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RESEARCH ARTICLE

High Bandwidth Utilization DWBA Algorithm for Upstream Channel in NG-EPON

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ABSTRACT In this paper, an (ONU-load and RTTs)-based (OLR) dynamic wavelength and bandwidth allocation (DWBA) algorithm for upstream channel in next-generational Ethernet passive optical network (NG-EPON) is proposed. By proposing adaptive threshold grouping algorithm, the waste of bandwidth resources caused by massive guard timeslots and mismatch between assigned transmission window and frame size is reduced. By adjusting the Optical Network Unit (ONU) scheduling order, the idle time caused by Round-Trip Times (RTTs) is reduced. By proposing joint ONU grouping and RTT scheduling mechanism, load balance among wavelengths is achieved. By proposing a fair allocation scheme, the fairness of bandwidth granting for each ONU is ensured. Finally, by the simulation, the effectiveness of proposed algorithm is demonstrated. The simulation indicates that the rate of bandwidth utilization, the average package delay, the scheduling cycle and the network throughput in the system based on proposed algorithm have better performance.

INDEX TERMS Upstream, DWBA, ONU-load, RTTs, NG-EPON.

I. INTRODUCTION

Next-generational Ethernet passive optical network (NG-EPON) has become the development field of optical access network (OAN) in the future because of its high network capacity and transmission rate [1], [2]. Due that NG-EPON adopts the multi-wavelength transmission, the massive guard timeslots will exist on the wavelengths. This will result in the serious waste of bandwidth resources. At the same time, when a grant is given to an Optical Network Unit (ONU)_on multiple wavelengths, it is given without knowing individual boundaries of frames. Therefore, it is quite possible that assigned transmission window on each assigned wavelength may not be able to accommodate integer number of Ethernet frames. Ethernet frames are non-fragmented [3]. Thus, some bandwidth in the transmission window is unused on each wavelength, and the last few frames may be denied to be transmitted. This will also lead to the waste of bandwidth resources and the increase of transmission delay.

In recent years, researches on NG-EPON have gotten more and more attentions. According to access architecture, these researches can be divided into three parts: multi-scheduling-domain (MSD) PON, single-scheduling-domain (SSD) PON and wavelength-agile (WA) PON [4], [5], [6]. The comparison of SSD-PON, MSD-PON and WA-PON is shown in TABLE 1. To MSD-PON, it is similar to Time and Wavelength Division Multiplexed PON (TWDM-PON), efficient dynamic wavelength and bandwidth allocation (DWBA) schemes already developed for TWDM-PON can be applied to MSD-PON. The representative examples are as follows: Butt *et al.* proposed a DWBA algorithm to minimize the waste of bandwidth resources [7]. Hao *et al.* proposed a novel DWBA algorithm to reduce the network delay and improve the network throughput [8]. To SSD-PON, it is similar to Time Division Multiplexed PON (TDM-PON). So, any efficient dynamic bandwidth allocation (DBA) scheme for TDM-PON can be applied in SSD-PON, for instance,

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Baqar *et al.* proposed a modified Interleaved Polling with Adaptive Cycle Time (modified-IPACT) DBA to reduce the network delay and improve the bandwidth utilization [9]. To WA-PON, a few DBA algorithms have been proposed, for example, Wu *et al.* proposed a modified Shortest Propagation Delay (modified-SPD) scheduling scheme to reduce transmission delay [10]. Lin W *et al.* proposed a water-filling DBA (WF-DBA) to achieve the load balance among wavelengths [11]. Due to massive guard timeslots and mismatch between assigned transmission window and frame size, system still has problem of bandwidth waste when the above algorithms are applied to NG-EPON. In order to solve the problem, Hussain *et al.* proposed a First-Fit DBA to reduce the guard timeslots [3]. However, if First-Fit DBA algorithm is adopted to schedule the upstream bandwidth resources, the waste of bandwidth resources in the system will still occurs due to load imbalance among wavelengths.

TABLE 1. The comparison of SSD-PON, MSD-PON and WA-PON.

Architectures	Whether the services of an ONU can be transmitted on multiple wavelengths	Whether the services of an ONU can be transmitted on the same transmission window of different wavelengths	Whether the services of each ONU can be flexibly allocated wavelengths
SSD-PON	✓	✓	×
MSD-PON	✓	×	✓
WA-PON	✓	✓	✓

Therefore, an algorithm is needed in WA-PON, which cannot only reduce the waste of bandwidth resources caused by excessive guard timeslots, the mismatch between assigned transmission window and frame size, but also achieve the load balance among wavelengths.

A. RELATED WORK

Several DBA algorithms have been studied while considering one wavelength in the system [12], [13], [14], [15], [16]. McGarry *et al.* provided a comprehensive study about throughput and delay performance of various DBAs with different combinations of grant scheduling frameworks, grant sizing and grant scheduling [13]. Usmani *et al.* presented a brief study of different DBA schemes for long reach PONs [14]. However, they cannot be directly implemented in NG-EPON without considering the underlying requirements [17], [18]. An example is IPACT [15], which is a well-known DBA for classical EPONs. IPACT (called modified-IPACT) can be implemented in NG-EPONs by assuming all four wavelengths are bonded together as a single wavelength. In this case, each grant will amortize the requested bandwidth over all four wavelengths equally, and thus assign the same TW size on these wavelengths to the ONU. However, since Ethernet frames have different sizes [19], the TW assigned on each wavelength may not accommodate an integer number of frames, which is known as a frame-size mismatching problem. As a result, the bandwidth in each TW will be wasted. Also, a guard time is needed on each wavelength to separate two successive TWs of two ONUs. This will also lead to bandwidth waste, especially when the traffic load of each ONU is light. Therefore, in such cases, the higher the number of wavelengths assigned to an ONU, the more bandwidth will be wasted.

Thus, two kinds of DBA algorithms were proposed for NG-EPONs based on two opposite ideas. The first one is called First-Fit DBA [3]. This kind of DBA algorithm always assigns only one wavelength to each ONU in each grant. In particular, the wavelength with the earliest start time will be selected for each upstream transmission. The bandwidth waste caused by frame-size mismatching and massive guard timeslot usage are solved. However, First-Fit algorithm lacks flexibility with respect to variation in the offered load of an ONU or with the change in number of ONUs in the network. The second one is named Modified-SPD algorithm [10]. Opposite to First-Fit algorithm, Modified-SPD algorithm tries to equalize the wavelength usage after each bandwidth assignment. In particular, Modified-SPD algorithm always starts the bandwidth assignment from the wavelength with the earliest start time, such that the difference among the start times of all the wavelengths can be as small as possible. To reduce bandwidth that the guard timeslots occupy, Hussain *et al.* propose a flexible wavelength and dynamic bandwidth allocation (FW-DBA) algorithm based on Modified-SPD algorithm [9]. The algorithm is based on the difference between the start time of the wavelengths and the effectiveness in reducing delay by transmitting on multiple wavelengths. Moreover, to evaluate the transmission effectiveness, an optimum criterion alpha is introduced in relation to the number of ONUs in the network. However, First-Fit algorithm can work well when the number of ONUs is large, and Modified-SPD algorithm works well when the number of ONUs in the network is small.

B. CONTRIBUTIONS

This paper will focus on reducing the waste of bandwidth resources caused by excessive guard timeslots, the mismatch between assigned transmission window and frame size, and load imbalance among wavelengths in WA-PON. Meanwhile, the corresponding DWBA algorithm called (ONU-load and RTTs)-based (OLR) DWBA algorithm for upstream channel will be proposed. The comparison of OLR-DWBA algorithm, First-Fit algorithm and Modified-SPD algorithm is shown in TABLE 2. Our contributions are summarized as follows:

1) An adaptive threshold grouping algorithm is proposed to assign wavelengths to each ONU. According to the load of the ONU, each ONU is flexibly assigned wavelengths. The services of the lightly loaded ONU are transmitted on fewer wavelengths. This can reduce the number of guard timeslots and the probability of mismatch between the assigned timeslots and frame size.

TABLE 2. The comparison of OLR-DWBA algorithm, First-Fit algorithm, Modified-SPD algorithm and FW-DBA algorithm.

Algorithms	Whether the excessive use of guard timeslots is considered	Whether the load balance among wavelengths is considered	Whether the peak transmission rate of services in a single ONU is considered
Modified-SPD	×	✓	✓
First-Fit	✓	×	×
FW-DBA	✓	×	✓
OLR-DWBA	✓	✓	✓

The services of the heavily loaded ONU are transmitted on more wavelengths. This can increase the peak rate of service transmission in the heavily loaded ONU and reduce the service transmission delay.

2) To solve the problem of wasted bandwidth resources due to load imbalance among wavelengths, a joint ONU grouping and RTT scheduling mechanism is proposed. It treats the ONUs in the first three groups as a whole for orderly scheduling by RTT. This can reduce the idle time caused by RTT. And ONUs in the fourth group are lastly scheduled to achieve load balancing among wavelengths.

The rest of this paper is organized as follows: The studied problem is described in Section II. The proposed OLR-DWBA algorithm is detailed in Section III. And the simulation and analysis is presented in Section IV. Finally, conclusions are drawn in Section V.

II. PROBLEM STATEMENT

A. THE MISMATCH BETWEEN ASSIGNED TRANSMISSION WINDOW AND FRAME SIZE

As a grant allocation mechanism, when an ONU sends REPORT to OLT for grant allocation, it sends only the size of occupied queue length. The OLT is unaware of the individual frame boundaries. This makes a bandwidth grant decision based on the accumulative size of all frames in the queue of ONU. Therefore, when a grant to an ONU is given on multiple wavelengths in each cycle, it is quite possible that some portion of the granted bandwidth is left unused due to the random frame size, and the last few frames may be denied to be transmitted due to the non-fragmentation of Ethernet frames.

Here, a specific example is taken to describe the problem. It is assumed that an ONU has 8 frames in its cache queue, including five 300 bytes frames and three 500 bytes frames. When different number of wavelengths are assigned to services of the ONU, the wasted bandwidth resources caused by the mismatch between the assigned transmission window and frame sizes are also different. We analyze the cases of assigning four wavelengths and two wavelengths to services of the ONU separately. The two cases are shown in Fig. 1 and Fig. 2 separately.

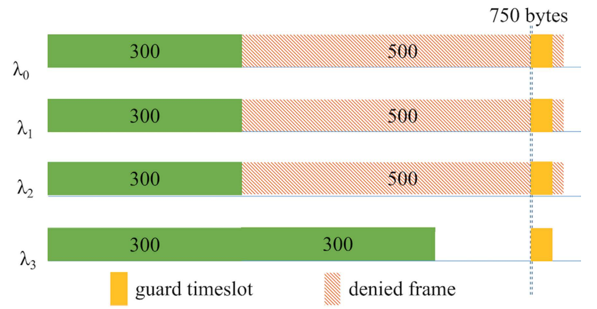

FIGURE 1. The services of an ONU are transmitted on four wavelengths.

It can be seen from Fig. 1 that the transmission window on each wavelength is 750 bytes when OLT allocates bandwidth equally on four wavelengths according to bandwidth requested by an ONU. After the first four 300 bytes frames are transmitted on four wavelengths. The remaining bandwidth in each wavelength is 450 bytes. Then, the three 500 bytes frames are allocated on λ_0, λ_1 and λ_2 respectively. The remaining bandwidth on the three wavelengths cannot accommodate 500 bytes frame. So, the three 500 bytes frames are denied to be transmitted. The last 300 bytes frame is transmitted on λ_3. Therefore, 450 bytes bandwidth resources are wasted on λ_0, λ_1 and λ_2 respectively. And 150 bytes bandwidth resources are wasted on λ_3. In summary, 1500 bytes bandwidth resources are wasted and the ratio of bandwidth utilization is 50%.

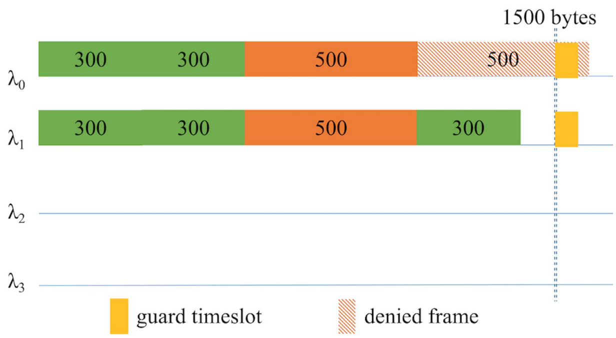

FIGURE 2. The services of an ONU are transmitted on two wavelengths.

It can be seen from Fig. 2 that the transmission window on each wavelength is 1500 bytes when OLT allocates bandwidth equally on two wavelengths according to bandwidth requested by the ONU. The first four 300 bytes frames are transmitted on λ_0 and λ_1 respectively. The first two 500 bytes frames are also transmitted on λ_0 and λ_1 respectively. The last 500 bytes frame is allocated on λ_0. However, the remaining bandwidth on λ_0 is no longer sufficient for transmission of the 500 bytes frame. The 500 bytes frame is denied to be transmitted. The last 300 bytes frame is transmitted on λ_1. In summary, 500 bytes bandwidth resources are wasted and the ratio of bandwidth utilization is 83.3%. Therefore, the fewer number of wavelengths is assigned to an ONU, the less bandwidth wasted caused by the mismatch between the assigned transmission window and frame size is.

B. MASSIVE GUARD TIMESLOTS

Recently, a Modified-SPD scheduling algorithm based on offline scheduling architecture has been proposed and applied to NG-EPON upstream resource scheduling [10]. Modified-SPD algorithm uses multiple wavelength channels as one logical channel through channel bonding technique. At the same time, the services of ONU with minimum RTT are scheduled firstly. Modified-SPD algorithm assigns services of ONUs to be transmitted on a multiple wavelength transmits the services in ONU on multiple wavelengths. And a guard timeslot between services of different ONUs on each wavelength. This inevitably introduces a large number of guard timeslots and causes a waste of bandwidth resources. Modified-SPD algorithm is shown in Fig. 3(a).

It can be seen from Fig. 3(a) that there are 8 ONUs in the system, and 32 guard timeslots need to be introduced. This leads to bandwidth resource waste.

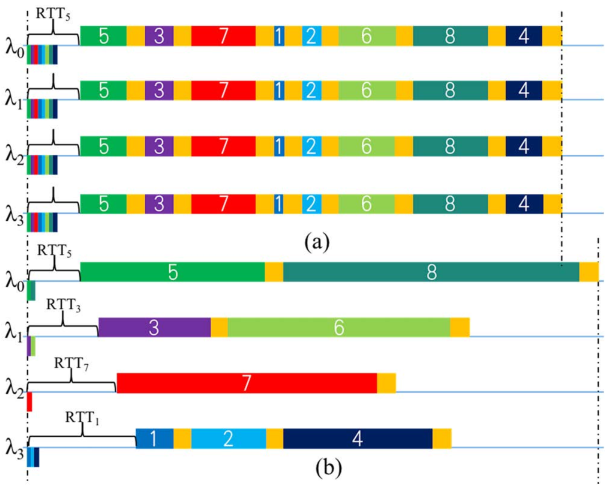

FIGURE 3. (a) Modified-SPD algorithm (b) First-Fit algorithm.

C. LOAD IMBALANCE AMONG WAVELENGTHS

Recently, considering the waste of bandwidth resources caused by massive guard timeslots and the mismatch between assigned TW and frame size, a First-Fit scheduling algorithm was proposed [3]. First-Fit algorithm assigns services of ONUs to be transmitted on a single wavelength regardless of the load. In one schedule cycle, the end of last finish wavelength channel determines the cycle's length. When First-Fit algorithm is adopted to schedule bandwidth resources and some ONUs are under high load, the earlier finish wavelengths will be idle to wait the last finish wavelength. In this case, there will be much wastage in the upstream channel. First-Fit algorithm is shown in Fig. 3(b).

It can be seen from Fig. 3(b) that ONU_8 is under high load. The services of ONU_8 are transmitted on λ_0. A large amount of idle time is generated on λ_1, λ_2 and λ_3. This also leads to bandwidth resource waste.

III. UPSTREAM DWBA ALGORITHM

In previous sections, the waste of bandwidth resources caused by massive guard timeslots, the mismatch between assigned transmission window and frame size and load imbalance among wavelengths has been discussed. Here, to improve the bandwidth utilization, an upstream DWBA algorithm called OLR-DWBA algorithm is proposed. The algorithm can be divided into three parts:

1) The ONU scheduling order: According to RTTs, the ONU scheduling order is determined. This can reduce the idle time caused by RTTs.
2) Wavelength allocation: According to the ONU load, the number of wavelengths assigned to the services of each ONU is determined. This can reduce the waste of bandwidth resources caused by massive guard timeslots, the mismatch between assigned transmission window and frame size.
3) Time allocation: According to the ONU scheduling order and wavelength allocation, the time slot allocated to services of each ONU on each wavelength is determined. This can achieve the load balance among wavelength and reduce the waste of bandwidth resources caused by load imbalance among wavelengths.

A. THE ONU SCHEDULING ORDER

In the offline scheduling framework, when an ONU registers in OLT, OLT obtains the RTT information of the ONU. The time between the OLT sending a GATE message and receiving the services of ONU takes at least RTT [10]. If there is no other ONU for service transmission within the RTT, the channels are under idle state during this time. Each ONU has a different RTT because of the distance between the ONU and OLT. Different ONU scheduling order will produce different idle time. The idle time can be shown in Fig. 4. Compare with the RTT of ONU_2, it of ONU_1 is smaller.

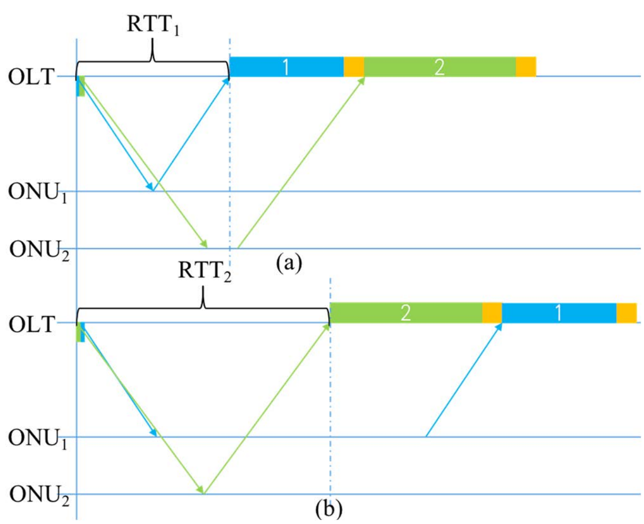

FIGURE 4. (a) Preferentially scheduling services of ONU with smaller RTT (b) Preferentially scheduling services of ONU with larger RTT.

It can be seen from Fig. 4 that the RTT_1 of ONU_1 is smaller than the RTT_2 of ONU_2. In Fig. 4(a), if the services of ONU_1 are scheduled firstly, the idle time of RTT_1 size will be generated in the channel. In Fig. 4(b), if the services of ONU_2 are scheduled firstly, the idle time of RTT_2 size will be generated in the channel. Therefore, system generates less idle time when the services of ONU with the smaller RTT is scheduled firstly. In summary, when the services of ONU with the smaller RTT are scheduled preferentially, the idle time caused by RTTs can be reduced.

In this paper, the ONUs will be sorted in ascending order according to the RTTs of all ONUs. The ONUs with smaller RTTs will be scheduled preferentially to reduce the idle time caused by RTT.

B. WAVELENGTH ALLOCATION ALGORITHM

NG-EPON uses channel bonding to enable services of each ONU to be transmitted simultaneously on four wavelengths. If the services of all ONUs are transmitted on four wavelengths, a large number of guard timeslots will be introduced. This causes the waste of bandwidth resources. If the services of each ONU are allowed to be transmitted only on a single wavelength, the services of high load ONU will occupy a large amount of bandwidth on a single wavelength. This leads to load imbalance among wavelengths. At the same time, if the services of ONU are transmitted only on a single wavelength, the peak transmission rate of services in individual ONU is not improved. This undoubtedly defeats the original purpose of NG-EPON design. In this section, an adaptive threshold grouping algorithm is proposed to assign wavelengths to each ONU. The specific algorithm is as follows:

1) Firstly, all ONUs are sorted in ascending order according to the amount of bandwidth requested by the ONUs: $ONU_1, ONU_2, ONU_3, \ldots, ONU_n$.
2) Then, according to the number of wavelengths assigned to ONUs, four wavelength groups are created: $group_1$, $group_2$, $group_3$, $group_4$. Let the number of all unassigned grouped ONUs be m.
3) According to the bandwidth requested by all unassigned grouped ONUs, adaptive threshold is set. The threshold can be calculated by:

$$Threshold = \frac{\sum_{i=n-m+1}^{n} R_i}{m} \tag{1}$$

The bandwidth requested by each unassigned grouped ONU is compared with *Threshold*.
If $R_i < Threshold$, ONU_i is assigned to $group_1$. After traversing all unassigned ONUs, the number of unassigned ONUs m is updated, and *Threshold* is updated.
4) The bandwidth requested by each unassigned grouped ONU is compared with the new Threshold. If $R_i < Threshold$, ONU_i is assigned to $group_2$. After traversing all unassigned ONUs, the number of unassigned ONUs m is updated, and *Threshold* is updated.
5) The bandwidth requested by each unassigned grouped ONU is compared with the new *Threshold*.
If $R_i < Threshold$, ONU_i is assigned to $group_3$. If $R_i \geq Threshold$, ONU_i will be assigned to $group_4$. At this time, ONU grouping is completed.

After all ONUs are grouped, wavelengths are assigned to all ONUs according to the grouping:

a) The loads of ONUs in $group_1$ are lowest. So, if they are all assigned to a single wavelength, there will be no load imbalance among wavelengths caused by the services of a single ONU occupying a large amount of bandwidth. And there will no too high transmission delay. So, the services of ONUs in $group_1$ are assigned to be transmitted on a single wavelength.
b) The loads of ONUs in $group_2$ are higher than the loads of ONUs in $group_1$. Therefore, if they are all assigned to a single wavelength, there may be a problem of load imbalance among wavelengths caused by the services of a single ONU occupying a large amount of bandwidth. And there will be a high transmission delay. Therefore, the services of ONUs in $group_2$ are assigned to be transmitted on two wavelengths.
c) Similarly, the services of ONUs in $group_3$ and $group_4$ are assigned three and four wavelengths respectively to reduce the transmission delay of individual ONUs.

C. BANDWIDTH ALLOCATION ANALYSIS

The network bandwidth capacity in NG-EPON is limited. If the length of a scheduling cycle exceeds the maximum polling cycle, the services of some ONUs will have no enough bandwidth to support their transmission. These services will be denied to be transmitted in current cycle and may only continue to be transmitted until the next polling cycle.

The ONUs in NG-EPON are put into four groups. and the number of ONUs in each group is counted. It is assumed that n_i represents the number of ONU in $group_j$. Then the number of guard timeslots on a single wavelength can be gotten by:

$$t = \sum_{j=1}^{4} \left\lceil \frac{j * n_j}{4} \right\rceil \tag{2}$$

Thus, the maximum available bandwidth on each wavelength is given by:

$$B_{available} = \left[T_{cycle} - RTT - t * T_g\right] * C \tag{3}$$

Correspondingly, the available bandwidth on the four wavelengths is gotten by:

$$B_{total} = 4 * B_{available} \tag{4}$$

If $R_{all} \leq B_{total}$, the bandwidth allocated to each ONU is its request.

If $R_{all} > B_{total}$, the total available bandwidth in the network can no longer satisfy the bandwidth requested by all ONUs. So, the services of some ONUs will be denied to be transmitted. This obviously does not satisfy the fairness principle.

Therefore, when the bandwidth requested by all ONUs is greater than the total available bandwidth in the network, the fair proportional allocation principle is adopted to allocate bandwidth to the services of ONUs. According to the bandwidth requested by ONU_i, its allocation ratio factor is set as:

$$\alpha_i = \frac{R_i}{R_{all}} \tag{5}$$

Then, according to α_i and the total available bandwidth of the network, the bandwidth allocated to ONU_i can be gotten by:

$$G_i = \alpha_i * B_{available} \tag{6}$$

Therefore, the bandwidth allocated to ONU_i is described by:

$$G_i = \begin{cases} R_i, & if\ R_{all} \le B_{available} \\ \alpha_i * B_{available} & , if\ R_{all} > B_{available} \end{cases} \tag{7}$$

D. TIME ALLOCATION ANALYSIS

In $group_1$, the services of each ONU are only transmitted on a single wavelength. So, it is necessary to determine the transmission timeslots for the services of these ONUs at the corresponding wavelengths. The services of ONUs in $group_2$, $group_3$ and $group_4$ are transmitted on two wavelengths, three wavelengths, and four wavelengths respectively. So, it is necessary to determine their transmission timeslots on each of the wavelengths assigned to them.

The services of ONUs in $group_4$ are transmitted on four wavelengths. Therefore, they can be used to achieve load balance among wavelengths. Thus, they are transmitted lastly. The ONUs in $group_1$, $group_2$ and $group_3$ are sorted in ascending order according to their RTTs. The services of ONUs with fewer RTTs in the three groups are scheduled firstly to reduce the idle timeslots caused by RTTs. The specific allocation scheme is shown as follows:

If ONU_i belongs to $group_1$, the wavelength with the smallest S_i^k (S_i^k denotes the start transmission time of ONU_i on λ_k) is selected to transmit the services of ONU_i. Then, the value of S_i^k is updated. The allocated timeslots are shown in Fig. 5.

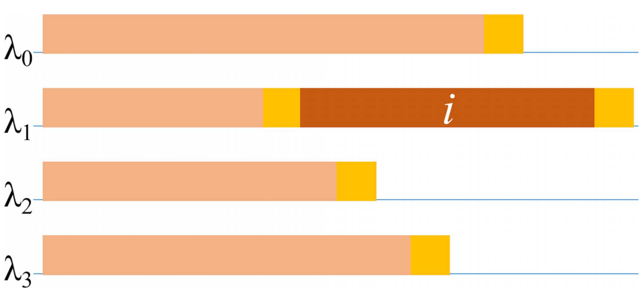

FIGURE 5. The time allocation about the services of ONU in $group_1$.

If ONU_i belongs to $group_2$, the two wavelengths with smaller S_i^k are selected to transmit the services of ONU_i. The services of ONU_i are firstly transmitted on the wavelength with the smallest S_i^k. When S_i^k increases to the same as the second smallest $S_i^{k'}$, the remaining services of ONU_i are evenly transmitted on these two wavelengths. Then, the values of S_i^k and $S_i^{k'}$ are updated. The allocated timeslots are shown in Fig. 6.

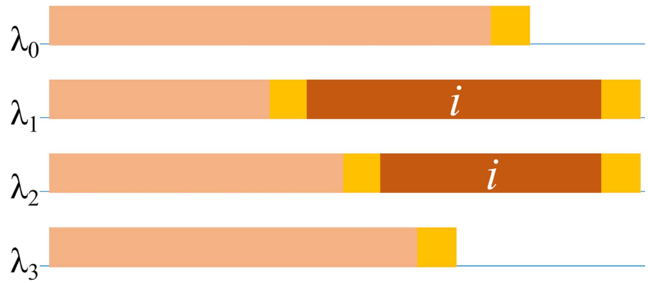

FIGURE 6. The time allocation about the services of ONU in $group_2$.

If ONU_i belongs to $group_3$, the three wavelengths with smaller S_i^k are selected to transmit the services of ONU_i. The services of ONU_i are firstly transmitted on the wavelength with the smallest S_i^k. When S_i^k increases to the same as the second smallest $S_i^{k'}$, the remaining services of ONU_i are evenly transmitted on these two wavelengths until S_i^k and $S_i^{k'}$ increase to the same as the third smallest $S_i^{k''}$. Then, the remaining services of ONU_i are evenly transmitted on these three wavelengths. The values of S_i^k, $S_i^{k'}$ and $S_i^{k''}$ are updated. The allocated timeslots are shown in Fig. 7.

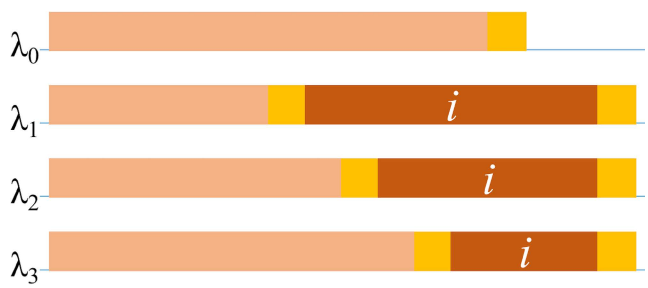

FIGURE 7. The time allocation about the services of ONU in $group_3$.

After all the services of ONUs in $group_1$, $group_2$ and $group_3$ have been transmitted. The services of ONUs in $group_4$ are then transmitted on four wavelengths. The scheduling strategy is similar to the strategy above. The main purpose is to achieve load balance among the four wavelengths. The allocated timeslots are shown in Fig. 8.

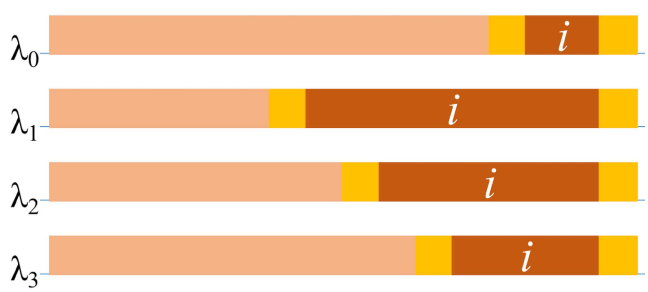

FIGURE 8. The time allocation about the services of ONU in $group_4$.

The final allocation results of the same group of ONUs using three scheduling algorithms are shown in Fig. 9.

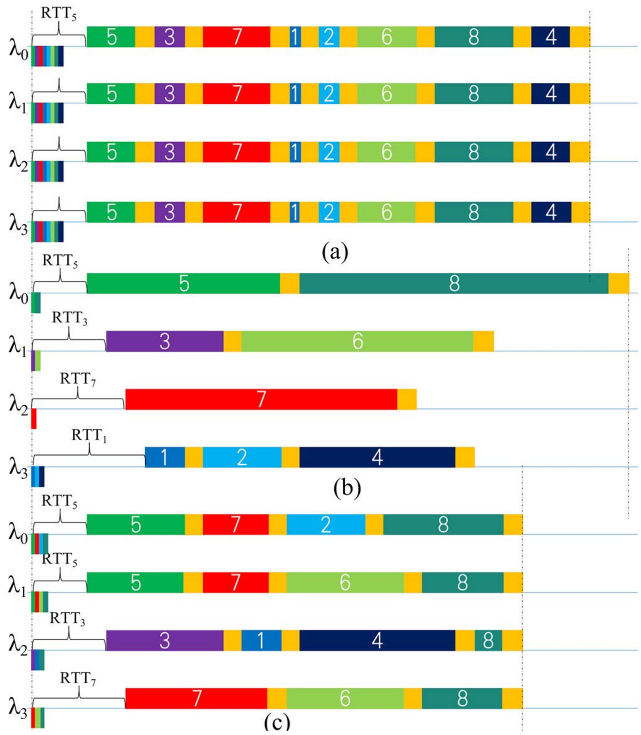

FIGURE 9. **(a) Modified-SPD algorithm (b) First-Fit algorithm (c) OLR-DWBA algorithm.**

IV. SIMULATION AND PERFORMANCE ANALYSIS

The simulation and analysis of algorithm will be developed by MATLAB and Simpy [25]. Here, the algorithms for comparison are mainly composed of three parts: OLR-DWBA algorithm, Modified-SPD algorithm, FW-DBA algorithm and First-Fit algorithm. The specific simulation contents mainly include: the average package delay, the scheduling cycle, the bandwidth utilization and the throughput.

In the simulation, to make the simulation more convenient, the resource scheduling on the upstream channel is only considered. The simulation is based on a typical tree network topology [20], [21], [22]. The number of wavelengths is set as 4 [23]. The number of ONUs is 64. The distances between users and OLT are simulated by the RTTs between ONUs and OLT. Here, we assume that all ONUs are equipped with multiple sets of transceivers and the services can be transmitted on any number of wavelengths. All ONUs have the same service level agreement (SLA) to ensure that all ONUs can occupy bandwidth resources fairly. The RTTs between ONUs and OLT are set to be uniformly distributed between 100 μs and 500 μs, corresponding to a physical distance of 30 km to 150 km [24]. The transmission rate of a single wavelength on the upstream channel is 25 Gb/s [23]. The total normalized network load is uniformly distributed from 0.1 to 1. This means that the ratio of the total service generated by all ONUs per second to the total bandwidth capacity of network is uniformly distributed from 0.1 to 1. Self-similar data is generated by Pareto distribution [26], [27]. The guard time is 1μs. The size of data frames varies randomly from 64 bytes to 1518 bytes [28]. The simulation parameters are shown in Table 3.

A. AVERAGE PACKET DELAY ANALYSIS

The average packet delay (Unit: ms) [28] is the average time from the generation of packages in ONUs to its arrival at OLT. It consists of waiting delay and transmission delay. The comparison of the average packet delay of system when OLR-DWBA algorithm, First-Fit algorithm, Modified-SPD algorithm and FW-DBA algorithm are adopted to schedule resources is shown in Fig. 10.

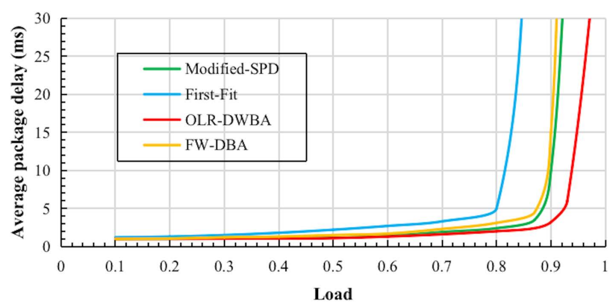

FIGURE 10. **The average package delays of system when OLR-DWBA algorithm, First-Fit algorithm, Modified-SPD algorithm and FW-DBA algorithm are adopted to schedule resources.**

It can be seen from Fig. 10 that the average packet delay of system when OLR-DWBA algorithm is adopted to schedule resources is always lower than the average packet delays of system when First-Fit algorithm, Modified-SPD algorithm and FW-DBA algorithm are adopted to schedule resources. It is because the network introduces massive guard timeslots when Modified-SPD algorithm is adopted to schedule resources. This increases the waiting delay of services. Furthermore, many frames are denied to be transmitted due to the mismatch between the assigned transmission window and frame size. This will increase the transmission delay of services. The services of a single ONU are transmitted on a single wavelength when First-Fit algorithm is adopted to schedule resources. This will lead to low peak transmission

TABLE 3. **The simulation parameters.**

Parameters	Values
The number of wavelengths	4
The number of ONUs	64
The RTTs between ONUs and OLT	100-500 µs
Buffer size of each ONU	Infinite
Control message (MPCP)	64 bytes
Inter-frame gap in upstream	12 bytes
The transmission rate of a single wavelength	25 Gb/s
The guard time	1 µs
The size of data frames	64-1518 bytes

rate of services in each ONU. In particular, when ONUs are under high load, their services will have higher transmission delay. The wavelengths are allocated to the services of ONUs according to *alpha* when FW-DBA algorithm is adopted to schedule bandwidth resources. This will cause more services to be transmitted on a single wavelength and increase the transmission delay. OLR-DWBA algorithm flexibly assigns wavelengths to ONUs according to their requested bandwidth. This not only reduces the additional overhead caused by the guard timeslots, but also reduces the probability of the mismatch between assigned transmission window and frame size. In addition, this also reduces the transmission delay of services in high-loaded ONUs. Therefore, the system has a better performance in average package delay when OLR-DWBA algorithm is used for resource scheduling.

B. SCHEDULING CYCLE ANALYSIS

The scheduling cycle time is the actual transmission time of the all services during the scheduling cycle. The maximum value of a single scheduling cycle is set as 2ms. According to the system load and ONU scheduling, the scheduling cycle can be terminated earlier to save bandwidth resources. The shorter the scheduling cycle is, the better the load balancing performance of scheduling algorithm is. The comparison of the scheduling cycle of system when OLR-DWBA algorithm, First-Fit algorithm Modified-SPD algorithm and FW-DBA algorithm are adopted to schedule resources is shown in Fig. 11.

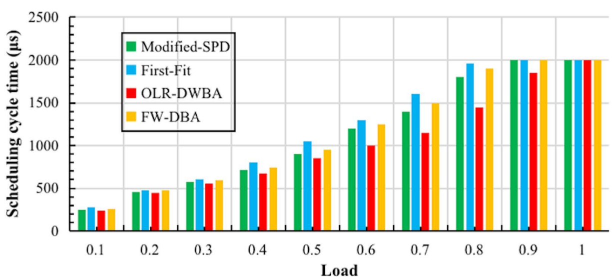

FIGURE 11. The scheduling cycles of system when OLR-DWBA algorithm, First-Fit algorithm, Modified-SPD algorithm and FW-DBA algorithm are adopted to schedule resources.

It can be seen from Fig. 11 that the scheduling cycles of network when OLR-DWBA algorithm, First-Fit algorithm, Modified-SPD algorithm and FW-DBA algorithm are adopted to schedule resources are same when the load rate is up to 1. It is because the scheduling cycles all reach the maximum scheduling cycle when the three algorithms are adopted to schedule resources at this time. When the load rate is greater than 0.8, the scheduling cycles of First-Fit algorithm is adopted to schedule resources reaches the maximum scheduling cycle firstly. It is because the high load ONU occupies a large amount of bandwidth on a single wavelength when the First-Fit algorithm is used for resource scheduling. When the load rate increases to 0.85, the scheduling cycles of FW-DBA algorithm reaches the maximum scheduling cycle. It is because the imbalance among wavelengths occurs when FW-DBA algorithm is adopted to schedule bandwidth resources. When the load rate increases to 0.9, the scheduling cycles of Modified-SPD algorithm reaches the maximum scheduling cycle. It is because the large number of guard timeslots are introduced into network when Modified-SPD algorithm is adopted to schedule resources. When the load rate is less than 0.9, the scheduling cycles of OLR-DWBA algorithm is the lowest under the same load. It is because the service transmission is completed earliest when OLR-DBWA algorithm is used for resource scheduling.

C. THE BANDWIDTH UTILIZATION ANALYSIS

Bandwidth utilization is the ratio of the transmitted services to the total occupied bandwidth in a single scheduling cycle. The bandwidth utilization in upstream direction can be expressed as follows:

$$BW = \frac{B}{W * T_{\text{cycle}}} \tag{8}$$

where, BW is the bandwidth utilization. B represents the number of services transmitted in this cycle. T_{cycle} denotes the scheduling cycle. W represents the number of wavelengths.

The comparison of the bandwidth utilizations of system when OLR-DWBA algorithm, First-Fit algorithm, Modified-SPD algorithm and FW-DBA algorithm are adopted to schedule resources is shown in Fig. 12.

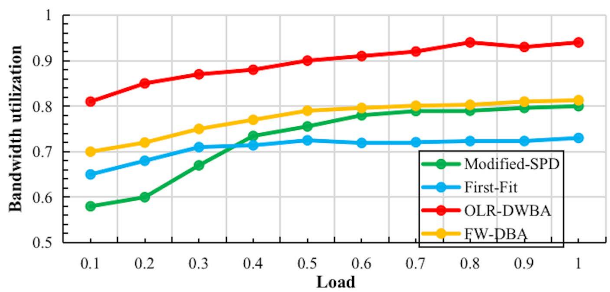

FIGURE 12. The bandwidth utilizations of system when OLR-DWBA algorithm, First-Fit algorithm, Modified-SPD algorithm and FW-DBA algorithm are adopted to schedule resources.

It can be seen from Fig. 12 that the bandwidth utilization when OLR-DWBA algorithm is adopted to schedule resources is significantly larger than the bandwidth utilizations when First-Fit algorithm, Modified-SPD algorithm and FW-DBA algorithm are adopted to schedule resources under the same network load. The load balance among four wavelengths is achieved when OLR-DWBA algorithm and Modified-SPD algorithm are adopted to schedule resources. However, network introduces more guard timeslots when Modified-SPD algorithm is used for resource scheduling. At the same time, the more times the mismatch between assigned transmission window and frame size occurs when Modified-SPD algorithm is used for resource scheduling. Therefore, the bandwidth utilization of OLR-DWBA algorithm is larger than the bandwidth utilization of Modified-SPD algorithm. The load imbalance among the four wavelengths occurs when First-Fit algorithm and FW-DBA algorithm are adopted to schedule resources. This results in the waste of bandwidth resources. So, the bandwidth utilization of OLR-DWBA algorithm is larger than the bandwidth utilization of First-Fit algorithm and FW-DBA algorithm. When the load rate is less than 0.3, the guard timeslots account for a larger proportion of the services. Thus, the bandwidth utilization of Modified-SPD algorithm is lowest at this time. When the load rate is greater than 0.3, the proportion of guard timeslots decreases. the bandwidth utilization of Modified-SPD algorithm is higher than the bandwidth utilization of First-Fit algorithm and FW-DBA algorithm at this time. In summary, under the same network load, the bandwidth utilization of OLR-DWBA algorithm increases by at least 14% compared with the bandwidth utilization of Modified-SPD algorithm. The bandwidth utilization of OLR-DWBA algorithm increases by at least 20% compared with the bandwidth utilization of First-Fit algorithm. The bandwidth utilization of OLR-DWBA algorithm increases by at least 10% compared with the bandwidth utilization of FW-DBA algorithm. Therefore, system has better performance in terms of bandwidth utilization when the proposed algorithm is adopted to schedule resources.

D. THROUGHPUT ANALYSIS

Throughput refers to the ratio of services transmitted in a single polling cycle to the total system capacity. The comparison of the throughput of system when OLR-DWBA algorithm, First-Fit algorithm, Modified-SPD algorithm and FW-DBA algorithm are adopted to schedule resources is shown in Fig. 13.

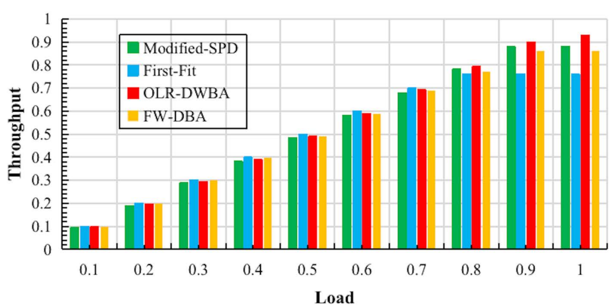

FIGURE 13. The throughputs of system when OLR-DWBA algorithm, First-Fit algorithm Modified-SPD algorithm and FW-DBA algorithm are adopted to schedule resources.

It can be seen from Fig. 13 that throughput of First-Fit algorithm is largest, followed by throughput of OLR-DWBA algorithm and FW-DBA algorithm, and throughput of Modified-SPD algorithm is smallest when the load rate is less than 0.8. It is because that the services in all ONUs are efficiently transmitted when First-Fit algorithm is used for resource scheduling. The system has the problem of mismatch between assigned transmission window and frame size when OLR-DWBA algorithm, Modified-SPD algorithm and FW-DBA algorithm are adopted to schedule resources. When

TABLE 4. When the ratio of network load is 0.9, the performances of OLR-DWBA algorithm, First-Fit algorithm and Modified-SPD algorithm.

algorithm	Average package delay (ms)	Scheduling cycle time (μs)	Bandwidth utilization (%)	Throughput (%)
Modified-SPD	10	2000	79.6	88
First-Fit	60	2000	72.3	76
FW_DBA	15	2000	81	86
OLR-DWBA	3.2	1850	94	90

OLR-DWBA is used for resource scheduling, the services of light load ONUs are transmitted on fewer wavelengths. Fewer frames are denied to be transmitted due to mismatch between the transmission window and frame size. When the load rate is between [0.8, 0.9], throughput of OLR-DWBA algorithm is largest, followed by throughput of FW-DBA algorithm and Modified-SPD algorithm, throughput of First-Fit algorithm is smallest. It is because the scheduling cycle has exceeded the maximum scheduling cycle when First-Fit algorithm is used for resource scheduling. The packet loss occurs in the system at this time. Therefore, system has better performance in terms of the network throughput when the proposed algorithm is adopted to schedule resources.

When the ratio of network load is up to 0.9, the performances of three algorithms are shown in Table 4.

V. CONCLUSION

In this paper, an OLR-DWBA algorithm for NG-EPON has been proposed to provide high bandwidth utilization. Firstly, an adaptive threshold grouping algorithm has been proposed in order to reduce the waste of bandwidth resources caused by massive guard timeslots and mismatch between assigned transmission window and frame size. Next, the ONU scheduling order has been adjusted through RTTs to reduce the idle time caused by RTTs. Then, joint ONU grouping and RTT scheduling mechanism has been constructed to achieve load balance among wavelengths. Moreover, a fair allocation scheme has been proposed to ensure the fairness of bandwidth granting for each ONU. Finally, the effectiveness of the proposed algorithm is demonstrated by simulation and analysis. Compared with Modified-SPD algorithm, OLR-DWBA algorithm makes the bandwidth utilization increase by at least 14%. Compared with First-Fit algorithm, OLR-DWBA algorithm makes the bandwidth utilization increase by at least 20%. The bandwidth utilization of OLR-DWBA algorithm increases by at least 10% compared with the bandwidth utilization of FW-DBA algorithm.

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