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Fair Resource Allocation Based on User Satisfaction in Multi-OLT Virtual Passive Optical Network

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ABSTRACT In this paper, a fair resource allocation mechanism based on user satisfaction in multiple optical line terminal (multi-OLT) virtual passive optical network (VPON) is proposed. By introducing user satisfaction functions, the satisfaction of users can be quantified. By presenting multi-OLT VPON in metro-access optical network (MAON), different priority services can be effectively handled separately. Based on user satisfaction, a fair resource allocation mechanism called double fair dynamic bandwidth allocation scheme (DFDBAS) is proposed. DFDBAS is a combination of two algorithms: wavelength fair allocation (WFA) algorithm and timeslot fair allocation (TFA) algorithm. In TFA algorithm, max-min fairness (MMF) algorithm is presented to allocate bandwidth for high priority service and Lagrange multiplier method is implemented to allocate bandwidth for low priority service. By implementing DFDBAS, not only user delay satisfaction can be improved, but also user bandwidth satisfaction can increase. By the simulation and analysis, the effectiveness of the proposed algorithms is demonstrated. Compared with modified limited service (LS) algorithm, DFDBAS makes both delay satisfaction and bandwidth satisfaction increase by at least 30% when the load is greater than 1.

INDEX TERMS User satisfaction, multi-OLT PON, max-min fairness, dynamic bandwidth allocation, virtual passive optical network.

I. INTRODUCTION

As we all know, passive optical network has been widely used in access network. With the rapid growth of network traffic, the traditional time division multiplexing passive optical network (TDM-PON) will not meet people's demand for bandwidth. TDM-PON has a single optical line terminal (OLT) and a single wavelength. As an alternative, multi-OLT-based PON will be a good selection to solve the above problem [1]–[4]. On the other hand, as an effective solution to improve the utilization of network resources, virtual PON (VPON) has been deeply studied. To realize virtualization in multi-OLT PON, a virtual multi-OLT PON system is proposed to improve the system performance [2]. When user traffic is large, there will be multiple subsystems in VPON system, especially in virtual multi-OLT PON system. At present, the related research on multi-subsystem-based VPON is scarce. In [5] and [6], we proposed a (multi-subsystem)-based virtual passive optical network (MS-VPON) in metro-access optical network (MAON) which can implement the syncretism of multiple systems such as TDM-PON, wavelength division multiplexing passive optical network (WDM-PON), and orthogonal frequency division multiplexing passive optical network (OFDM-PON). In [7], an optical network unit (ONU) transfer mechanism is put forward to share remaining bandwidth between subsystems. In [8], a two-stage bandwidth-allocated algorithm is proposed in the MS-VPON that can achieve the syncretism of multiple systems such as TDM-PON, WDM-PON, and OFDM-PON. As one of the evaluation indicators of network performance, user satisfaction also accounts for an increasing proportion in the network. As far as the current research is

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concerned, the utility function is mainly used to quantify user satisfaction. In [9], a utility-based resource allocation algorithm is proposed. This algorithm solves the problem of network utility maximization by using Karush–Kuhn–Tucker (KKT) conditions. In [10], a unified user satisfaction function is proposed, which normalizes multiple network parameters into the same function for calculation. However, these researches are studied in wireless network. In PON, the research for user satisfaction with utility function is rear. In [11], fair excess-dynamic bandwidth allocation (FEx-DBA) is presented for bandwidth allocation in long reach PON. This algorithm considering allocated bandwidth aims at network utility maximization. Moreover, the resource allocation algorithm in PON is widely studied, especially in PON data center architecture in recent years [12]–[14]. In [12] and [13], mixed integer linear programming (MILP) models are utilized to implement resource allocation and improve the network performance in PON-based data center network. In [14], a multi-objective genetic algorithm (GA) is proposed to dynamically forecast the resource utilization and energy consumption in cloud data center.

In PON, the indicator associated with user satisfaction is only the amount of bandwidth allocated currently. However, not only allocated bandwidth affects user satisfaction, but also network delay influences user satisfaction. In this paper, a bandwidth allocation scheme called double fair dynamic bandwidth allocation scheme (DFDBAS) is proposed to improve user satisfaction in multi-OLT VPON. To better allocate network resources, DFDBAS consists of two parts: wavelength fair allocation (WFA) algorithm for better user delay satisfaction, and timeslot fair allocation (TFA) algorithm for better user bandwidth satisfaction. Through the proposed allocation scheme, user satisfaction can be improved, and quality of service (QoS) can also be guaranteed.

This paper is divided into the following sections. Section II proposes user satisfaction functions in multi-OLT VPON. Section III presents a resource allocation scheme for different priority services in multi-OLT VPON. Section IV is the simulation and performance analysis. Section V is the conclusion of this paper.

II. USER SATISFACTION FUNCTION

In the access network, user satisfaction is mainly related to two network parameters: transmission delay and allocated bandwidth for users. According to the characteristics of services in the access network, the services transmitted by users can be divided into three priorities: expedited forwarding (EF), assured forwarding (AF) and best effort (BE). In order to quantify the user satisfaction of two different dimensions, the delay satisfaction function and bandwidth satisfaction function are presented in this section.

EF service is a constant bit rate service and has the characteristics of low latency. The delay satisfaction function of EF service is shown as follows:

$$\mathrm{U}_{\mathrm{delay\_EF}}(d) = \frac{1 + e^{-\delta d_m}}{1 + e^{-\delta (d_m - d)}} \quad (1)$$

This satisfaction function is a sigmoid function. In (1), d is the user's transmission delay. δ is the parameter that controls the shape of the curve. $\mathrm{d_m}$ is the user's satisfaction delay. When the actual transmission delay is lower than $\mathrm{d_m}$, the user satisfaction will be relatively large. Otherwise, the user satisfaction will be relatively small. For AF and BE services, their requirements for delay are not as high as those of EF service. Their delay satisfactions can be expressed by one delay satisfaction function:

$$\mathrm{U}_{\mathrm{delay\_AF\_BE}}(d) = e^{-\delta d} \quad (2)$$

This satisfaction function is an exponential function. In (2), δ controls the shape of the curve. Since the priority of AF service is higher than that of BE service, the δ value of AF service is smaller than the δ value of BE service. The delay satisfaction functions of three priority services can be intuitively shown in Fig. 1.

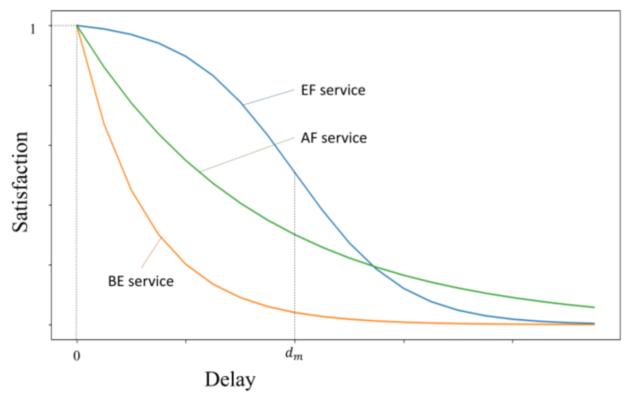

FIGURE 1. Delay satisfaction functions of three priority services.

Unlike delay satisfaction function, bandwidth satisfaction function is an increasing function. For EF and AF services, their bandwidth satisfactions can be uniformly expressed by one function, as shown in (3):

$$\mathrm{U}_{\mathrm{bw\_EF\_AF}}(b) = \frac{1}{1 + e^{\delta (b_m - b)}} \quad (3)$$

This satisfaction function is a monotonically increasing sigmoid function. b is the amount of bandwidth allocated to users in (3). δ is a parameter that controls the shape of the function. Since EF service is a constant bit rate service, as long as the allocated bandwidth reaches the request bandwidth, the corresponding user will be satisfied. Conversely, the corresponding user will be particularly dissatisfied. Therefore, δ value of EF service should approach infinity. $\mathrm{b_m}$ represents user's request bandwidth. The bandwidth satisfaction function of EF service approximates a step function. AF service also has higher bandwidth requirements, so users can be more satisfied when the allocated bandwidth is greater than the guaranteed bandwidth. When the allocated bandwidth reaches the request bandwidth, user satisfaction is close to 1. The δ of AF service should not be too large. $\mathrm{b_m}$ represents user's guaranteed bandwidth. Specific parameter settings for EF and

TABLE 1. Parameter settings of bandwidth satisfaction function.

Parameter	EF service	AF service
δ	Large	Not too large
b_m	Request bandwidth	Guaranteed bandwidth

AF services are shown in Table 1. BE service does not have high requirement for bandwidth. Therefore, a monotonically increasing exponential function can be used to express the bandwidth satisfaction of BE service:

$$U_{bw\_BE}(b) = 1 - e^{-\delta b} \tag{4}$$

where δ controls the shape of the function. The bandwidth satisfaction functions of three priority services can be intuitively shown in Fig. 2.

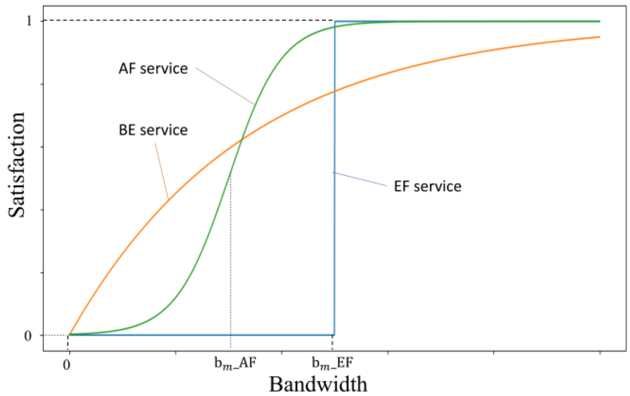

FIGURE 2. Bandwidth satisfaction functions of three priority services.

III. DOUBLE FAIR DYNAMIC BANDWIDTH ALLOCATION SCHEME

For users, every network performance can be reflected in user satisfaction indicators. For the previous passive access network, users' bandwidth requirements are difficult to meet, so that the allocated bandwidth is the main indicator of user satisfaction. However, with the continuous expansion of the network scale, user satisfaction is not only related to the allocated bandwidth. Aiming at this network scenario, this section first proposes the multi-OLT VPON architecture in MAON. Secondly, according to the expansion of the user satisfaction indicator in the previous section, a bandwidth allocation scheme with dual granularity called double fair dynamic bandwidth allocation scheme (DFDBAS) is proposed. For wavelength granularity, the WFA algorithm is used to optimize delay satisfaction. For timeslot granularity, the TFA algorithm is used to optimize bandwidth satisfaction.

A. MULTI-OLT VPON IN MAON

A multi-OLT VPON architecture in MAON is shown in Fig. 3. This architecture mainly contains a central node (CN), several flexible control nodes (FCNs) and numbers of ONUs. CN is the control center and is responsible for the centralized management of whole MAON. As a major role in communication with the core network, CN is located at the intersection of the core fiber ring and the metro-access fiber ring. FCN is the control node of VPON, which consists of remote node (RN) and multiple OLTs. With the existence of RN, ONU can be connected to any OLT via wavelength routing. Thus, ONU can realize flexible access under different VPONs. Meanwhile, wavelength resources can be allocated to each VPON along the metro-access fiber ring because of RN. Each OLT in one FCN and the ONUs it controls together form a VPON subsystem. One OLT handles the services of a single subsystem, making the operation more efficient. FCN is a virtual structure, and the number of OLTs it controls internally is flexible. When the VPON needs to be reconstructed, the number and type of OLTs in an FCN may change. During the operation of VPON, the number and type of OLTs will not change. It is worth mentioning that OLTs that are far apart can also be combined in one FCN to form a VPON. In this architecture, different VPONs can handle different types of services, so that access network can be more flexible for service processing under high network load.

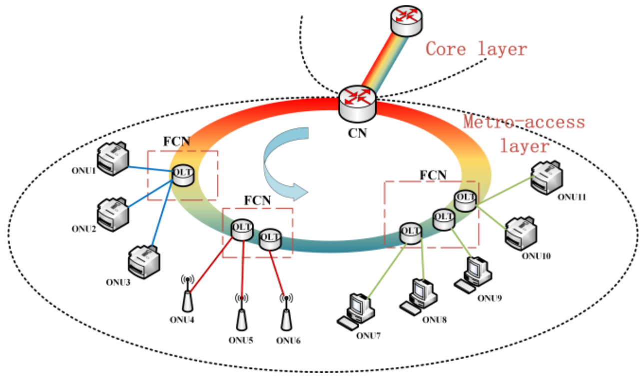

FIGURE 3. Multi-OLT VPON architecture in metro-access optical network.

B. WAVELENGTH FAIR ALLOCATION ALGORITHM

A wavelength allocation algorithm with variable polling cycle is presented in order to satisfy user's delay requirement. According to the delay satisfaction functions proposed in section 2, it can be seen that when the delay is small, the delay satisfaction of EF service changes slowly. Thus, a load Threshold $load_{th}$ can be set. When the load of VPON is less than $load_{th}$, there is no need to execute the wavelength fair allocation algorithm. Instead, wavelengths are allocated to various subsystems according to the proportion of services. When the load is greater than $load_{th}$, the wavelength fair allocation algorithm will be executed. WFA algorithm with three priority services is shown in Fig. 4.

In this algorithm, a VPON contains two subsystems, which are handled by two OLTs. ONUs transmitting the EF service are put into subsystem 1. At the same time, ONUs transmitting AF and BE services are put into subsystem 2. Each ONU transmits a priority service. The ONU sets of EF service, AF service and BE service are S_{EF}, S_{AF} and S_{BE}. The request bandwidth of ONU_i is represented by R_i. Thus, the total

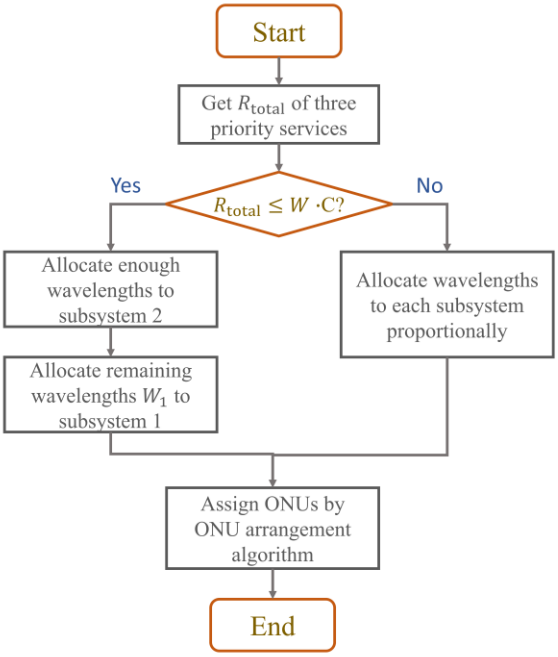

FIGURE 4. **The flow chart of WFA algorithm.**

request bandwidth can be expressed as follows:

$$\mathrm{R}_{\mathrm{total}} = \sum_{i \in S_{EF}} R_i + \sum_{i \in S_{AF}} R_i + \sum_{i \in S_{BE}} R_i \tag{5}$$

When the total request bandwidth is less than the available bandwidth, just enough wavelength resources are preferentially allocated to subsystem 2. Then all the remaining wavelength resources are allocated to subsystem 1. At this time, the amount of wavelengths assigned to subsystem 1 can be achieved as follows:

$$\mathrm{W}_1 = W - \left\lceil \frac{\sum_{i \in S_{AF}} R_i + \sum_{i \in S_{BE}} R_i}{C} \right\rceil \tag{6}$$

where the amount of wavelengths assigned to subsystem 1 is W_1. The amount of wavelength resources in a multi-OLT VPON is W. The capacity of a single wavelength is C. When the total request bandwidth is greater than the available bandwidth, the corresponding wavelength resources are assigned to each subsystem in proportion to the request bandwidth. If the amount of allocated wavelengths is not an integer, the amount of wavelengths rounded up is allocated to subsystem 1. Thus, the amount of wavelengths assigned to subsystem 1 can be derived as follows:

$$\mathrm{W}_1 = \left\lceil W \cdot \frac{\sum_{i \in S_{EF}} R_i}{R_{total}} \right\rceil \tag{7}$$

After assigning wavelengths to each subsystem, a reasonable ONU arrangement algorithm needs to be designed to minimize the ONU polling cycle. Taking subsystem 1 as an example, the pseudo code of the ONU arrangement algorithm is shown in Fig. 5. Firstly, arrange the ONUs in subsystem 1 in descending order according to the request bandwidth.

Algorithm

```
sort(S_EF) in descending order
sort(S_W1) in descending order according to remaining bandwidth
while S_EF ≠ ∅, do:
    for i=1 to W1:
        if R_onu i > B_wavelengt hi, do:
            break
        allocate ONU_i to wavelength_i
    if S_EF = ∅, do:
        break
    remove allocated ONU from S_EF
    sort(S_W1) in descending order according to remaining bandwidth
end
```

FIGURE 5. **The pseudo code of the ONU arrangement algorithm.**

Meanwhile, the wavelengths assigned to subsystem 1 are also sorted in descending order according to the remaining bandwidth of the wavelength. Secondly, take the first W_1 ONUs and place them on each wavelength in the order of the sorted wavelengths. After placement, the wavelengths are sorted in descending order according to the remaining bandwidth of the wavelength again. After that, place the next W_1 ONUs on these wavelengths in sequence. Finally, repeat these steps until all ONUs are allocated or there is not enough remaining bandwidth for ONUs.

C. TIMESLOT FAIR ALLOCATION ALGORITHM

The purpose of the timeslot fair allocation algorithm is to make users achieve optimal bandwidth satisfaction. This algorithm is operated after allocating the wavelength resources of multi-OLT VPON. Since there are two subsystems inside VPON, the timeslot fair allocation algorithm contains two parts: timeslot allocation for EF service in subsystem 1 and timeslot allocation for AF and BE services in subsystem 2.

1) ALGORITHM IN SUBSYSTEM 1

EF service is the highest priority service. Therefore, not only high user satisfaction needs to be satisfied, but fairness among users also needs to be ensured. Thus, max-min fairness (MMF) strategy is introduced to allocate timeslots for EF services [15]. The flow chart of the bandwidth allocation algorithm for EF service is shown in Fig. 6. Specific steps are described as follows.

The weight of ONU can be expressed by the following matrix:

$$\Omega = [\,\omega_1 \quad \omega_2 \quad \ldots \quad \omega_N\,] \tag{8}$$

where ω_{i} is the weight of $\mathrm{ONU_i}$, and N is the number of ONUs in subsystem 1. The request bandwidth of ONUs can also be expressed by a matrix:

$$R_{EF} = [\,R_1 \quad R_2 \quad \ldots \quad R_N\,] \tag{9}$$

where $\mathrm{R_i}$ is the request bandwidth of $\mathrm{ONU_i}$. The total available bandwidth of subsystem 1 is B_{EF}^{total}. If $B_{EF}^{total} \geq \sum_{i=1}^{N} R_i$,

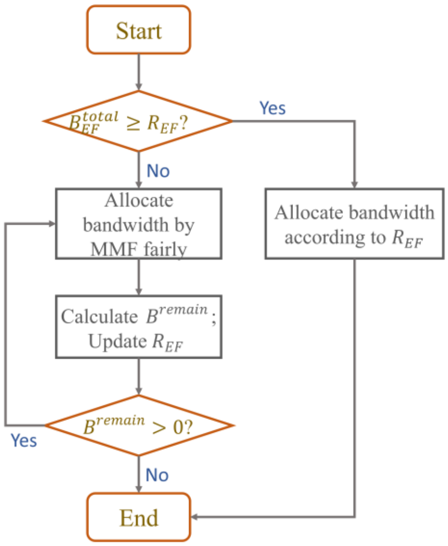

FIGURE 6. The flow chart of the bandwidth allocation algorithm for EF service.

it means that the bandwidth in subsystem 1 is sufficient. Therefore, the bandwidth allocated to each ONU is their request bandwidth. If $B_{EF}^{total} < \sum_{i=1}^{N} R_i$, it means that the bandwidth in subsystem 1 is insufficient. The MMF algorithm needs to be executed to allocate bandwidth. The specific process is described as follows:

Step 1: Divide the available bandwidth resources into N shares according to the proportion of ONU weight. The available bandwidth resources after dividing can be illustrated by a matrix:

$$B^{pre} = \Omega \cdot \frac{B^{remain}}{\sum_{i=1}^{N} \omega_i} = [\, B_1^{pre} \quad B_2^{pre} \quad \ldots \quad B_N^{pre} \,] \tag{10}$$

where B^{remain} is the bandwidth that is available in subsystem 1. B^{pre} is the amount of bandwidth pre-allocated to ONU_i after dividing resources.

Step 2: Compare each ONU's pre-allocated bandwidth B^{pre} with its request bandwidth R_{EF}. For ONU_i, if $B_i^{pre} > R_i$, only allocate to R_i bandwidth to ONU_i. Otherwise, allocate B_i^{pre} bandwidth to ONU_i. The amount of the allocated bandwidth can be calculated by the following formula:

$$B_i^{allocate} = \min(B_i^{pre}, R_i) \tag{11}$$

After traversing all ONUs, calculate the sum of remaining bandwidth and set it to B^{remain}. Meanwhile, update the request bandwidth matrix R_{EF}:

$$R_{EF} =: R_{EF} - B^{allocate} \tag{12}$$

Step 3: Reallocate bandwidth to ONUs. If $B^{remain} > 0$, it means some ONUs have been satisfied and other ONUs have been allocated bandwidth but not satisfied. Meanwhile, there are bandwidth left after step 2. Divide B^{remain} into N shares just like Step 1. However, the difference from step 1 is that the number of shares N here is the number of ONUs that have not been satisfied. Then, repeat step 1 to allocate bandwidth. If $B^{remain} \leq 0$, it means that the bandwidth allocation is completed and turn to step 4.

Step 4: End the MMF algorithm and complete the bandwidth allocation of EF service.

2) ALGORITHM IN SUBSYSTEM 2

AF and BE services are transmitted in subsystem 2. The priorities of these services are low. In addition, their requirements for fairness are not as high as EF service. Therefore, the bandwidth allocation algorithm with utility maximization is implemented to allocate timeslots in subsystem 2. The flow chart of the bandwidth allocation algorithm for AF and BE services is shown in Fig. 7. Specific steps are described as follows:

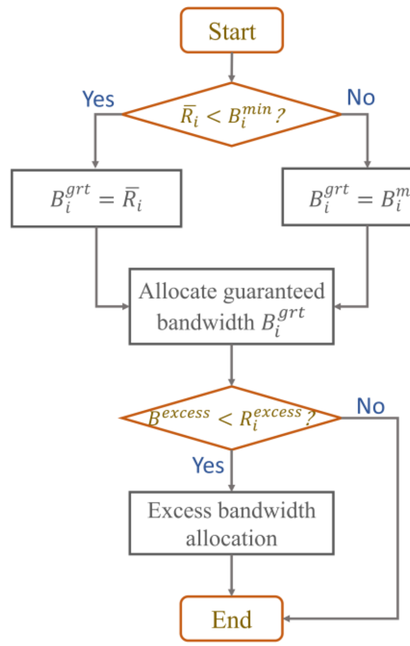

FIGURE 7. The flow chart of the bandwidth allocation algorithm for AF and BE services.

Step 1: Allocate guaranteed bandwidth. The guaranteed bandwidth is the smaller of the ONU's request bandwidth and the minimum allocated bandwidth. It can be derived as follows:

$$B_i^{grt} = \min(\overline{R_i}, B_i^{\min}) \tag{13}$$

where $B_i^{\min}$ is the minimum allocated bandwidth of ONU_i according to service level agreement (SLA). $\overline{R_i}$ is the average request bandwidth of ONU_i in last T cycles. $\overline{R_i}$ can be achieved as follows:

$$\overline{R_i} = \frac{1}{T} \sum_{t=1}^{T} R_i^t \tag{14}$$

where R_i^t is the amount of request bandwidth in the t^{th} polling cycle.

Step 2: Allocate excess bandwidth. After allocating guaranteed bandwidth, the total remaining bandwidth B^{excess} in subsystem 2 and the remaining request bandwidth R_i^{excess} of each ONU will be calculated. If $B^{excess} \geq R_i^{excess}$, it means that the bandwidth of subsystem 2 is sufficient to meet the needs of each ONU. Thus, allocate the remaining request bandwidth to each ONU. If $B^{excess} < R_i^{excess}$, it means that the bandwidth is insufficient. Allocating additional bandwidth for the purpose of utility maximization is necessary. The problem is abstracted into the following mathematical model:

$$\max: \sum_{i\in S_{AF}} \omega_i \cdot U_{bw\_AF}(b_i+B_i^{grt}) + \sum_{j\in S_{BE}} \omega_j \cdot U_{bw\_BE}(b_j+B_j^{grt})$$

$$s.t.: \begin{cases} \sum_{i\in S_{AF}} b_i + \sum_{j\in S_{EF}} b_j \leq B^{excess} \\ 0 \leq b_i \leq R_i - B_i^{grt}, \quad \forall i \in S_{AF} \\ 0 \leq b_j \leq R_j - B_j^{grt}, \quad \forall j \in S_{BE} \end{cases} \tag{15}$$

To solve this problem, Lagrange multiplier method can be used. Substituting the expression of the utility function into the objective function in (15), the objective function can be derived as follows:

$$f(b)=\sum_{i\in S_{AF}} \omega_i \cdot \frac{1}{1+e^{\delta_1(b_m-b_i-B_i^{grt})}} + \sum_{j\in S_{BE}} \omega_j \cdot [1-e^{-\delta_2(b_j+B_j^{grt})}] \tag{16}$$

The Lagrange function established based on (15) is given as follows:

$$\begin{aligned} F(b,x,y,z) = &-f(b) + x(\sum_{i\in S_{AF}} b_i + \sum_{j\in S_{EF}} b_j - B^{excess}) \\ &+ \sum_{i\in S_{AF}, j\in S_{EF}} y_{i,j} \cdot (b_{i,j} - R_{i,j} + B_{i,j}^{grt}) \\ &- \sum_{i\in S_{AF}, j\in S_{EF}} z_{i,j} \cdot b_{i,j} \end{aligned} \tag{17}$$

After establishing the Lagrange function, the constrained extremum problem will be converted into an unconstrained extremum problem. Partial derivation of $F(b, x, y, z)$ to b, x, y, z respectively can derive the results we want. The partial derivative equation is given as follows:

$$\begin{cases} \frac{\partial F(b,x,y,z)}{\partial b} = 0 \\ \frac{\partial F(b,x,y,z)}{\partial x} = 0 \\ \frac{\partial F(b,x,y,z)}{\partial y} = 0 \\ \frac{\partial F(b,x,y,z)}{\partial z} = 0 \end{cases} \tag{18}$$

From (18), the optimal solution b' of the allocated bandwidth can be obtained. The additional allocated bandwidth of ONU_i in subsystem 2 is b_i'.

Step 3: Perform bandwidth allocation to ONU_i. The total allocated bandwidth is the sum of guaranteed bandwidth and excess allocated bandwidth. The guaranteed bandwidth is B_i^{grt} and it can be obtained in step 1. The excess allocated bandwidth is bi' and it can be obtained in step 2.

IV. SIMULATION AND PERFORMANCE ANALYSIS

The DFDBAS algorithm used in multi-OLT VPON is evaluated with MATLAB. The simulation parameters are set as follows. The number of OLTs in a multi-OLT VPON is 2. The number of ONUs is 64. The number of wavelengths in the VPON is 16. The single wavelength transmission rate is 10Gbps. The guard time (T_g) is $1\mu s$. The maximum polling cycle (T_{cycle}) is 2ms. For each ONU, its round trip time (RTT) is $100\mu s$. The sizes of the generated packets sent by ONUs are evenly distributed between 64 and 1518 bytes. The time interval for ONUs to generate data packets follows the Poisson distribution. Three sets of experiments with different service ratios are set for better comparison. They are: (1) EF: AF: BE=1: 1: 1; (2) EF: AF: BE=3: 2: 1; (3) EF: AF: BE=6: 2: 1. Moreover, the modified version of LS algorithm is chosen for comparison with the DFDBAS algorithm [3]. The limited service (LS) algorithm is a typical upstream bandwidth allocation algorithm. LS grants each ONU its requested bandwidth, but no more than the threshold $W_{\max} = B^{total}/N$. Compared with other algorithms, it has the characteristics of low latency and high bandwidth utilization. In multi-OLT PON, LS is modified to transmit multi-wavelength services to multiple OLTs. In the simulation, the performance of these two algorithms on user's delay satisfaction and bandwidth satisfaction is mainly compared.

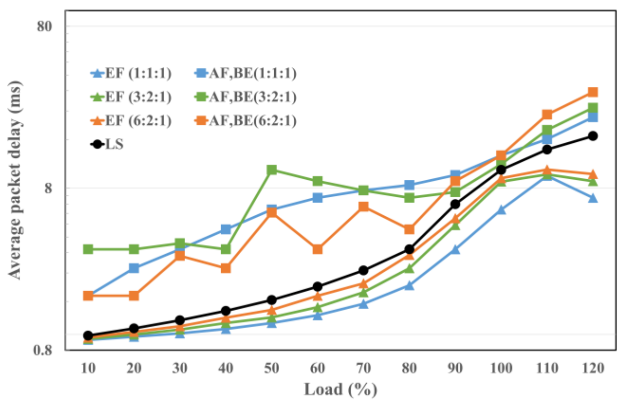

FIGURE 8. Average packet delay of two algorithms.

Fig. 8 shows the average packet delay of the two algorithms. For the DFDBAS algorithm, there are three experimental groups to simulate the delay of subsystem 1 and subsystem 2 respectively. For the LS algorithm, the average packet delay of the entire VPON is simulated. It can be seen from Fig. 8 that the EF subsystem's delay of the DFDBAS algorithm is lower than the average delay of the LS algorithm. Meanwhile, the delay of subsystem 2 by the DFDBAS algorithm is higher than the average delay of the LS algorithm. This is because WFA algorithm in the DFDBAS algorithm causes frequent scheduling of wavelengths between the two subsystems. The wavelength resources of subsystem 2 are scheduled to subsystem 1, so that the delay of subsystem 2 rises. Furthermore, due to the uncertainty of the scheduling wavelength, the delay in subsystem 2 fluctuates greatly with the change of the load. Moreover, for the DFDBAS algorithm, as the proportion of EF service increases, the delay of subsystem 1 will also decrease.

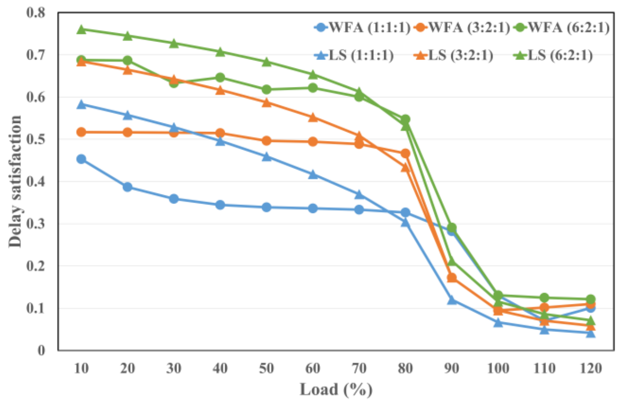

FIGURE 9. Delay satisfaction of two algorithms.

For delay satisfaction, the difference between the WFA algorithm and the LS algorithm is compared. The comparison is shown as Fig. 9. The delay satisfaction within a single VPON is given as follows:

$$Satisfy\_delay = \frac{1}{\sum\limits_{i \in S_{EF}, S_{AF}, S_{BE}} \omega_i} \Big[\sum_{i \in S_{EF}} \omega_i \cdot U_{delay\_EF}(d_i) + \sum_{j \in S_{AF,BE}} \omega_j \cdot U_{delay\_AF\_BE}(d_j) \Big] \quad (19)$$

where ω_i is the user's weight. The weight assigned to each user in the simulation is randomly distributed between 0 and 1. The delay d_i of each ONU has been standardized. The values of δ_{EF} in (1) and δ_{AF} in (2) are set to 1. The value of δ_{BE} in (2) is set to 5. The user's satisfaction delay d_m in (1) is half the average packet delay under full load. It can be known from Fig. 9 that when the load is lower than 0.75, the LS algorithm makes users more satisfied than the WFA algorithm. When the load is higher than 0.75, the WFA algorithm makes users more satisfied. It is because the delay satisfaction of EF service changes slowly when the delay is low. Therefore, it is not worth allocating more wavelength resources to EF service. According to this, the load threshold $load_{th}$ mentioned in section 3.2 can take the value 0.75. When the service ratio is balanced, compared with LS algorithm, WFA makes delay satisfaction increase by at least 30% when the load is greater than 1.

For bandwidth satisfaction, the two subsystems are considered separately. In Subsystem 1, the bandwidth allocation method adopted is the max-min fairness allocation, and MMF algorithm is used for bandwidth allocation. Here, another fair bandwidth allocation algorithm called proportional fair (PF) algorithm is chosen to compare with MMF algorithm. Fig. 10 shows user's bandwidth satisfaction of two different algorithms in subsystem 1. It can be seen from Fig. 10 that when

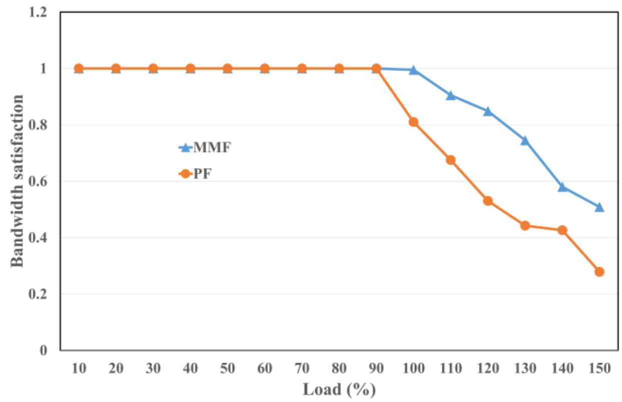

FIGURE 10. Bandwidth satisfaction in subsystem 1.

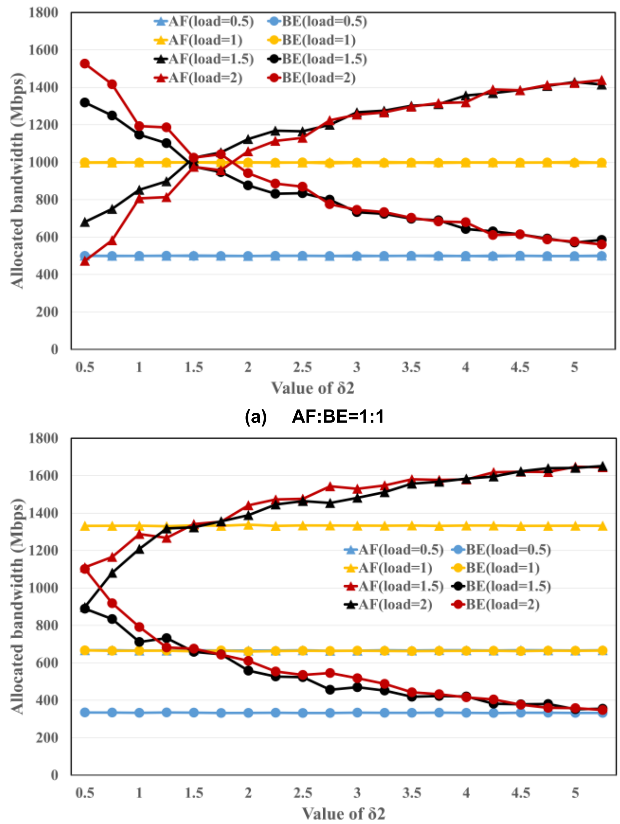

FIGURE 11. Allocated bandwidth in subsystem 2: (a) AF:BE=1:1; (b) AF:BE=2:1.

the load is less than 1, the bandwidth resources of system 1 are sufficient, so that all users can be satisfied. Therefore, no matter which allocation algorithm is used, user satisfaction is always 1. When the load is more than 1, the bandwidth resources are insufficient. The MMF algorithm can ensure that as many users as possible get the maximum satisfaction. Thus, the MMF algorithm can significantly improve bandwidth satisfaction compared to the PF algorithm.

Two priorities of service are involved in subsystem 2, so the Lagrange algorithm is used to allocate bandwidth. Similarly, the bandwidth satisfaction in subsystem 2 can be expressed by (16). In (16), the values of δ_1 and δ_2 need to be limited. If no restrictions are imposed, it may happen that all bandwidth is allocated to BE service or AF service. Here, δ_1 is fixed to 1. Change the value of δ_2, and observe the bandwidth allocated to BE service and AF service. The results are shown in Fig. 11. The service ratio in Fig. 11 (a) is AF: BE=1: 1. The service ratio in Fig. 11 (b) is AF: BE=2: 1. When the load is less than or equal to 1, the bandwidth allocated to users hardly changes with the change of δ_2. When the load is greater than 1, as δ_2 increases, more bandwidth is allocated to AF service and less bandwidth is allocated to BE service. This is because as δ_2 increases, the amount of bandwidth allocated to BE service will have a smaller impact on BE bandwidth satisfaction. When δ_2 is very large, we only need very little bandwidth to satisfy the BE service. Therefore, the bandwidth allocated to AF service is greater than the bandwidth allocated to BE service. After that, user satisfaction can reach a large value. On the contrary, when δ_2 is very small, we need large bandwidth to satisfy the BE service. Therefore, the bandwidth allocated to AF service needs to be smaller than the bandwidth allocated to BE service to reach a high user bandwidth satisfaction. These two extreme situations are obviously not very reasonable. From Fig. 10, it can be seen that when δ_2 is 1.5, the bandwidth allocated to AF service and BE service is relatively balanced. Therefore, the value of δ_2 should be set to 1.5.

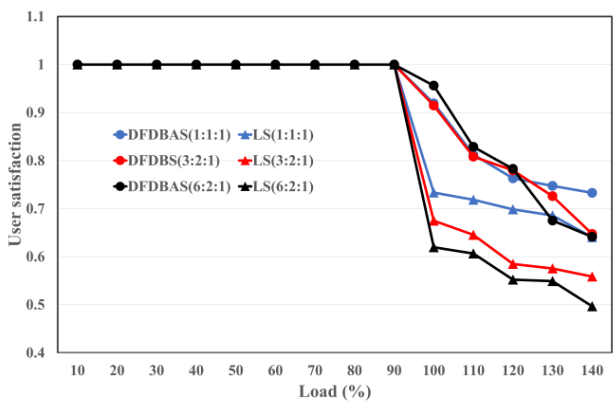

FIGURE 12. Average user bandwidth satisfaction in multi-OLT VPON.

The average user bandwidth satisfaction of DFDBAS algorithm and LS algorithm of in multi-OLT VPON is shown in Fig. 12. When the load is less than 1, the bandwidth resources of the system are sufficient, so that all users can be satisfied. At this situation, the DFDBAS scheme will directly allocate the bandwidth required by each ONU, and will not execute the MMF algorithm and Lagrange multiplier method. The bandwidth satisfaction of both scheme is 1. When the load is greater than 1, the improvement of user bandwidth satisfaction with DFDBAS algorithm is obviously better than LS algorithm. Meanwhile, when system resources are insufficient, the increase in the proportion of EF service will reduce user bandwidth satisfaction. The reason is that EF service is a constant bit rate service. If the proportion of EF service is large, a large number of users will not be satisfied and their user bandwidth satisfaction will be low. As a result, the average satisfaction of the system will also decrease. Compared with LS algorithm, DFDBAS makes average bandwidth satisfaction increase by at least 30% when the load is greater than 1.

For LS scheme and DFDBAS scheme, the time complexity of them needs to be analyzed and compared. For LS scheme, it is an online polling algorithm, which needs to be executed n times in a polling cycle (where n is the number of ONUs). The time complexity in one polling cycle is $O(n)$. For DFDBAS scheme, it contains two parts: WFA algorithm and TFA algorithm. WFA is divided into two steps. The first step is wavelength allocation. Its time complexity is $O(1)$. The second step is ONU arrangement. It includes sorting ONUs and determining the arrangement of ONUs at various wavelengths. The ONU sorting algorithm is merge sorting, and the time complexity is $O(n \log n)$. When determining the arrangement of the ONU at each wavelength, the ONUs need to be traversed, so the time complexity is $O(n)$. From a macro perspective, the time complexity of WFA is $O(n \log n)$. TFA can also be divided into two parts. The first part is the timeslot allocation for EF service, and the second part is the timeslot allocation for AF and BE services. The MMF algorithm is used for timeslot allocation of EF service. The amount of ONU request bandwidth is uncertain in each polling cycle, so that the best time complexity of MMF is $O(n)$, the worst time complexity is $O(n^2)$, and the average time complexity is $O(n \log n)$. The Lagrange multiplier method is used for the timeslot allocation of AF and BE services. Its time complexity is related to the number of ONUs, which is $O(n)$. Therefore, the average time complexity of TFA is $O(n \log n)$. After analysis, the average time complexity of the DFDBAS scheme is $O(n \log n)$. Although the time complexity of the proposed scheme is slightly higher than the LS scheme, DFDBAS can bring higher user satisfaction. Meanwhile, the slight increase in complexity is not so unacceptable. Thus, the DFDBAS scheme is reasonable and effective.

V. CONCLUSION

In this paper, a fair resource allocation mechanism based on user satisfaction in multi-OLT VPON has been proposed. Firstly, user satisfaction functions have been introduced to quantify the satisfaction of users. Next, multi-OLT VPON in MAON has been presented to handle different priority services effectively. Then, a fair resource allocation mechanism called DFDBAS has been proposed based on user satisfaction. DFDBAS is a combination of two algorithms: WFA algorithm and TFA algorithm. By implementing DFDBAS, not only user delay satisfaction can be improved, but also user bandwidth satisfaction can increase. Finally, the effectiveness of the proposed algorithms has been demonstrated by simulation and analysis. The simulation results show good performances of DFDBAS in delay satisfaction and bandwidth satisfaction. Compared with modified LS algorithm, DFDBAS makes both delay satisfaction and bandwidth satisfaction increase by at least 30% when the load is greater than 1.

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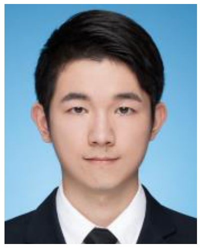

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