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Bandwidth-allocated mechanism and its algorithm for multi-subsystem-based virtual passive optical network in metro-access optical network

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Abstract: In the metro-access optical network, bandwidth-allocated mechanism and its algorithm are proposed for the multi-subsystem-based virtual passive optical network (VPON) that can implement the syncretism of multiple systems such as time division multiplexing-PON, wavelength division multiplexing-PON and orthogonal frequency division multiplexing-PON. To avoid frequent bandwidth reallocation, the matrix of bandwidth-demanded variation is introduced. According to the norm of this matrix, admission condition of bandwidth allocation for VPON users is established. To distinguish different bandwidth-demanded variation of multiple subsystems and allocate bandwidth fairly and efficiently for VPON, the bandwidth-allocated scheme is employed. To the increase of VPON's bandwidth demand, the multi-granularity-based bandwidth-allocated algorithm is proposed to promote the admission probability of new VPONs. MATLAB is used to evaluate the performance of the proposed mechanism and algorithm. Considering the representativeness of various situations, the admission condition of bandwidth allocation for VPON users is demonstrated with ten VPONs. The bandwidth-allocated scheme and algorithm are verified effectively in bandwidth-utilised ratio with two original VPONs of high priority and two new VPONs of low priority, as well as in admission probability with four new VPONs.

1 Introduction

Network virtualisation is an effective solution to improve the utilisation of network resource [1, 2]. In the backbone network, the network virtualisation such as virtual private network (VPN) has been deeply studied and widely used. Through VPN, the intra-network is available for remote users. In the access network, passive optical network (PON) as its main technology has already been employed [3, 4]. Thus, the research on virtualisation of access network mainly aims at the virtualisation of PON, i.e. virtual PON (VPON) [5]. VPON can realise the virtualisation of resource and can be dynamically constructed based on the real applications and requirements. Moreover, VPON can support open access network. Thus, the huge infrastructure can be shared by several operators to lower their capital expenditure and operating expense [6–8]. So far, the studies on VPON are conducted from different perspectives. For example, a VPON-based FlexPON architecture is proposed in [6–8] to achieve the full service access. A hybrid wavelength division multiplexing (WDM)/time division multiplexing (TDM) PON with dynamic VPON capability is proposed in [9, 10]. A VPON based on orthogonal frequency division multiplexing (OFDM) is proposed in [11, 12]. It can support various types of custom access experiments. The above studies are all adapted to the development of PON and existing three-layer (i.e. core layer, convergence layer and access layer) architecture of metro optical network. On the other hand, flattening is the inevitable trend of telecommunication network. To the metro optical network, the existing three-layer architecture will be evolved into the two-layer (i.e. core layer and metro-access layer) architecture in the future [13–15]. Now the architectures of metro-access optical network (MAON) have been widely studied. For example, an architecture for metro-access integrated networks by utilising polarisation multiplexed band interleaving of optical OFDM is proposed in [16] to achieve high spectral efficiency. An OFDM-based metro-access integrated network with dynamic sub-carrier allocation and power distribution is proposed in [17]. An OFDM-based metro-access network is proposed in [18] to enable scalable and reconfigurable all-optical VPN. In addition, the evolution to the MAON will be smooth. However, existing technologies of access network mainly include TDM-PON, WDM-PON, OFDM-PON [19–21] etc. It means these subsystems will be syncretised in MAON in the future. At present, the related research on multi-subsystem-based VPON (MS-VPON) in MAON is little. Therefore, the research is quite necessary. Since the implementation of the VPON is a sophisticated process and includes many aspects, this paper mainly focuses on bandwidth-allocated mechanism and its algorithm to maximise the utilisation of finite bandwidth and promote the admission probability of new VPON applications.

2 MS-VPON in MAON

An MS-VPON scenario in MAON is shown in Fig. 1. The corresponding programmable VPON architecture is illustrated in Fig. 2. Considering the smoothness of network evolution, this scenario contains a central node (CN), several flexible control nodes (FCNs), a traditional optical line terminal (OLT) and a number of optical network units (ONUs). The CN, FCNs and OLT are distributed in the fibre ring. Each FCN (or OLT) connected with ONUs is in tree topology. The centralised management of the whole network is realised in the CN that is the unique node between core layer and metro-access layer. The FCN as the intermediate node of the network has the functions of remote node (RN) and OLT. It includes a wavelength-routed module and an advanced OLT. As shown in Fig. 2, the wavelength-routed module can route the wavelength from the CN to the advanced OLT. In addition, it can also route the wavelength to ONU and achieve the function of RN. At this time, the upstream/downstream communications are controlled by the CN. Thus, a WDM-PON in

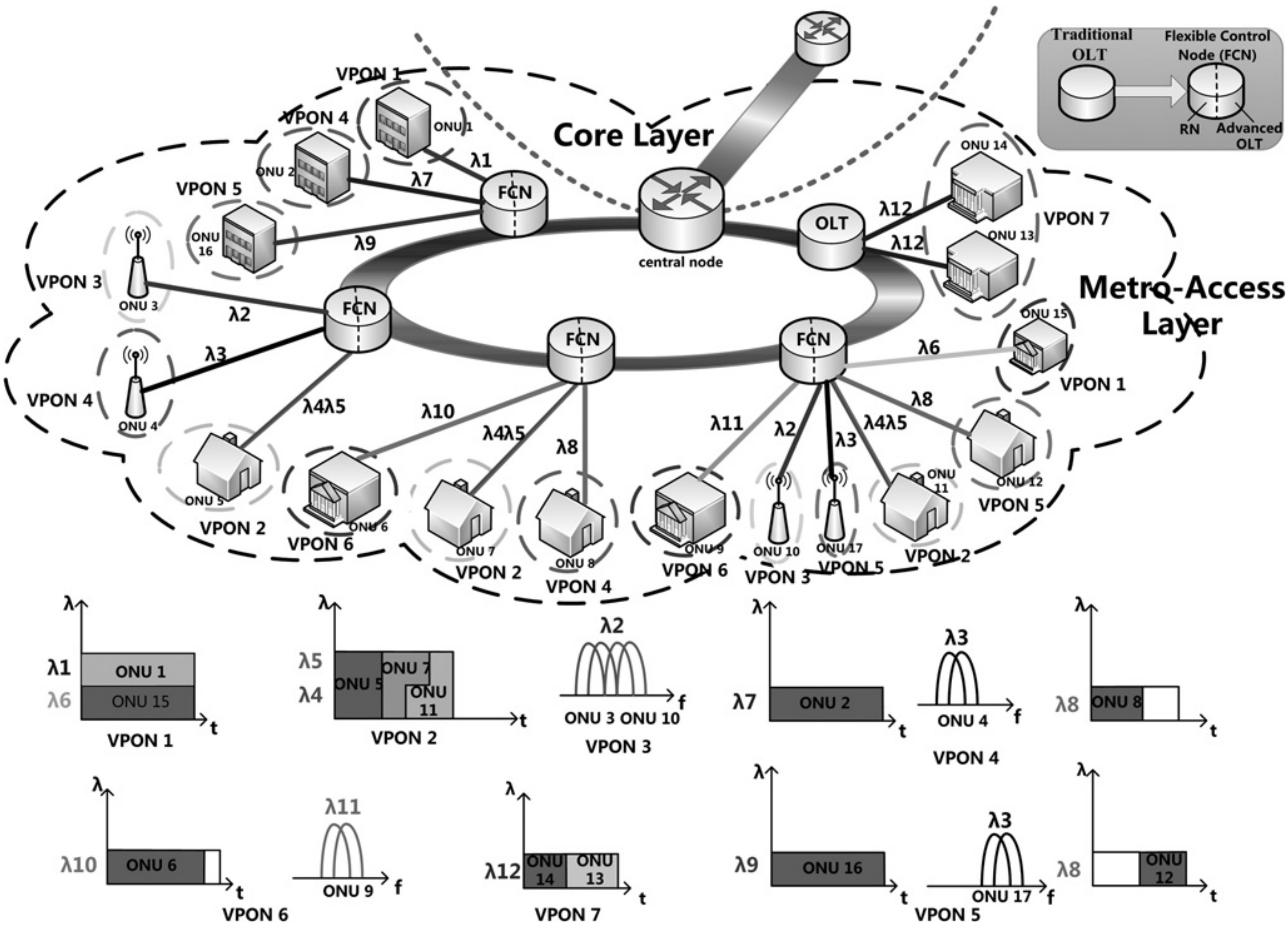

Fig. 1 *MS-VPON scenario*

the metro-access network is formed. The advanced OLTs are made up of adaptive transceivers, buffer and media access control (MAC) group. The adaptive transceivers have the capability to transmit and receive data streams in different subsystems such as TDM-PON and OFDM-PON. The MAC group can achieve the access control of these subsystems. According to the above, the syncretism of multiple subsystems can be realised. In a word, a VPON can be made up of multiple subsystems. The composition of each VPON is shown at the bottom of Fig. 1. Considering the representativeness of MS-VPON, VPON 4 is taken as an example to be illustrated here. As shown in Fig. 1, VPON 4 is consisted of three ONUs, i.e. ONU 2, ONU 4 and ONU 8. Among them, ONU 2 is served by wavelength λ_7 and thus it can be thought as a WDM-PON subsystem. ONU 4 is served by subcarrier of λ_3 and thus it can be thought as an OFDM-PON subsystem. ONU 8 is served by timeslot of λ_8 and thus it can be thought as a TDM-PON subsystem. Through the FCN that has the functions of RN and OLT, these three ONUs can be accessed to the network and controlled by the CN.

3 Bandwidth-allocated mechanism and its algorithm

As mentioned above, the centralised management is realised in the CN. Therefore, the bandwidth-allocated mechanism and its algorithm should be embedded in the CN as shown in Fig. 2. If a VPON has new demand, it will send requested information to the CN and it will gather the information to form a VPON information pool. Then, the mechanism and algorithm will be executed with the information taken from the information pool. For example, if a new VPON wants to be admitted, it will send related information to the CN. After that, the mechanism will be executed to allocate corresponding bandwidth to meet the demand of this new VPON. The detailed mechanism and algorithm are described as follows.

3.1 Admission condition of bandwidth allocation for VPON users

The bandwidth demand of VPON may change during network operation, which will result in bandwidth reallocation. However, frequent bandwidth reallocation is not desirable for any VPON [12]. Thus, a rational admission condition of bandwidth allocation for VPON users is needed to filter some non-necessary bandwidth demand. On this basis, the bandwidth allocation will be executed.

As mentioned before, a VPON can be made up of multiple subsystems. Its bandwidth demand should also consist of multiple resource granularity. The bandwidth demand of VPON i can be denoted by

$$\boldsymbol{d}_i = \begin{bmatrix} d_{i1} & d_{i2} & d_{i3} \end{bmatrix} \quad (1)$$

where $d_{ij}(j=1,\ 2,\ 3)$ is the VPON i's demand for wavelength, time slot and subcarrier, respectively.

To avoid frequent bandwidth reallocation, two thresholds (i.e. the low threshold η_1 and the high threshold η_2) and a matrix of bandwidth-demanded variation are defined. The matrix is given as follows

$$\boldsymbol{a}_i = \begin{bmatrix} a_{i1} & a_{i2} & a_{i3} \end{bmatrix} \quad (2)$$

where a_{ij} represents the change of d_{ij}. If d_{ij} compared with that in the previous round lies below η_1, the a_{ij} will be set to -1. It means d_{ij} has a significant decrease in bandwidth demand. If d_{ij} compared with that in the previous round lies above η_2, the a_{ij} will be set to 1. It means

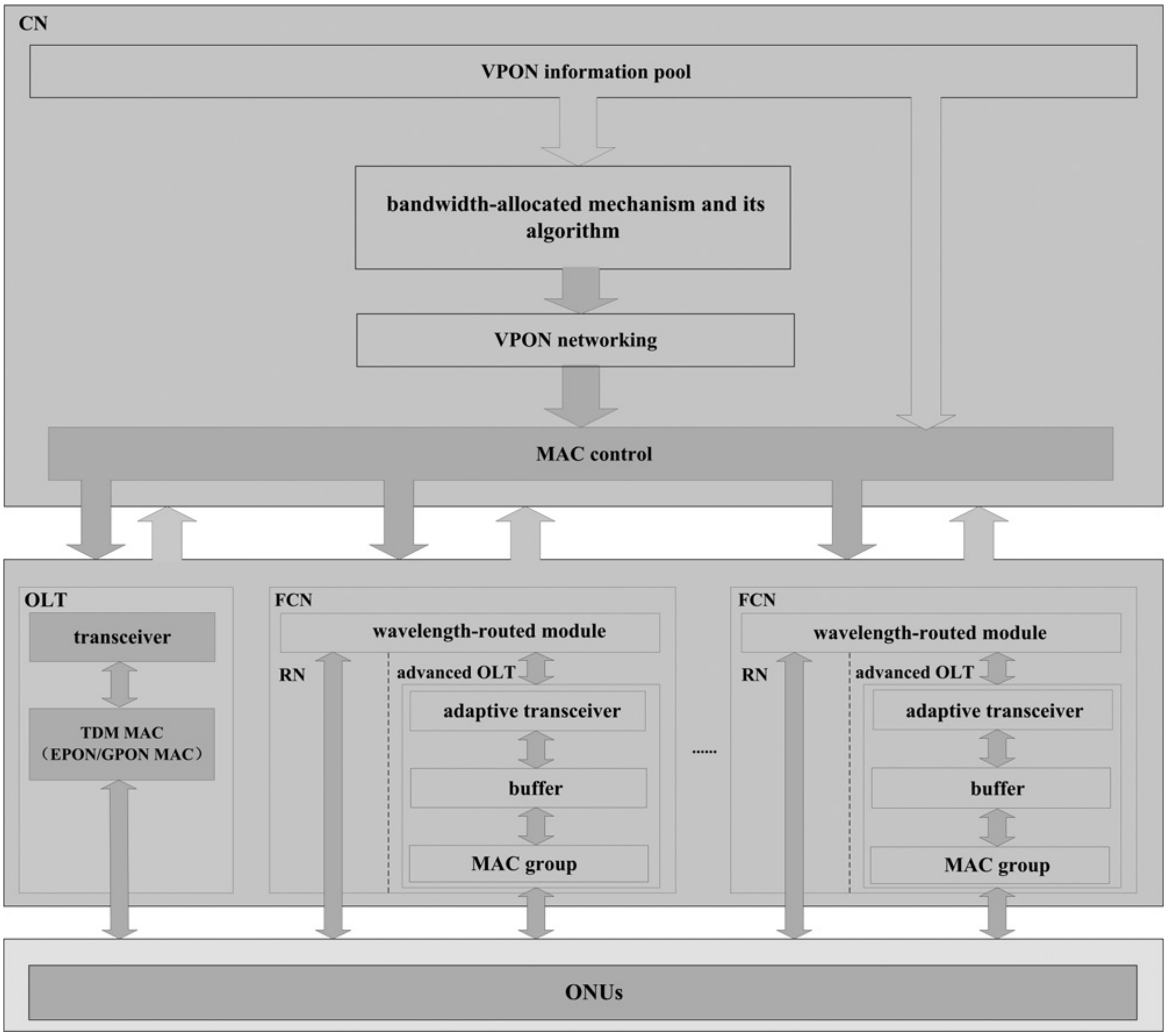

Fig. 2 *Programmable VPON architecture*

d_{ij} has a significant increase in bandwidth demand. Otherwise, we assume d_{ij} does not have a significant change in bandwidth demand. The a_{ij} will be set to 0. Then, a variable v_i is used to present whether VPON i needs to be reallocated or not. The value of v_i is given as follows

$$v_i = \begin{cases} 1, & |a_i| \neq 0 \\ 0, & |a_i| = 0 \end{cases} \tag{3}$$

where $v_i = 1$ means that VPON i needs to be reallocated. This indicates the bandwidth demand of VPON i has a significant change according to the norm of matrix $\boldsymbol{a}_i$. To present the situation of all VPONs, a matrix $\boldsymbol{V}$ is defined as follows

$$\boldsymbol{V} = [v_1\ v_2 \ldots v_q] \tag{4}$$

where v_i $(1 \le i \le q)$ is defined in formula (3) and q is the number of all VPONs. When the norm of matrix $\boldsymbol{V}$ is equal to 0, the bandwidth allocation will not be executed. Otherwise, it will be executed and bandwidth will be reallocated to VPON i when its v_i equals 1.

3.2 Bandwidth-allocated scheme

VPON has the capacity of reconfigurability and scalability [18, 22]. When the VPON is reconfigured or escalated, it will lead to the change of bandwidth demand. In the proposed MS-VPON, it means different bandwidth-demanded variations of multiple subsystems. To distinguish different bandwidth-demanded variations and allocate bandwidth fairly and efficiently for VPON, a bandwidth-allocated scheme is employed. As described in Section 3.1, the scheme will reallocate bandwidth to VPON i when $v_i = 1$.

First, to distinguish different bandwidth-demanded variations, according to the value of a_{ij}, $\boldsymbol{d}_i$ can be divided into three parts: demand-decreased part (DDP), demand-unchanged part (DUP) and demand-increased part (DIP). Thus, the formula (1) can be expressed as the sum of three sub-matrices as follows

$$\boldsymbol{d}_i = \boldsymbol{d}_i^1 + \boldsymbol{d}_i^2 + \boldsymbol{d}_i^3 \tag{5}$$

Each sub-matrix is corresponding to the DDP, DUP and DIP. To the first sub-matrix $\boldsymbol{d}_i^1$, it only represents bandwidth demand when a_{ij} equals −1. To the second sub-matrix $\boldsymbol{d}_i^2$, it only represents bandwidth demand when a_{ij} equals 0. To the last sub-matrix $\boldsymbol{d}_i^3$, it only represents bandwidth demand when a_{ij} equals 1. Therefore, if $a_{i1} = -1$, $a_{i2} = 0$ and $a_{i3} = 1$, the matrix $\boldsymbol{d}_i$ can be expressed as follows

$$\boldsymbol{d}_i = [\,d_{i1} \quad 0 \quad 0\,] + [\,0 \quad d_{i2} \quad 0\,] + [\,0 \quad 0 \quad d_{i3}\,] \tag{6}$$

The flowchart of the proposed bandwidth-allocated scheme is illustrated in Fig. 3. First, $\boldsymbol{d}_i$ is divided into three parts according to

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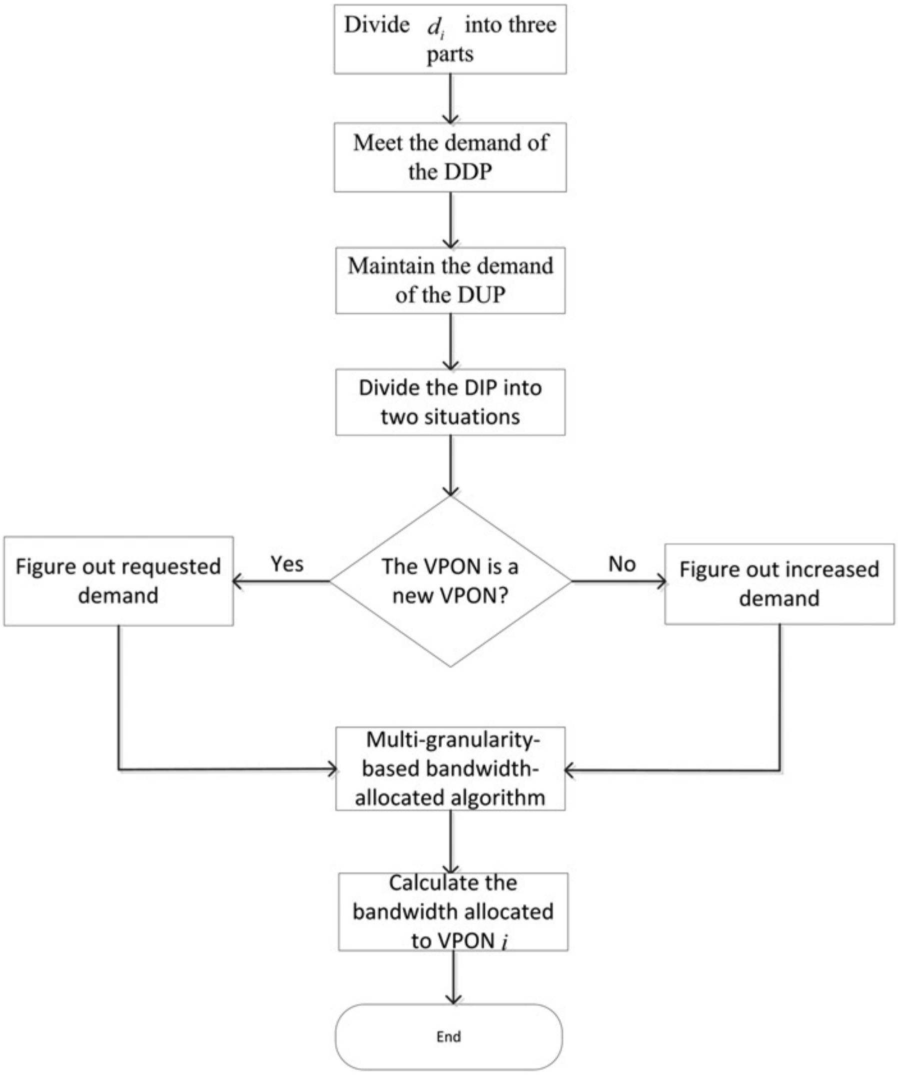

Fig. 3 *Flowchart of proposed bandwidth-allocated scheme*

the value of a_{ij}. These three parts are corresponding to the above three sub-matrices. Considering the fairness and efficiency of the bandwidth allocation, here, the demand of the DDP is first allocated because its bandwidth demand compared with that in the previous round is decreased and its excess bandwidth can be used by other VPONs. Then, the demand of the DUP is maintained. To the demand of the DIP, we need to figure out its available bandwidth first. The available bandwidth consists of two parts: one is the remaining bandwidth of the previous round and the other is the bandwidth released by the DDP. After calculating the available bandwidth, the demand of DIP needs to be divided into two situations according to the bandwidth demand belonging to original VPON or new VPON. If the demand belongs to the original VPON that has already existed in the previous round, we need to figure out its increased demand compared with the demand in the previous round. If the demand belongs to the new VPON that wants to be admitted, we only need to figure out its requested demand. Then, the multi-granularity-based bandwidth-allocated algorithm is proposed to allocate bandwidth to these two situations. Finally, the bandwidth allocated to VPON i equals the sum of the DDP, DUP and DIP.

3.3 Multi-granularity-based bandwidth-allocated algorithm

The bandwidth allocated to VPON i contains three parts as shown in Fig. 3. To the previous two parts (i.e. DDP and DUP), the bandwidth allocation is easy to implement. We only need to directly allocate the bandwidth according to the demand. However, to the last part (i.e. DIP), the bandwidth allocation is not easy to implement because of many factors involved in the multiple subsystems. Here, the multi-granularity-based bandwidth-allocated algorithm is proposed to promote the admission probability of new VPONs. To facilitate the illustration of the algorithm, several matrices are defined here. The matrix of available bandwidth is denoted as follows

$$\boldsymbol{S} = [\,s_1 \quad s_2 \quad s_3\,] \tag{7}$$

where $s_j(j = 1,\ 2,\ 3)$ represents the available number of wavelengths, time slots and subcarrier resources, respectively.

The matrix of remaining bandwidth after each VPON allocation is denoted as follows

$$\boldsymbol{T} = [\,t_1 \quad t_2 \quad t_3\,] \tag{8}$$

where $t_j(j = 1,\ 2,\ 3)$ represents the remaining number of wavelengths, time slots and subcarrier resources, respectively.

The matrix of VPON's requested (or increased) bandwidth is denoted as follows

$$\boldsymbol{R} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ \vdots & \vdots & \vdots \\ r_{n1} & r_{n2} & r_{n3} \end{bmatrix} \tag{9}$$

where n is the number of VPONs related to the DIP. $r_{kj}(1 \le k \le n, j = 1, 2, 3)$ represents VPON k's requested (or increased) bandwidth of wavelength resource, time slot resource and subcarrier resource, respectively. Each row of the matrix is sorted with descending order by VPON's priority. The priority of VPON (*VPON_pri*) is defined as the weighted sum of client priority (*Client_pri*) and service priority (*Service_pri*). The relational expression is given as follows

$$VPON\_pri = \omega_{\rm cli} \cdot Client\_pri + \omega_{\rm ser} \cdot Service\_pri \qquad (10)$$

where $\omega_{\rm cli}$, $\omega_{\rm ser}$ are the weights of client priority and service priority, respectively.

The matrix of new VPON's guaranteed bandwidth is denoted as follows

$$\boldsymbol{P} = \begin{bmatrix} p_{11} & p_{12} & p_{13} \\ p_{21} & p_{22} & p_{23} \\ \vdots & \vdots & \vdots \\ p_{m1} & p_{m2} & p_{m3} \end{bmatrix} \qquad (11)$$

where m is the number of new VPONs. $r_{hj}(1 \le h \le m, j = 1, 2, 3)$ represents VPON h's guaranteed bandwidth of wavelength resource, time slot resource and subcarrier resource, respectively. Each row of the matrix is also sorted with descending order by VPON's priority.

To facilitate the calculation, we can convert the requested bandwidth into the number of requested resource. Therefore, by the matrices $\boldsymbol{R}$ and $\boldsymbol{P}$, the matrices $\boldsymbol{N}$ and $\boldsymbol{G}$ can be gotten as follows

$$\boldsymbol{N} = \begin{bmatrix} n_{11} & n_{12} & n_{13} \\ n_{21} & n_{22} & n_{23} \\ \vdots & \vdots & \vdots \\ n_{n1} & n_{n2} & n_{n3} \end{bmatrix} \qquad (12)$$

$$\boldsymbol{G} = \begin{bmatrix} g_{11} & g_{12} & g_{13} \\ g_{21} & g_{22} & g_{23} \\ \vdots & \vdots & \vdots \\ g_{m1} & g_{m2} & g_{m3} \end{bmatrix} \qquad (13)$$

where $n_{kj} = r_{kj}/c_j$ and $g_{hj} = p_{hj}/c_j$. $c_j(j = 1, 2, 3)$ is the resource granularity of wavelengths, time slots and subcarriers, respectively.

The matrix of the number of resource finally allocated to VPON is denoted as follows

$$\boldsymbol{M} = \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ \vdots & \vdots & \vdots \\ m_{n1} & m_{n2} & m_{n3} \end{bmatrix} \qquad (14)$$

where $m_{kj}(1 \le k \le n, j = 1, 2, 3)$ represents the number of wavelengths, time slots and subcarrier resources finally allocated to VPON k.

The flowchart of multi-granularity-based bandwidth-allocated algorithm is illustrated in Fig. 4. First, the initial value of remaining bandwidth T is set as the available bandwidth S. Then, we need to sort the VPON's priority with descending order. The algorithm starts to allocate bandwidth according to the priority order. If the remaining bandwidth T can meet the demand of VPON k ($N(k, :)$, $N(k, :)$ presents the kth row of matrix $\boldsymbol{N}$), the algorithm will allocate bandwidth to VPON k according to its demand. Otherwise, it will check whether VPON k is a new VPON or not. If it is a new VPON, we then check whether the remaining bandwidth T can meet the demand of its guaranteed bandwidth ($G(h, :)$, if VPON k is a new VPON, h is the priority order of VPON k among m new VPONs). If the remaining bandwidth can meet the demand, the algorithm will allow the

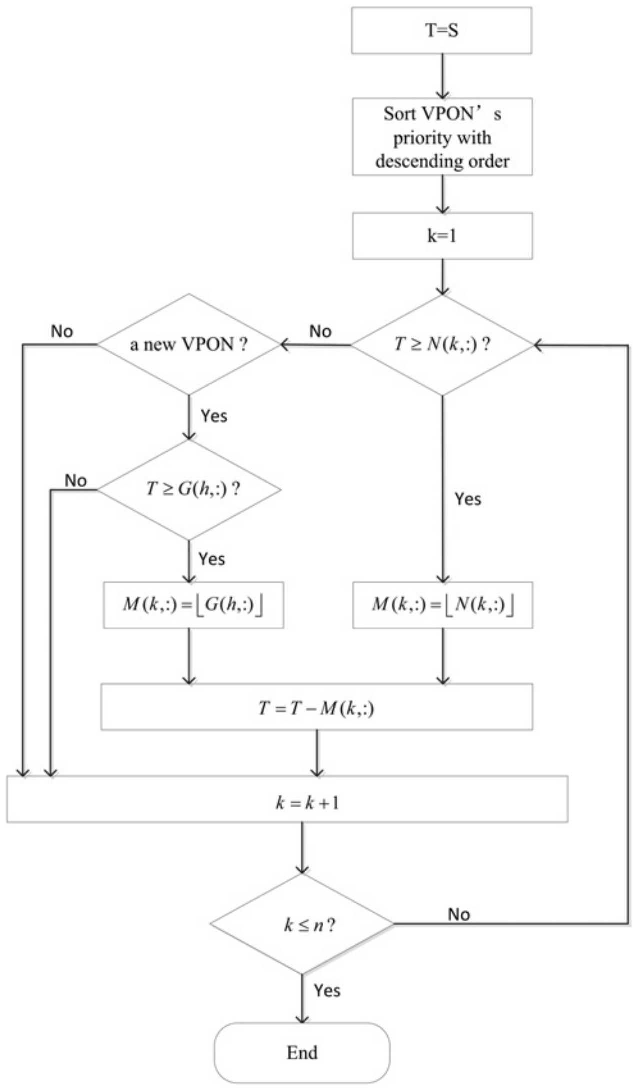

Fig. 4 *Flowchart of multi-granularity-based bandwidth-allocated algorithm*

admission of new VPON and allocate corresponding bandwidth. After each allocation, the remaining bandwidth T will be renewed. The algorithm will be over when all VPONs have been allocated. As shown in Fig. 4, this algorithm can promote the admission probability of new VPON because a new VPON can be immediately admitted as long as the remaining bandwidth is no less than its guaranteed bandwidth.

4 Performance evaluation

In this section, MATLAB is used to evaluate the performance of the bandwidth-allocated mechanism and its algorithm. To facilitate the illustration, $q = 10$ is taken as an example to demonstrate the effectiveness of the admission condition of bandwidth allocation for VPON users. In addition, several variables are defined here. For example, a variable z is defined to present execution state of the bandwidth allocation. When the norm of matrix $\boldsymbol{V}$ is zero, the variable z will be set to '0'. It means the bandwidth allocation will not be executed. Otherwise, the variable will be set to '1'. The corresponding bandwidth allocation will be executed. A variable ρ is used to present the load of VPON as follows

$$\rho = \frac{\sum_{i=1}^{n} \sum_{j=1}^{3} n_{ij} \cdot c_j}{\sum_{j=1}^{3} s_j \cdot c_j} \qquad (15)$$

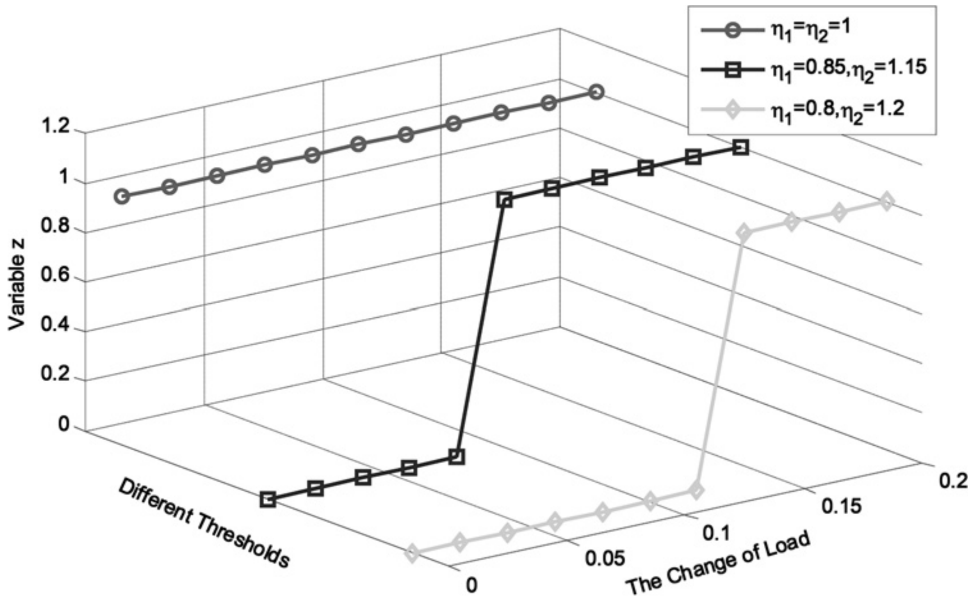

Fig. 5 *Variable z against the change of load under different thresholds*

A variable μ is defined to present the bandwidth-utilised ratio. It can be derived from the following formula

$$\mu = \frac{\sum_{i=1}^{n} \sum_{j=1}^{3} m_{ij} \cdot c_j}{\sum_{j=1}^{3} s_j \cdot c_j} \tag{16}$$

A variable f is defined to present utility ratio. The utility ratio is the rate of two types of bandwidths (i.e. bandwidth allocated to VPON and bandwidth requested by VPON). It is given as follows

$$f = \frac{\sum_{i=1}^{n} \sum_{j=1}^{3} m_{ij} \cdot c_j}{\sum_{i=1}^{n} \sum_{j=1}^{3} n_{ij} \cdot c_j} \tag{17}$$

Finally, the bandwidth-allocated scheme and algorithm can be evaluated from three aspects: the bandwidth-utilised ratio, the utility ratio and the admission probability.

Fig. 5 plots the value of variable z under different thresholds. Here, the change of load ($\Delta\rho$, $0 < \Delta\rho < 1$) is used to present the change of VPON's bandwidth demand. As shown in Fig. 5, when $\eta_1 = \eta_2 = 1$, the variable is always '1'. The bandwidth allocation will be executed as long as the load changes. When $\eta_1 = 0.85$ and $\eta_2 = 1.15$, the bandwidth allocation will not be executed until the change of load is above 0.08. Thus, the influence of bandwidth-demanded fluctuation can be eliminated and frequent bandwidth reallocation can be avoided. Specially, this effect is more obvious when $\eta_1 = 0.8$ and $\eta_2 = 1.2$.

The bandwidth-utilised ratio of the proposed scheme and algorithm is depicted in Fig. 6. Here, we assume only four VPONs among all ten VPONs need to be reallocated. The previous two VPONs are assumed as original ones. The other two are assumed as new VPONs. The priority of new VPON is lower than that of original VPON. The resource granularity of wavelength, time slot and subcarrier is 1 Gb/s, 2 Mb/s and 4 Mb/s, respectively. In addition, the bandwidth demand of VPON is characterised by the

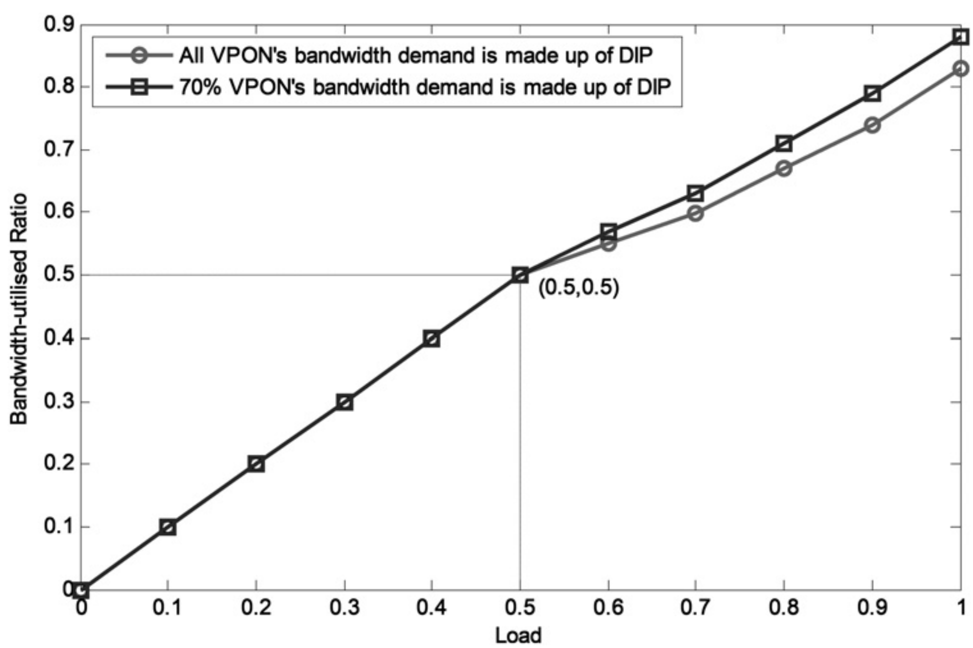

Fig. 6 *Bandwidth-utilised ratio against load*

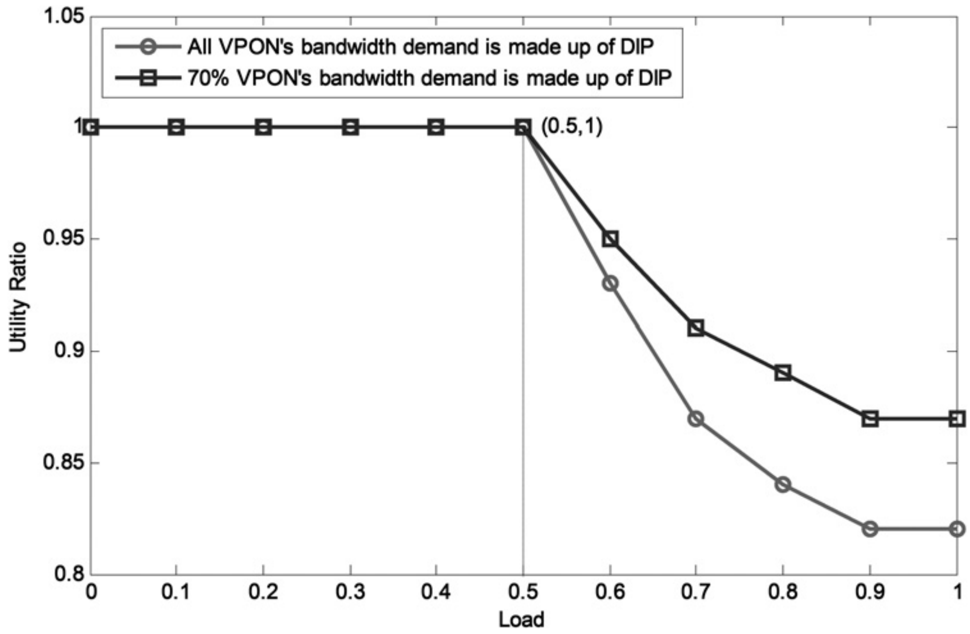

Fig. 7 *Utility ratio against load*

load of VPON (i.e. ρ). As shown in Fig. 6, the bandwidth-utilised ratio is proportional to the load when the load is below 0.5. However, when the load is above 0.5, the bandwidth-utilised ratio is not proportional to the load. This is because when the load is low, the demand of VPON can be fully met. However, as the load increases, the demand of VPON cannot be fully met. At this time, the demand of high-priority VPON will be met first. Thus, the bandwidth allocated to low-priority VPON cannot be guaranteed. In other words, the remaining bandwidth may not meet the demand of low-priority VPON due to the lack of proper bandwidth resource that the low-priority VPON really needs. For example, a low-priority VPON needs wavelength resource, while the remaining resource only has time slot or subcarrier resource. This will significantly decrease the bandwidth-utilised ratio. In addition, the bandwidth-utilised ratio of diamond legend line is higher than that of the circle legend line. The reason is 30% of the bandwidth demand is made up of the DDP and the DUP. Therefore, the bandwidth released by the DDP can be utilised by the DIP. This will make more bandwidth belong to the DIP.

The utility ratio of the proposed scheme and algorithm is depicted in Fig. 7. The utility ratio is always '1' when the load is below 0.5. It means the demand can always be met. This result consists with that in Fig. 6. When the load increases from 0.5 to 0.9, the utility ratio decreases dramatically because the bandwidth cannot fully meet the demand of VPON. However, when the load is above 0.9, the utility ratio is almost unchanged because the remaining bandwidth can only ensure the guaranteed bandwidth of new VPON instead of fully meeting its demand. In addition, the utility ratio of the diamond legend line is higher than that of the circle legend line. The reason is 30% of the bandwidth demand is made up of the DDP and the DUP. This demand will be fully met as mentioned in Section 3.2. Obviously, the utility ratio of the whole VPON will be elevated.

To better evaluate the admission probability of new VPON, all four VPONs are supposed as new VPONs here. The admission

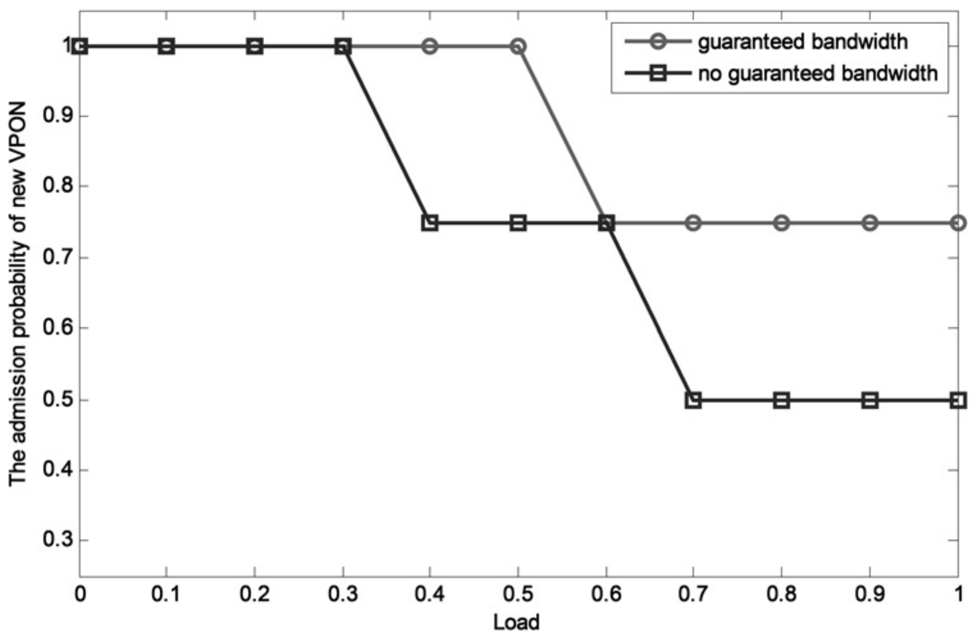

Fig. 8 *Admission probability of new VPON against load*

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probability of new VPON is depicted in Fig. 8. As presented in Fig. 8, if the guaranteed bandwidth is used, the admission probability is always '1' when the load is below 0.5. However, as the load increases, the admission probability is decreased to 0.75. If the guaranteed bandwidth is not used, the admission probability is reduced to 0.75 when the load is from 0.4 and 0.6. When the load is above 0.6, the admission probability is further decreased to 0.5, i.e. half of the VPONs cannot be admitted in this situation. This is because without guaranteed bandwidth, these new VPONs can only be admitted when the demand is fully met. However, to the situation of having guaranteed bandwidth, these new VPONs can be immediately admitted as long as the remaining bandwidth is no less than their guaranteed bandwidth. Therefore, to these new VPONs, using guaranteed bandwidth is obviously an effective solution to improve their admission probability. As shown in this figure, the admission probability of using guaranteed bandwidth is higher than that of not using guaranteed bandwidth, especially in the high-loaded situation. For example, the admission probability shows an improvement of 25% when the load is above 0.6.

5 Conclusion

Bandwidth-allocated mechanism and its algorithm for MS-VPON in MAON are proposed in this paper. To the MS-VPON scenario, the programmable VPON architecture is designed. As the significant part of MS-VPON in MAON, the bandwidth-allocated mechanism is established and its algorithm is proposed. According to the mechanism, the admission condition of bandwidth allocation for VPON users can be constructed to avoid frequent bandwidth reallocation. The different bandwidth-demanded variations of multiple subsystems can be distinguished. The bandwidth requested by VPON can be allocated fairly and efficiently. The admission probability of new VPON can be promoted. The simulation results demonstrate the effectiveness of the bandwidth-allocated mechanism and its algorithm.

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