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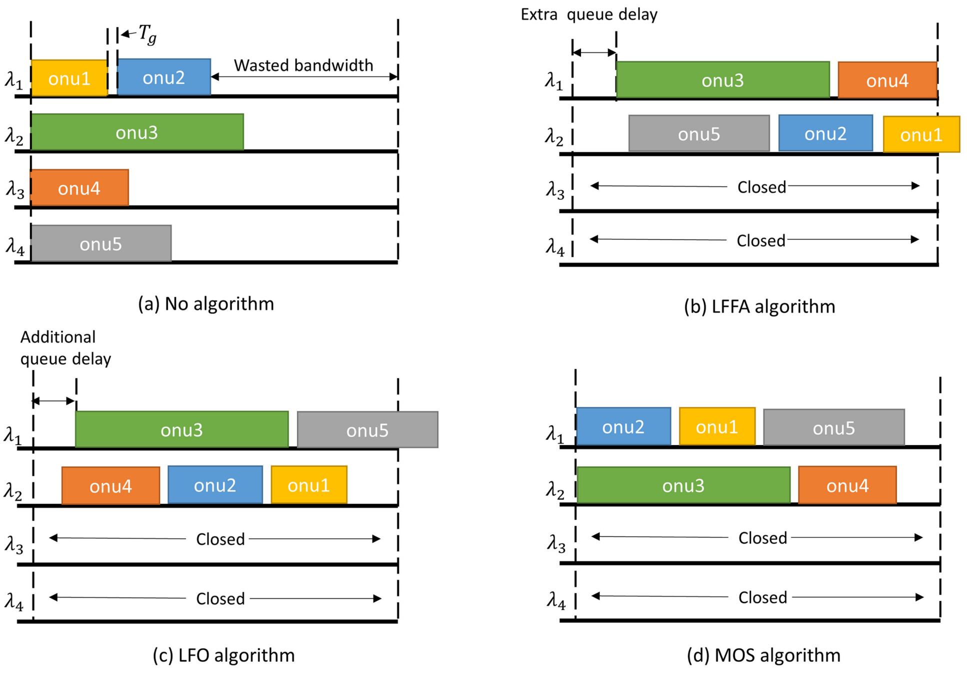

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Adaptive Scheduling Algorithm for the Coexistence of ONUs with Different Tuning Time in Virtual Passive Optical Network

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Abstract: Optical network unit (ONU)'s wavelength tuning time is a key factor that cannot be ignored in ONU scheduling algorithm for multi-wavelengths passive optical network (PON). In this paper, we propose an adaptive scheduling algorithm for the coexistence of ONUs with different tuning time in virtual PON, which is called multi-tuning-time ONU scheduling (MOS) algorithm. The simulation shows that the MOS algorithm can effectively avoid the extra queue delay caused by ONUs' wavelength tuning and reduce the waste of bandwidth resources.

Index Terms: ONU scheduling algorithm, multi-tuning-time, virtual passive optical network.

1. Introduction

As the bandwidth requirements in the access network is gradually increasing, traditional single-wavelength passive optical network (PON) is inadequate in the face of high bandwidth requirements. Multi-wavelengths PON is a good choice to solve this problem [1]. Current popular multi-wavelengths PON technologies include Time and Wavelength Division Multiplexed (TWDM)-PON and Virtual PON (VPON). In the data center network (DCN), which is the key technology of the backbone network, there are quite a lot of researches on scheduling algorithms, which can ensure high network utilization, fair bandwidth sharing and low service delay [2]. Similarly, ONUs scheduling is an important research topic for multi-wavelength PON. By scheduling ONUs between multiple wavelengths, the wavelengths usage can be saved and the bandwidth utilization can be improved. Therefore, the ONUs' wavelength tuning time is a key factor that cannot be ignored in ONU scheduling algorithm. At the same time, because VPON supports multiple standards PON coexistence and the virtual access of ONU, the ONU scheduling algorithm based on TWDM-PON is not suitable for VPON. According to the tuning time factor and network standard, the ONU scheduling algorithms can be divided into the following four parts: (1) ONU scheduling algorithm for TWDM-PON with zero tuning time [3]. (2) ONU scheduling algorithm for TWDM-PON with non-zero tuning time [4], [5]. (3) ONU scheduling algorithm for VPON with zero tuning time [6]. (4) ONU scheduling algorithm for VPON with non-zero tuning time. The “zero tuning time” here means that the delay caused by wavelength tuning is not considered in the algorithm, however the tuning time of the device is not zero.

At present, there are few studies on the ONU scheduling algorithm for VPON with non-zero tuning time. Especially in the scene where different tuning time ONUs coexist. In this paper, we propose an adaptive scheduling algorithm for the coexistence of ONUs with different tuning time in VPON, which is called multi-tuning-time ONU scheduling (MOS) algorithm. Through adaptively scheduling ONUs based on the bandwidth demand and the initial distribution of each ONU, the MOS algorithm can effectively avoid the extra queue delay caused by ONUs' wavelength tuning and reduce the waste of bandwidth resources.

2. The MOS Algorithm

The MOS algorithm is developed extending the longest-first first-available (LFFA) algorithm. The LFFA algorithm is a classical offline ONU scheduling algorithm. However, the tuning time factor is not taken into account in the LFFA algorithm, extra queue delays may occur in the process of ONUs' data transmission. The main functionalities of the MOS algorithm is described as follows.

Firstly, the number of the wavelength required in scheduling cycle is computed as:

$$n_{required} = \left\lceil \frac{\sum_{i=1}^{n_{onu}} b_i + (n_{onu} - 1) * T_g^b}{\sum_{j=1}^{n_{wave}} w_j} \right\rceil \tag{1}$$

Where n_{wave} is the number of wavelengths in VPON and n_{onu} is the number of ONUs under VPON. b_i is the bandwidth demand of onu_i. w_j is the bandwidth amount of $wavelength_j$. $T_g^b(bit)$ is the Bandwidth converted from guard time slot.

Then, all available wavelengths are sorted according to their bandwidth occupancy of previous cycle from high to low, and the first $n_{required}$ wavelengths are the selected wavelengths in this cycle.

Meanwhile, a a∗b ($a = n_{required}$, $b = n_{onu}$) ONU scheduling matrix will be created to represent the time slot allocation size and order of ONUs.

$$M_{a*b} = \begin{bmatrix} m_{11} & \cdots & m_{1b} \\ \vdots & \ddots & \vdots \\ m_{a1} & \cdots & m_{ab} \end{bmatrix} \tag{2}$$

Where m_{ij} ($i \leq$ a, $j \leq$ b) represents the bandwidth value of the time slot allocated to the j-th ONU on $wavelength_i$. In order to facilitate subsequent operations, the dimension of m_{ij} is bandwidth (bit). The initial elements of M_{a*b} are all 0. Once the time slot of one ONU is determined, the M_{a*b} will be updated.

The time slots allocation for ONUs is divided into two steps. In first step, time slots are allocated to the ONUs that are on the selected wavelength in last cycle. In current cycle, these ONUs can still work on their original wavelengths, so they do not generate tuning delays. The ONU's original wavelength refers to the wavelength at which the ONU works in the last cycle.

On each wavelength, these ONUs are allocated time slots in descending order of their bandwidth demand. During the first step, the value of m_{ij} is determined as follows:

$$m_{ij} = \begin{cases} 0 & \text{if } \sum_{x=1}^{j-1} m_{ix} + b_{ing} > w_i \\ b_{ing} & \text{if } \sum_{x=1}^{j-1} m_{ix} + b_{ing} \leq w_i \end{cases} \tag{3}$$

Where w_i is the total bandwidth of $wavelength_i$, and b_{ing} is the bandwidth demand of the ONU which is being allocated time slot.

At the same time, for each wavelength, when equation (4) is satisfied, the first step time slot allocation of this wavelength ends. The remaining ONUs at this wavelength are placed in the ONU

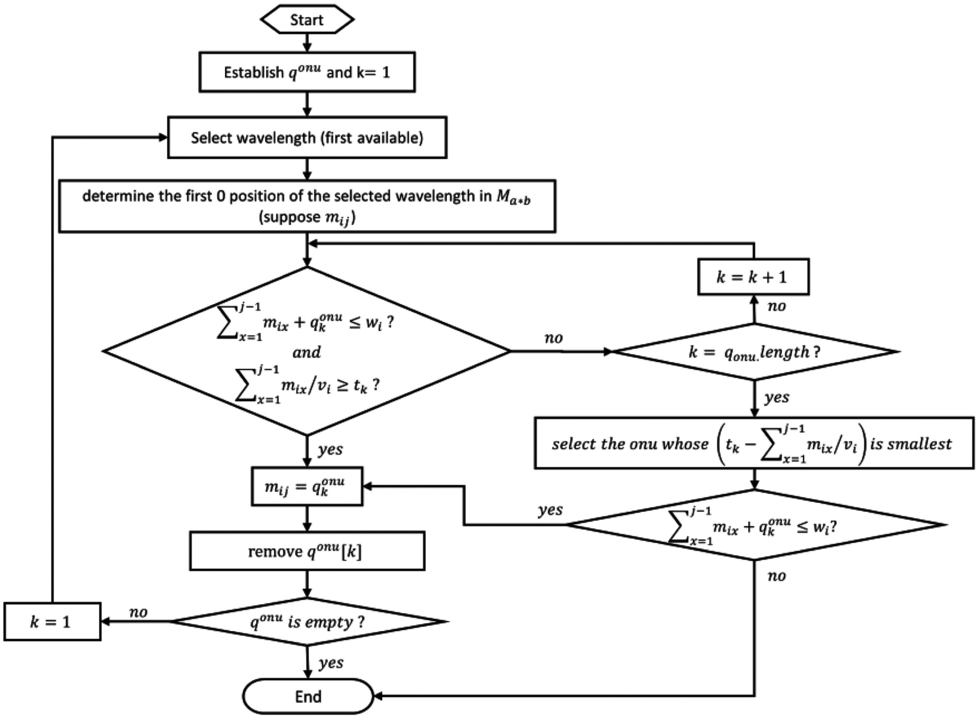


Fig. 1. The flowchart of the second step of the MOS algorithm.

pool, waiting for the second step time slot allocation.

$$\sum_{j=1}^{n_{onu}} m_{ij} / v_i > t_{\text{MAX}} \tag{4}$$

Where t_{MAX} (s) is the longest tuning time among all ONUs and $v_i(bit/s)$ is the bit rate of $wavelength_i$. The purpose of the first step is to provide buffering time for other ONUs that need tuning by arranging some ONUs to transmit preferentially at their original wavelengths.

In second step, time slots are allocated to the remaining ONUs in the ONU pool. The flowchart of the second step is shown in Fig. 1. Firstly, a queue q^{onu} will be established, all remaining ONUs are populated into q^{onu} and sorted by their bandwidth demand from largest to smallest. q_k^{onu} represents bandwidth demand of the k-th ONU in q^{onu}. Next, the first ONU in q^{onu} will be assigned to the wavelength which is first available. To judge whether the time slot allocated to one ONU may generate extra queue delay, equation (5) is used to make the decision.

$$m_{ij} = \begin{cases} q_k^{onu} \text{ if } t_k \le \frac{\sum_{x=1}^{j-1} m_{ix}}{v_i} \text{ and } \sum_{x=1}^{j-1} m_{ix} + \ q_k^{onu} \ \le w_i \\ 0 \qquad\qquad\qquad\qquad \text{else} \end{cases} \tag{5}$$

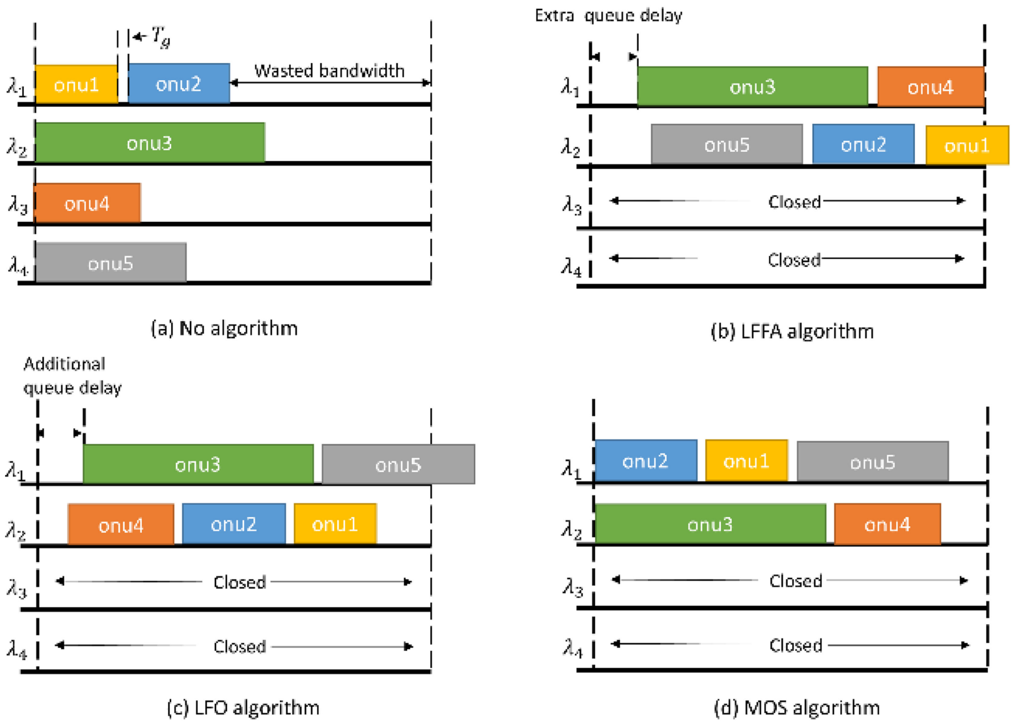
Where $t_k(s)$ is the tuning time of the k-th ONU in q^{onu} and $v_i(bit/s)$ is the bit rate of $wavelength_i$. The ONUs which has been allocated time slot will be removed from q^{onu}. If the ONU cannot meet the requirement of Equation (5), this ONU will be skipped and algorithm is performed for the next ONU in q^{onu}. Each time one ONU is removed from q^{onu}, the algorithm will go back to the first ONU in q^{onu} and starts executing.

If no ONU in q_{onu} can meet the requirement of Equation (5), the ONU with the smallest tuning delay in q^{onu} will be allocated time slot. The MOS algorithm will continue until q^{onu} is empty.

To illustrate the MOS algorithm clearly, a simple example of a VPON with four wavelength and five ONUs is given as follows. The tunable devices are divided into three classes [7]. Among them,

TABLE 1
The Parameters of ONUs

	Supported wavelengths	Tuning time (μs)
ONU1	$\lambda_1, \lambda_2, \lambda_3, \lambda_4$	8
ONU2	$\lambda_1, \lambda_2, \lambda_3, \lambda_4$	10
ONU3	$\lambda_1, \lambda_2, \lambda_3, \lambda_4$	8
ONU4	$\lambda_1, \lambda_2, \lambda_3, \lambda_4$	6
ONU5	$\lambda_1, \lambda_2, \lambda_3, \lambda_4$	10



(a) No algorithm
(b) LFFA algorithm
(c) LFO algorithm
(d) MOS algorithm

Fig. 2. Comparison of three algorithms.

class 1 tunable devices, characterized by the shortest tuning time, may enable a future dynamic wavelength and bandwidth allocation feature in the system. The tuning time standard of class 1 devices is less than 10 μs. Without loss of generality, we consider here three different tuning time ONUs, 6 μs, 8 μs and 10 μs, respectively. The parameters of ONUs are shown in Table 1.

For comparison, two other ONU schedule algorithms for VPON are also introduced into the example. They are the longest first ordering (LFO) algorithm and the LFFA algorithm [6]. In LFFA and LFO algorithms, the wavelength selection mechanism is not included. Therefore, these two algorithms preferentially select the small serial number wavelength for time slot allocation.

The results of the example is shown in Fig. 2. Fig. 2(a) is the original status of VPON when no algorithm is performed. This is a scenario where the VPON go from high load to low load. Multiple wavelengths provide service but there is a large amount of idle bandwidth. Fig. 2(b) is the result of the LFFA algorithm. ONU3 is assigned to λ_1(scheduled from λ_2 to λ_1), and ONU5 is assigned to λ_2(scheduled from λ_4 to λ_2). Since ONU3 and ONU5 require wavelength tuning, their data cannot be transmitted during the given time slot. Extra queue delays are generated at the beginning of the queue. Fig. 2(c) is the result of the LFO algorithm. The first ONU of λ_1 and λ_2 is ONU3 and ONU4, respectively. ONU3 is assigned to λ_1(scheduled from λ_2 to λ_1), and ONU4 is assigned to λ_2(scheduled from λ_3 to λ_2). ONU3 and ONU4 require wavelength tuning, their data

TABLE 2
Symbols and Meaning

Parameter	Definition	Value
n_{wave}	Number of wavelengths	4
n_{onu}	Number of ONUs	32–128
v_i	Wavelength bit rate	10 Gb/s
T_{cycle}	Maximum scheduling cycle time	125 μs
T_g	Guard time slot	100 ns

cannot be transmitted during the given time slot. Fig. 2(d) is the result of our proposed MOS algorithm. Firstly, the number of wavelengths is determined based on the total load. λ_1 and λ_2 are selected according to the bandwidth occupancy order in last cycle. Then, the original ONUs on λ_1 and λ_2 are allocated time slots. Next, the remaining ONUs are allocated time slots according to the flowchart shown in Fig. 1. During the data transmission of ONU1, ONU2, and ONU3, ONU4 and ONU5 complete the wavelength tuning. Therefore, they can transmit data during the given time slots, thus avoiding extra queue delays.

3. The Simulation and Analyses

In this section, the performance of the proposed MOS algorithm is studied. The simulation is developed in MATLAB. By simulation, the MOS algorithm is compared with the LFFA algorithm and LFO algorithm. The simulation is focused on three aspects: average tuning delays (ATD), scheduling cycle time (SCT) and effective bandwidth ratio (EBR). In the simulation, the initial wavelength of each ONU are randomly assigned. The data packet generated with Poisson distribution, and packet size ranges from 64 bytes to 1518 bytes (The unit will be converted to bits during the operation process). Some simulation parameters are summarized in Table 2.

The load of VPON is defined as follows:

$$\text{Load} = \frac{\sum_{onu \in VPON} b_i}{\sum_{j=1}^{n_{wave}} w_j} \tag{6}$$

The ATD refers to the extra uplink transmission queue delay caused by ONU’s wavelength tuning. According to the example in Section 2, we can find that the generation of ATD is related to the initial distribution of ONUs, the ONUs’ tuning time and other factors. We evaluate the ATD performance of the three algorithms through two boundary scenarios, namely, scenario A: the scenario where ATD is least likely to occur and scenario B: the scenario where ATD is most likely to occur. Since the initial distribution of ONUs are different when load is different. At each load, we randomly generate 20 different initial distributions of the ONUs and take the average as the result.

In scenario A, the ONUs have a greater probability of being initially distributed over the small serial number wavelength, while all the ONUs’ tuning time are 6 μs. Fig. 3 presents the comparison of ATD among three algorithms in scenario A. It should be noted that the ATD value for each load is the average of multiple simulation results. Through simulation, it is found that for LFFA and LFO algorithm, their ATD is independent of load. When the load is between [0.1,1], the ATD of both algorithms is distributed in the interval [3 μs,6 μs]. The ATD of MOS algorithm is always 0.

In scenario B, the ONUs have a greater probability of being distributed over the large serial number wavelengths, while all the ONUs’ tuning time are 10 μs. Fig. 4 presents the comparison of ATD among three algorithms in scenario B. When the load is between [0.1,1], the ATD of LFFA and LFO algorithm are distributed in the interval [7 μs, 10 μs]. The ATD of MOS algorithm is always 0.

Combining the simulation data of Fig. 3 and Fig. 4, we can conclude that the LFFA and LFO algorithms may generate ATD when considering the tuning time factor. The value of ATD is independent of the load, and is related to the initial distribution of the ONUs and ONUs’ tuning time.

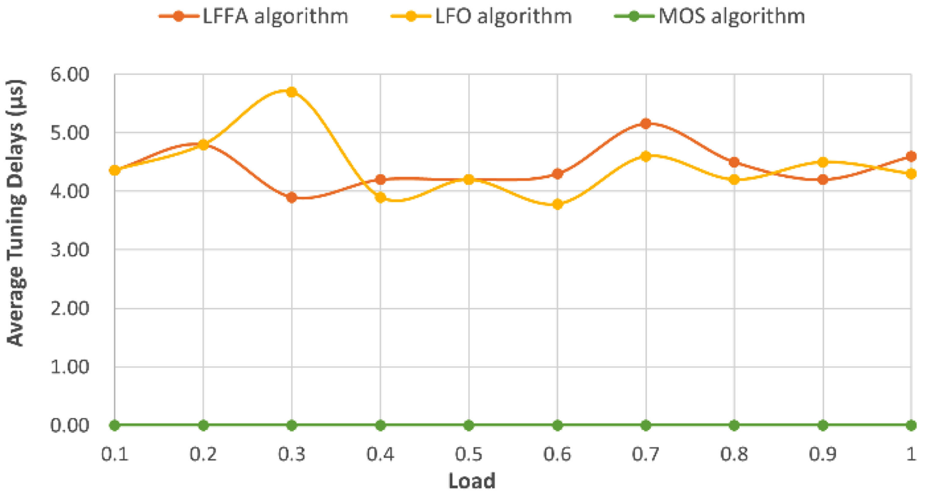


Fig. 3. The ATD comparison in scenario A.

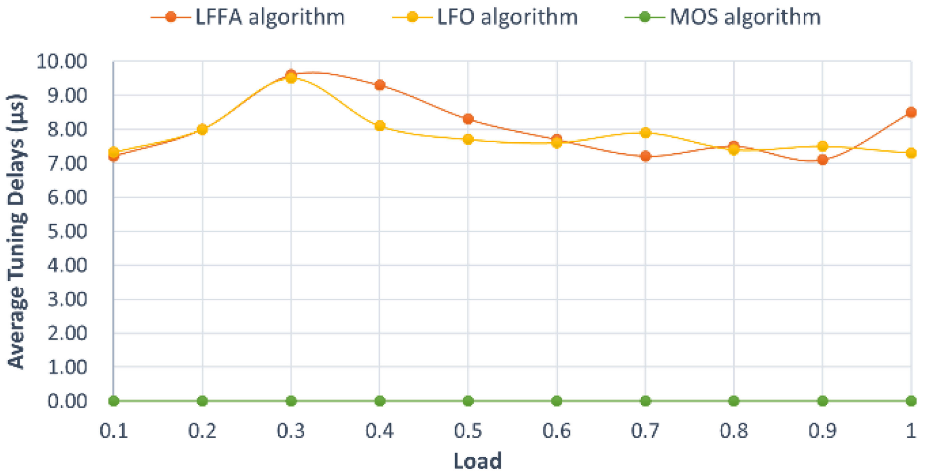


Fig. 4. The ATD comparison in scenario B.

Meanwhile, we can see from Fig. 3 and Fig. 4 that the ATD of MOS algorithm is always zero regardless of any scenarios. This is because in the MOS algorithm, the ONUs' tuning time is offset by the inevitable queue delay by reasonable wavelength selection and ONU scheduling.

SCT refers to the actual transmission cycle time in an uplink scheduling cycle. The maximum scheduling cycle time is 125 μs. According to the load and the scheduling of ONUs, the scheduling cycle can be terminated early to save resources. When the number of wavelengths is the same, the smaller the value of SCT, the better the load balancing performance of the ONU scheduling algorithm.

Fig. 5 presents the comparison of SCT among three algorithms. When load is between [0.1,1], the SCT of LFO algorithm is the largest among three algorithms. This is because of the LFO algorithm's mechanism. After allocating all time slots of one wavelength, LFO algorithm begins to allocate time slots of the next wavelength. When load is 0.3, 0.6 and 0.8, the SCT of the LFO algorithm is especially large compared to the other two algorithms. This is because new wavelength have just been enabled in these three load cases, but are not fully utilized. For the LFFA and MOS algorithms, the load is evenly distributed to each wavelength through their excellent load balancing

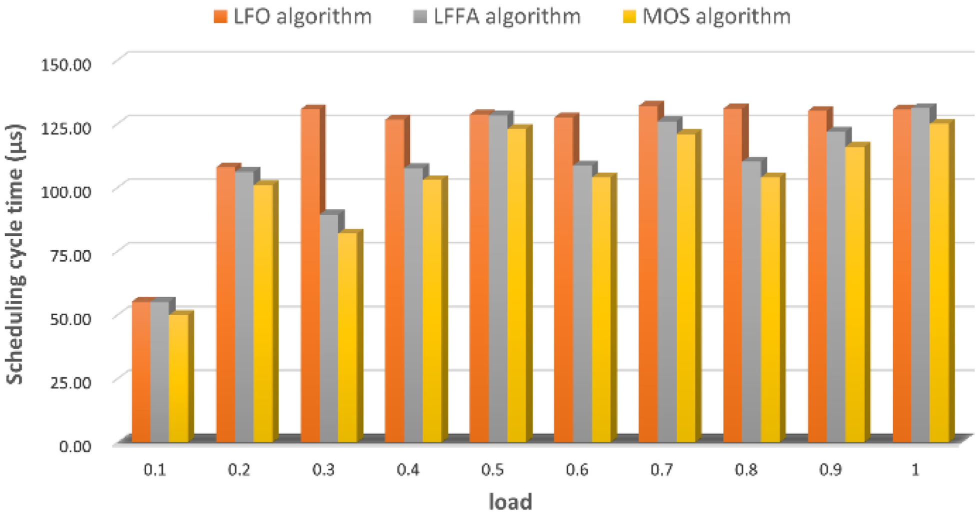


Fig. 5. The SCT comparison.

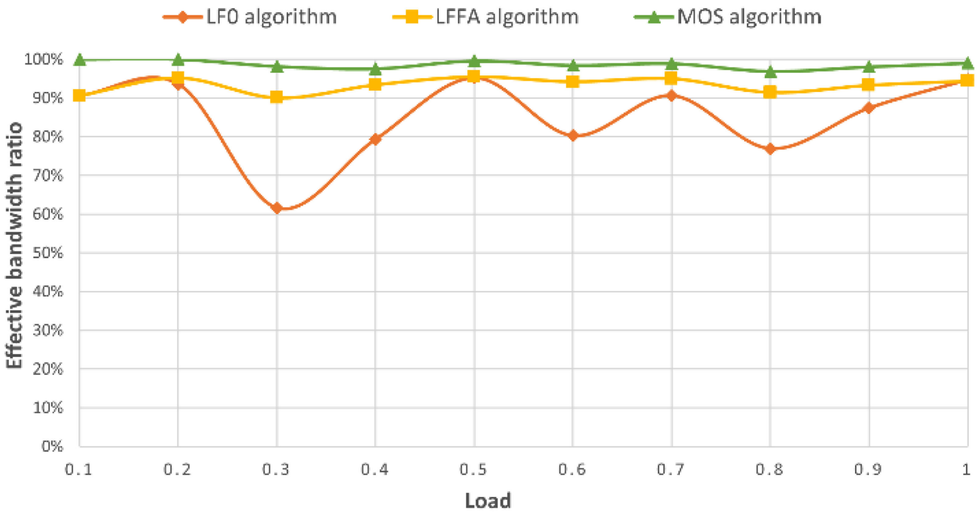


Fig. 6. The EBR comparison.

mechanism, thereby reducing the SCT. When the load is between [0.1,1], the SCT of the MOS algorithm is always smaller than the LFFA algorithm. This proves that the MOS algorithm further reduces the SCT by avoiding the generation of ATD while preserving the excellent load balancing performance of the LFFA algorithm. From Fig. 5 we can find that for the LFFA and LFO algorithms, their SCT is greater than 125 μs under some load cases. This is quite severe when there is a maximum limit on the scheduling cycle. The data beyond 125 μs is required to be transmitted until the next scheduling cycle, which greatly increases the data transmission delay.

The EBR refers to the ratio of the amount of transmitted data to the amount of total occupied bandwidth. Since the three algorithms are all ONU scheduling algorithms, the amount of uplink transmitted data under the same load is the same. Therefore, the lower the EBR, the more bandwidth the algorithm wastes.

Fig. 6 presents the comparison of SCT among three algorithms. When the load is between [0.1,1], the EBR of MOS algorithm is always the highest among three algorithms, and the part less than 100% is the necessary guard time slot. Since the LFFA algorithm would generate ATD, its EBR is lower than that of the MOS algorithm, which is close to 90%. The fluctuation of the EBR of LFO algorithm is large, because the mechanism of LFO algorithm determines its SCT is large. When new wavelengths are enabled but not fully utilized, the bandwidth resources of the new wavelengths are greatly wasted, so the EBR is low.

Finally, we analyze and compare the time complexity of the three algorithms. All three algorithms belong to the offline scheduling algorithm, the bandwidth requests of all ONUs need to be obtained before algorithm implements. Therefore, the time complexity of the algorithm depends mainly on the ordering and time slots allocation process for ONUs. Taking the MOS algorithm as an example, the MOS algorithm is divided into two steps. The first step contains the sorting and time slots allocation for the ONUs on the selected wavelength. The sorting process is merge sorting, and the time complexity is $\mathrm{O}(\mathrm{n}\log n)$. Where n is the number of the ONU in process. The time complexity of the process of allocating time slots is O(n). The second step contains the sorting and time slots allocation for the remaining ONUs. The time complexity of the sorting process is still $\mathrm{O}(\mathrm{n}\log n)$. In the time slots allocation process, Equation (4) shows that ONU may be allocated time slots after multiple traversals, therefore the best time complexity is O(n) and the worst time complexity is $\mathrm{O}(\mathrm{n}+\mathrm{k})$. k is a constant less than n. From the macro perspective, the time complexity of the MOS algorithm is $\mathrm{O}(\mathrm{n}\log n)$. According to the same analysis method, the time complexity of the LFFA algorithm and the LFO algorithm are both $\mathrm{O}(\mathrm{n}\log n)$.

Simulation include algorithm performance simulation based on software and experimental measurement based on optoelectronics and modulator to verify the performance [9], [10]. Due to the length limitation, this paper focus on the analysis of algorithm performance through software simulation. Our group will further verify the performance through experiments based on photoelectrons and modulators in subsequent research.

4. Conclusions

In this paper, we propose to include the factor of ONUs' wavelength tuning time into ONU scheduling algorithm for VPON, and propose the multi-tuning-time ONU scheduling (MOS) algorithm. According to the simulation results, the MOS algorithm can effectively avoid the extra queue delay caused by ONUs' wavelength tuning. Thereby better balancing the load and reducing the waste of bandwidth resources.

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