each ONU and the grant utilization when compared with FF-DBA and WF-DBA.

4. Simulation Model and Results

4.1 Simulation Model

Simulation experiments are performed in this work for generic tree topology based network of ONUs with three different number of ONUs in the network, i.e. N= 32, 64 and 128. Among ONUs, we considered that 90% users are residential users with only 10% of total network traffic and 10% are business users generating 90% of the total network traffic at any offered load. This assumption is done to reflect the adaptive working of our FW-DBA. The performance of proposed FW-DBA is compared with modified-IPACT, WF-DBA and FF-DBA algorithms. Only upstream grant scheduling is considered in this work for simplicity. For grant sizing, gated policy is assumed. We considered online grant scheduling framework in this work. In online grant scheduling, grant is given to every ONU upon the arrival of REPORT message from that ONU in round robin. 4 wavelengths are assumed with an individual capacity of 25 Gbit/s, which gives a total capacity of 100 Gb/s.

The normalized offered load is varied uniformly from 0.1 to 0.9 during the simulation. Two-state Markov Modulated Poisson Process (MMPP) [39, 40] is used to generate burst traffic to further test the working of FW-DBA; whereas, the mean arrival rate of the two-state MMPP is given by the following equation.

$$\lambda=\frac{\lambda_h\beta+\lambda_l\alpha}{\alpha+\beta} \quad (5)$$

where, the traffic arrival switches between two Poisson processes with arrival rates λ_h and λ_l, and the durations of

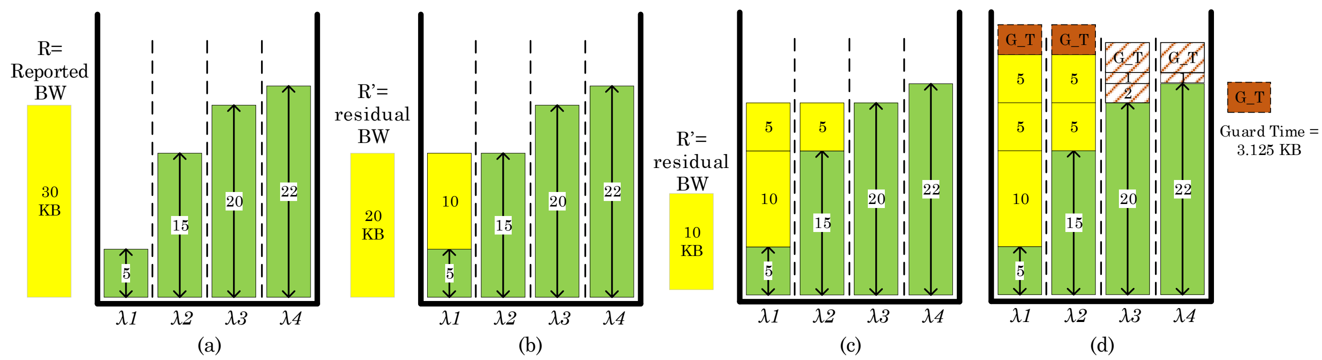
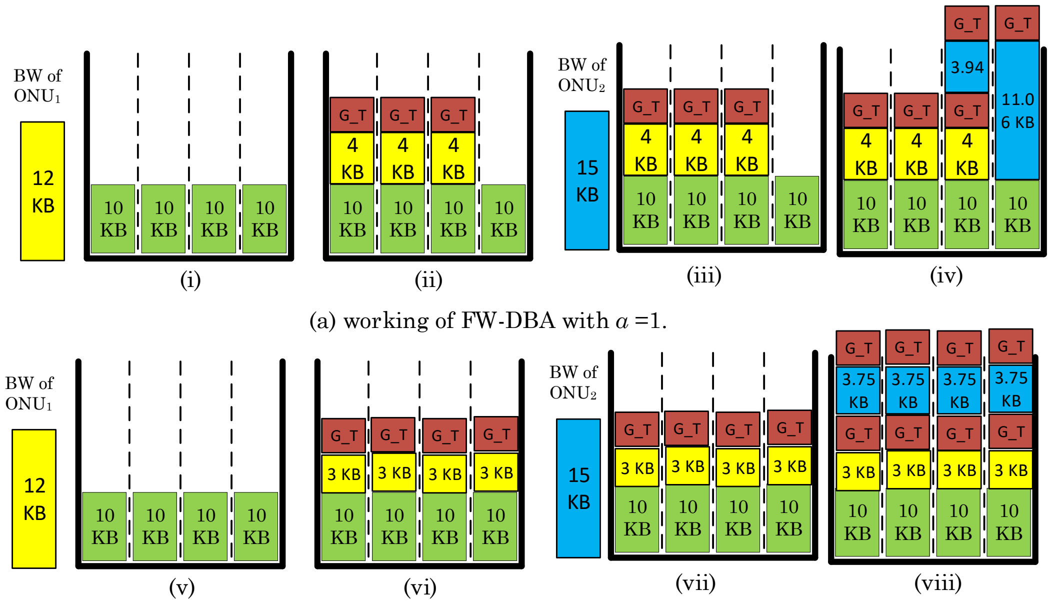


Fig. 2. Working of FW-DBA with $\alpha=2$: (a) initial condition, (b) after first and second step, (c) after another iteration of first and second step, and (d) final allocation. Bandwidth wasted in case of WF-DBA is highlighted with patterned lines.



(b) working of WF-DBA

Fig. 3. Comparison of (a) FW-DBA with α=1, and (b) WF-DBA.

high arrival rate and low arrival rate are exponentially distributed random variables with mean duration of 1/α and 1/β respectively. round-trip time of 100 µs is assumed for all the ONUs in the network, and a guard time of 1 µs and infinite Buffer size is considered at every ONU. Simulation results of FW-DBA are shown only for two values of alpha (i.e. *alpha*=1, 3). All the simulation parameters are listed in Table 1.

Table 1: Simulation Parameters

Parameter	***Value***
Number of wavelengths	4
Data rate per wavelength	25 Gb/s
Number of ONUs	32, 64, 128
Buffer size of each ONU	Infinite
Ethernet packet size distribution	64 bytes~ 1518 bytes
Control message (MPCP)	64 bytes
Inter-frame gap in upstream	12 bytes
Frame preamble	8 bytes
Guard Time	1 µsec
RTT_i	100 µsec
Alpha	1, 3

4.2 Simulation Results

To evaluate the performance of all the DBA algorithms under test, average packet delay, number of wavelengths assigned in each grant allocation, grant utilization and jitter analysis are evaluated.

4.2.1 Average Packet Delay

Average packet delay performance of proposed FW-DBA with $\propto = 1$ *and* 3, WF-DBA, modified-IPACT and FF-DBA with different number of ONUs in the network, i.e. N= 32, 64, 128 is shown in Fig. 4. It can be seen that performance of different DBA algorithms gets better or worse with the change in the number off ONUs, whereas the performance of FW-DBA is always better in all cases irrespective of the number of ONUs in the network and load of the network.

4.2.2 Number of Wavelengths assigned in each Grant

Figure 5 shows the number of wavelengths assigned to each ONU in a grant for the proposed FW-DBA, WF-DBA, modified-IPACT and FF-DBA. It can be seen that all algorithms are assigning fixed number of wavelengths to ONUs at every offered load; only FW-DBA is assigned flexible number of wavelengths in every grant in all the cases assumed.

4.2.3 Grant Utilization

Figure 6 shows grant utilization of every DWBA algorithm under observation. WF-DBA and modified-IPACT are giving lowest grant utilization with any number of ONUs in the network. Whereas, FW-DBA has better grant utilization than these two DBAs; however, FF-DBA is having best grant utilization. The reason for this is non-

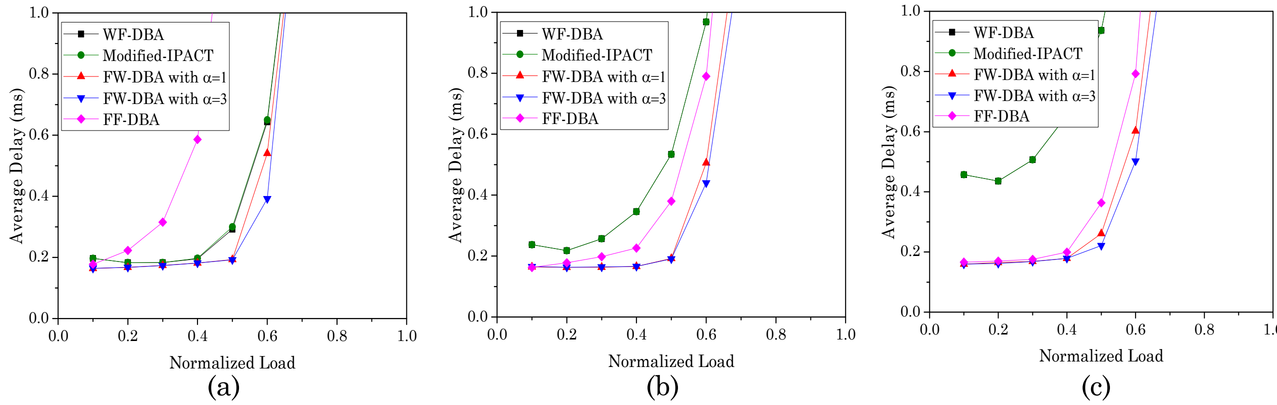


Fig. 4. Average packet delay: (a) N=32, (b) N=64, and (c) N=128

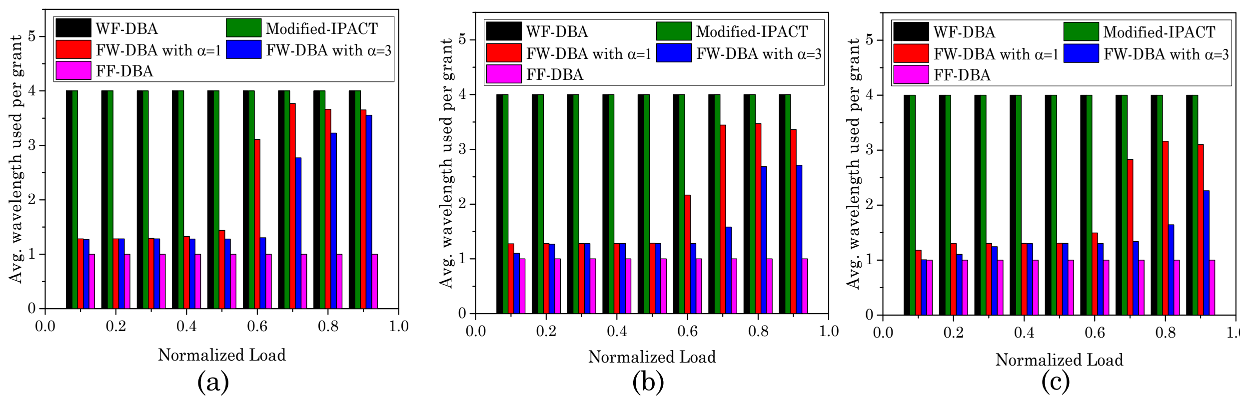


Fig. 5. Average number of wavelengths used per grant: (a) N=32, (b) N=64, (c) N=128

fragmentability of Ethernet frames and frame-size

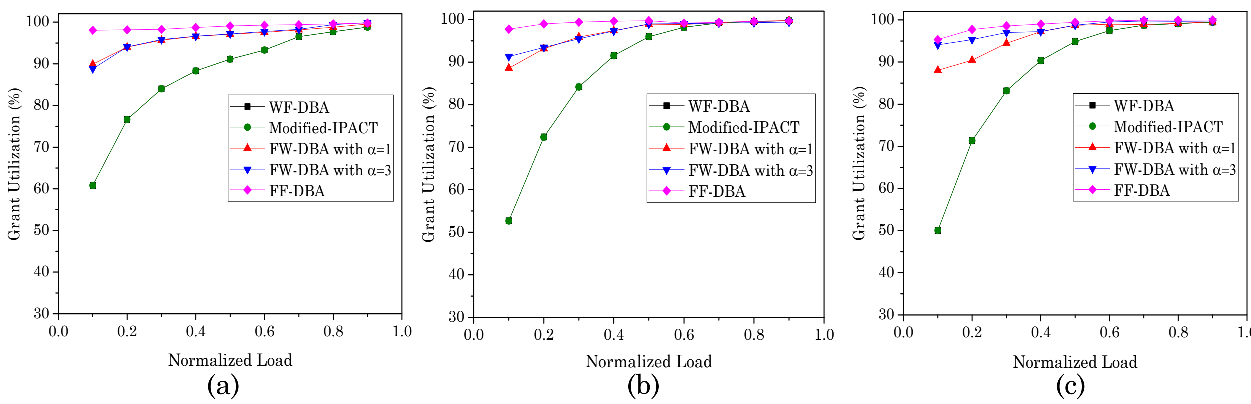


Fig. 6. Grant Utilization: (a) N=32, (b) N=64, and (d) N=128

mismatching problem.

4.2.4 Jitter Analysis

Jitter analysis (the standard deviation of delay) is another important parameter to access the performance of any DWBA. Jitter analysis comparison is shown in Fig. 7. It is evident that at low loads, WF-DBA and modified-IPACT are showing higher jitter. Frame-size mismatching and denial of service are the reason of this degraded performance. FW-DBA is giving lower jitter at all offered loads.

4.2.5 Analysis for optimal value of Alpha

Value of *alpha* plays a vital role in deciding number of wavelengths to be given to an ONU while giving grant. WF-DBA and FF-DBA are two special cases of the

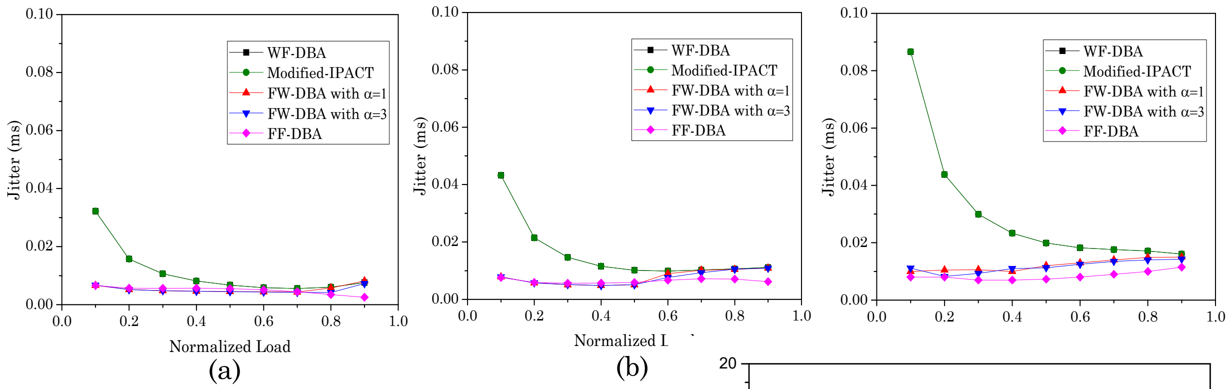


Fig. 7. Jitter analysis: (a) N=32, (b) N=64, and (c) N=128

proposed FW-DBA with $\propto = 0$ and $\propto = \infty$ respectively. Hence, change in value of *alpha* will change behavior of FW-DBA. It can be seen that for smaller number of ONUs in the network, smaller value of *alpha* is giving optimum performance. On the other hand, higher value of *alpha* is giving optimum performance for larger number of ONUs in the network. Therefore, value of *alpha* decides how flexible number of wavelengths we can assign to an ONU and is an optimality factor here.

Selection of optimal value of *alpha* is mainly dependent on the offered load of an ONU in the network and classification of ONUs in the network. Therefore, in a separate simulation experiment, we evaluated the impact of *alpha* on the network performance with change in number of ONUs, N. Optimal value of alpha is calculated through machine learning based curve fitting model with a change in number of ONUs (i.e. N=8, 16, 32, 64, 128 and 256) for every offered load. For every value of N, optimal value of alpha—giving lowest delay performance— is calculated, and the following equation is derived.

$$\propto = 0.0002N^2 + 0.0979N - 0.2229 \qquad (6)$$

Figure 8 shows the relationship between *N* and *alpha*. Our simulation results show if there is large number of ONUs in the network, higher value of *alpha* will give optimal solution, because transmission on less number of wavelengths would be required.

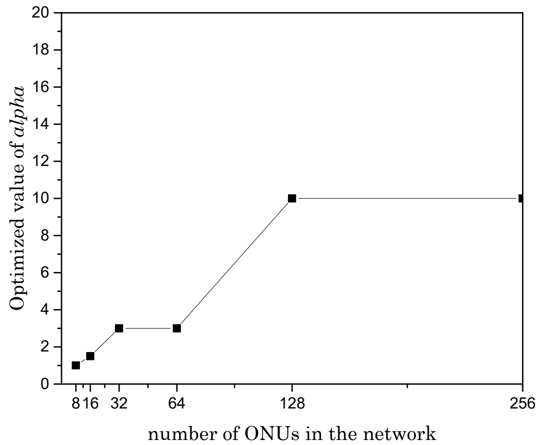


Fig. 8. Relationship between *alpha* and total number of ONUs in the network

5. Conclusions

A novel DWBA is proposed and analyzed to assign flexible number of wavelengths to provide low transmission delay. Simulation results confirm that FW-DBA always gives better delay performance, better utilization, and assigns flexible number of wavelengths to every ONU as compared to other DWBA algorithms in the NG-EPON. Moreover, we defined an optimum criterion, *alpha*, to decide flexible and optimized number of wavelengths to be used in every grant. The relationship between optimum value of alpha and number of ONUs in the network is derived using machine learning.

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