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A Dynamic Restructuring Algorithm Based on Flexible PON Slices

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Abstract: In recent years, with the introduction of the concept of the Internet of Things, a large number of terminals connected to the network, the pressure of network bandwidth is increasing. The bandwidth resources wasted by the traditional fixed access network architecture have attracted more and more attention of researchers. In order to meet the different needs of different users for service quality and improve the flexibility of network, network slicing technology arises at the right moment. Based on the slicing idea of the flexible time- and wavelength-division multiplexing passive optical network (TWDM-PON), a dynamic PON slice restructuring algorithm (DRA) is proposed in this paper. The proposed algorithm avoids the influence of previous slicing on subsequent slicing in the step-by-step slicing process, slices at the global level, and is less affected by the randomness of initialization. The simulation results show that the performance of DRA is about 10∼30% higher than that of the dynamic optical network units (ONUs) grouping algorithm (DGA) and the dynamic ONU slicing algorithm (DONUSA) when there are 8 OLTs, and is about 30% higher than that of DGA and 10% higher than that of DONUSA when there are 16 OLTs. Therefore, the proposed DRA has more positive significance to relieve the traffic pressure in the increasingly tight bandwidth resources.

Keywords: passive optical network; network slicing; software defined network; traffic dredging

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1. Introduction

The increasing demand for networks has caused great pressure on the networks since the 21st century [1]. The PON has shown great superiority in improving network speed and became one of the main technologies of access networks [2]. Subsequently, at the full-service access network (FSAN) meeting in April 2012, TWDOM-PON was selected as the primary technology for next generation passive optical network stage 2 (NG-PON2) due to its strong scalability [3]. Furthermore, the implementation details and key technologies of TWDM-PONs were verified in the following year. However, in recent years, with the rise of the Internet of Things (IoT)/Internet of Underwater Things (IoUT), and the proposal of the "Internet of Everything" concept, a large number of terminals are connected to the network, and different types of terminals (e.g., underwater terminals, smart farming terminals, etc.), which have different requirements for network reliability, delay, and other indicators [4–8]. The 3GPP classifies the scenarios for next-generation access technologies as follows: Enhanced Mobile Broadband (eMBB), Massive Machine Type Communication (mMTC), and Ultra-Reliable Low-latency Communication (uRLLC) [8]. In order to meet the diversified business needs of users and vertical industries, relieve the network pressure, and improve the intelligence and flexibility of the network, the concept of network slicing was put forward [9,10]. Network slicing divides the underlying physical network into multiple logical slices that adapt to different scenarios to achieve network as a service.

In recent years, studies on slicing technology have emerged in an endless stream. Network slicing technology was first proposed for resource classification management in end-to-end transmission networks [11–13]. In the process of constructing virtual network slices and providing dedicated protection in Fifth generation (5G) transmission networks, Nashid et al. introduced bandwidth compression and multipath supply to reduce the backup resources required for dedicated protection, which not only divided the virtual links' demand on the multipath, but also divided the virtual links' demand on multiple spectrum segments on one path, greatly saving spectrum resources [11]. Muhammad et al. proposed a dynamic slicing method for an optical transmission network by applying mixed integer linear programming and the heuristic algorithm, which reduced the rejection probability of virtual network slicing by more than one order of magnitude at the cost of a little service degradation [12]. Yin et al. proposed an end-to-end dynamic slicing scheme based on prediction in Fi-Wi networks, which uses a double exponential smoothing algorithm to predict traffic in advance, and allocates resources for multiple slices according to the predicted results [13]. Later, with the deepening and expansion of research, the outstanding characteristics of network slicing technology in flexible resource management have also been considered in access networks, including wireless access networks [14,15] and fiber access networks [16,17]. Domenico et al. proposed a scheme to deploy virtual network function (VNF) chains with heterogeneous requirements in mixed cloud infrastructure, which greatly improved the efficiency of resource utilization and the success rate of VNF chain deployment [14]. Oriol et al. proposed four possible slicing schemes for Radio Access Networks (RANs) for the problem of cutting radio resources, and analyzed their advantages and disadvantages as well as applicable scenarios [15]. Kunitaka et al. proposed a dynamic slicing method for an active optical access network, which can guarantee quality of service (QoS) requirements of each user of the access network based on the QoS level of the core network [16]. Hiroyuki et al. proposed a dynamic bandwidth allocation scheme for a time-division multiplexing passive optical network (TDM-PON). The scheme integrates the characteristics of 5G fronthaul and IoT, and can provide guaranteed bandwidth for each slice on the premise of meeting the delay requirements of fronthaul [17]. In addition, some studies have considered the fusion scenario of fiber access and wireless access, such as the Fi-Wi access. Tian et al. proposed a slicing scheme based on LSTM neural network prediction in elastic optical access networks, which not only has higher prediction accuracy than traditional algorithms, but also can adjust the slicing boundaries in advance to offset the delay of moving resource boundaries when resources are scarce [18]. Slicing technology is favored by researchers of various components of the network. In recent years, the hybrid communication scenario with multiple slicing technologies has also become one of the key research directions [19].

Although the slicing technique is widely used at present, there are few studies in the access network scenario with multiple OLTs. This study mainly focuses on network slicing technology on large campuses with multi-OLT centralized deployment. In order to make full use of the exchange capability of OLTs and relieve the traffic pressure of the access network, there have been some excellent studies [20,21]. Zhang et al. proposed a dynamic optical network units (ONUs) grouping algorithm (DGA) based on centralized flexible PON to reduce the outbound traffic of optical line terminals (OLTs) and relieve the traffic pressure of the core network. DGA divides all nodes into two parts in each iteration to calculate the optimal allocation scheme, and deletes nodes in one part after that. The remaining nodes are then divided into two parts to calculate the optimal allocation scheme, and so on until all nodes are deleted [20]. However, DGA does not make further selection when the node switch gain is equal to 0 in each graph cutting, which will affect the subsequent graph cutting and may miss some better results. Therefore, another dynamic ONU slicing algorithm (DONUSA) was proposed in [21], which not only achieves a better traffic gain in the case of a large number of OLTs and ONUs under each OLT, but also has lower complexity. However, the performance of DONUSA is affected by the number of devices. Considering that the problems of DGA are caused by multi-step iteration, a new dynamic restructuring algorithm (DRA) is proposed in this paper, which directly divides the graph into subgraphs of the target number and puts all the cyclic calculations and operations in a one-step iteration. In this way, the influence of the previous node selection and exchange process on all the subgraphs will be considered in the next calculation. Simulation results show that DRA can obtain a better traffic gain than DGA and DONUSA, which indicates that the proposed DRA has more positive significance to relieve the traffic pressure.

The rest of the paper is organized as follows: Section 2 introduces the access network architecture used in this paper and models the dynamic slicing problem based on the system architecture. Section 3 displays the proposed algorithm and the parameters used in the algorithm. Then in Section 4, the simulation conditions and the performance index of the algorithm are given, and the simulation results are preliminarily summarized. In Section 5, the reasons for the simulation results are explained and our future research direction is summarized. Finally, Section 6 is the summary of the full text.

2. Architecture and Network Model

The centralized flexible PON architecture is shown in Figure 1. Multiplexers/demultiplexers and an optical connection matrix consisting of WSS or AWG are deployed at the local end to form a flexible optical distribution network (ODN) with the existing traditional ODN, and tunable lasers are added to the ONUs. Each splitter can receive signals from different OLTs through the flexible ODN, and ONUs can change the wavelength used. Therefore, the affiliation between ONUs and OLTs becomes dynamically tunable and a method of traffic grooming is considered; allocate the ONUs with high communication traffic between each other to the same OLT, so that the traffic transmitted across different PON trees can be converted to the same PON tree as much as possible. In this way, the incoming traffic to the core network can be reduced and the bandwidth resources of the core network can be saved.

A PON tree is abstracted as a virtual slice, so the internal communication of the PON tree is the traffic within the slice, and the traffic that needs to be transmitted through the core network is the traffic between slices. The whole dynamic adjustment process is controlled by the Software Defined Network (SDN) controller. The SDN controller firstly obtains the communication traffic relationship among all ONUs through the Mac table of the OLT, and then finds an allocation scheme that minimizes the traffic between slices. Finally, according to the calculation results, the controller sends adjustment instructions to the OLT through the southbound interface to adjust the affiliation between ONUs and OLTs.

Since the traffic between users changes over time, the current affiliation may not be optimal after a while, which will result in a waste of core network bandwidth. Therefore, a criterion is need to be set in actual scenarios, such as a time period or OLT outbound traffic threshold. When this condition is met, the SDN controller recalculates and allocates the affiliation between OLTs and ONUs to reduce the traffic to the core network.

Considering the factor that influences the bandwidth of the core network is the value of traffic between ONUs, rather than the direction of the traffic, the access network scenario is defined as an undirected graph $G(V,E)$. As shown in Figure 2, each ONU represents a node in V, each edge in E represents the communication between two ONUs, and the weight of the edge represents the traffic between the two ONUs. Since each ONU belongs to and can only belong to one OLT, the nodes corresponding to ONUs belonging to one OLT are classified as a subset. Suppose there are M OLTs in the scene, then there are M subsets, which do not intersect each other and together form the set V. At the same time, the nodes and the traffic between them in each subset together form a subgraph. Therefore, the problem of ONU regrouping in a centralized flexible PON is transformed into dividing the $G(V,E)$ into M subgraphs G_i $(i = 1,2 \ldots M)$, and the goal of minimizing the traffic into core network is transformed to minimize the sum of edge weights between M subgraphs.

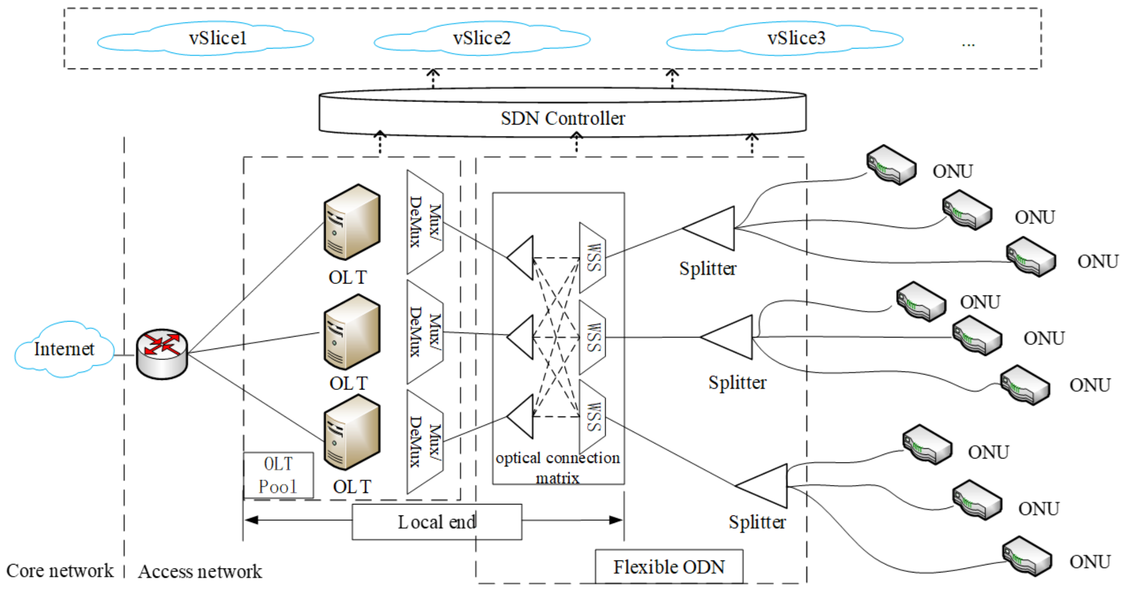


Figure 1. Centralized flexible PON architecture.

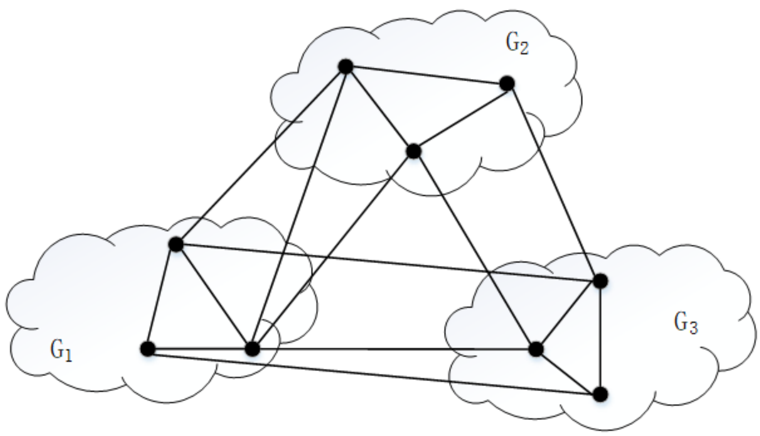


Figure 2. Network model

3. Proposed Algorithm

Based on the above model, a dynamic restructuring algorithm is proposed for the case when the number of OLTs is greater than 2 (that is, the number of subgraphs is greater than 2). At the beginning of the algorithm, the $G(V,E)$ is divided into subgraphs of the target number, and the following calculation and adjustment operations are carried out simultaneously for all subgraphs. In this way, in the subsequent calculation, the changing traffic between subgraphs caused by node exchange after each calculation will be considered, and finally a global optimal solution will be obtained. In order to facilitate the description of the proposed algorithm flow, first, the definitions of various parameters used in the algorithm are given. These parameters are shown in Table 1.

Where $N = M \times K$, and the edge weight matrix E satisfies the following conditions:

$$E(i,j) = \begin{cases} E(j,i) & i \neq j \\ 0 & i = j \end{cases} \tag{1}$$

In addition, since $E(i, i) = 0$ when calculating the traffic between i and itself. Therefore, $TT(i, X)$ can be calculated as follows regardless of whether i is in subgraph X:

$$TT(i, X) = \sum_{j \in G_X} E(i, j) \tag{2}$$

Table 1. Algorithm parameters.

Parameters	Definitions
N	Total number of ONUs/Number of nodes in $G(V,E)$
M	Total number of OLTs/Number of subgraphs to be divided
K	Number of ONUs of each OLT/Number of nodes in each subgraph
$E(i,j)$	Traffic between ONUi and ONUj/Edge weight between nodes i and j
$TT(i,X)$	Traffic between node i and subgraph X
$Gex(i,j)$	Traffic gain after swapping nodes i and j

$Gex(i,j)$ is defined as the reduction in the total edge weights between M subgraphs after two nodes are swapped. Since our algorithm initially divides $G(V,E)$ into subgraphs of the target number, the traffic gain after swapping any two nodes is related to the subgraphs they belong to. Assuming that node i belongs to subgraph X and j belongs to subgraph Y, then $Gex(i,j)$ can be calculated as follows:

$$Gex(i, j) = TT(j, X) + TT(i, Y) - TT(j, Y) - TT(i, X) - 2E(i, j) \tag{3}$$

According to the definition of $Gex(i,j)$, if all the $Gex(i,j)$ between any nodes in the whole undirected graph $G(V,E)$ are less than or equal to 0, it indicates that any exchange of two nodes will no longer result in the reduction of the total edge weights between subgraphs. Therefore, the proposed DRA sets it as the algorithm end decision condition.

Figure 3 shows the flow of the algorithm. The SDN controller firstly obtains the communication relationship between all ONUs through the MAC table of OLTs, and generates the traffic relationship matrix E between them. Then, it divides all ONUs into M subgraphs, and each subgraph has K nodes. It should be noted that, in real life, all ONUs have been configured before the controller obtains information, and the current OLT to which it links to can be known. The initial state is M subgraphs. Therefore, there are two methods for the SDN controller to divide all ONU nodes into M subgraphs. One is to directly use the obtained M subgraphs as the initial state to calculate, the other is to disarrange all the nodes and randomly generate M subgraphs as the initial state. Due to the randomness of the arrival of new traffic, the initial state of the two methods is essentially random and both can be used. However, the former is recommended to be used because it does not need to re-randomize, which can reduce the amount of computation of the controller and save computing resources. After $G(V,E)$ is divided into M subgraphs, the controller calculates the $Gex(i,j)$ of any two nodes in all the M subgraphs and swaps the two nodes with the largest $Gex(i,j)$ until all $Gex(i,j)$ are less than or equal to 0. The subgraph to which the two nodes swapped in each loop belong is not immutable. Finally, the SDN controller converts the calculated results into instructions using the Openflow protocol and sends them to OLTs, and OLTs inform ONUs to switch wavelength for slice reorganization.

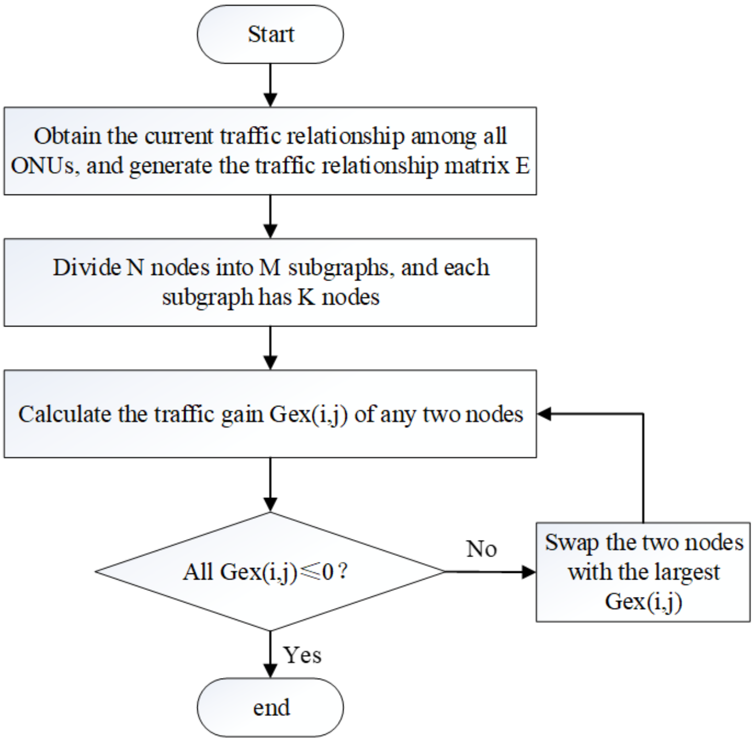


Figure 3. The flow of DRA

4. Results and Analysis

Considering the application of the actual scenario, this paper conducts a simulation based on the P2P communication model, and chooses the BA scale-free network which is closest to the actual complex network as the basic network model. In this section, the proposed DRA in this paper, DGA in [20], and DONUSA in [21] are simulated and their performance is compared. In view of the clustering characteristics of nodes, the Clustering Coefficient (CC) of the network is set at 0.4 in the generation of network. After the communication relationship between all nodes is determined, Poisson distribution is used to generate the initial traffic in each link. Considering the different arrival rates of users over different time periods, the eigenvalue λ is set at 40 Mbps and 80 Mbps, respectively, to test its impact on the performance of the algorithms.

Since the number of ONUs that belong to one OLT depends on the number of PON ports on OLTs and the bandwidth resources, different manufacturers and different loads cause diverse K. So the number of ONUs (N) and the number of OLTs (M) are not the same in different campuses. The simulation takes into account the following factors:

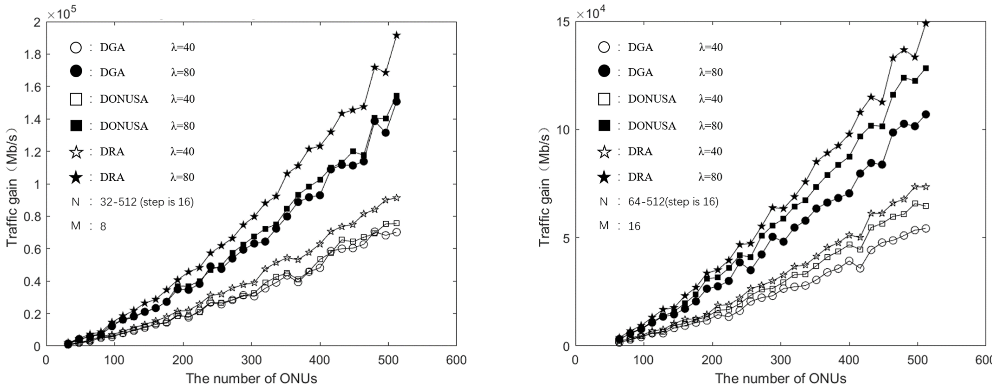
- DRA is proposed to solve the influence of previous steps on subsequent slicing when the number of OLTs is greater than 2. Therefore, the number of OLTs is set at 8 and 16 to test the influence of the number of OLTs on the performance.
- The performance of DONUSA fluctuates when the number of nodes in the initial subgraph is too small [21]. In order to better compare the performance of the three algorithms, the number of nodes (K) in each subgraph is increased from four.
- With the expansion of large campuses in the future, the number of ONUs will increase. To verify the effectiveness of the algorithm in the process when the number of ONUs increases, the number of ONUs is set to grow to 512.The growth interval depends on the number of OLTs in different scenarios.

Based on the above parameters, the traffic gain of the three algorithms is simulated, and the performance improvement percentage of DRA compared with DONUSA or DGA is calculated. The traffic gain is defined as the reduced value of cross-OLT traffic after running the algorithm compared with the cross-OLT traffic randomly grouped before running the algorithm, that is, the bandwidth resources saved for the core network. Furthermore, the percentage of performance improvement is calculated as follows (Imp_{DGA} is used to represent the improved performance of DRA compared to DGA, Imp_{DONUSA} is used to represent the improved performance of DRA compared to DONUSA, TG is used to represent the flow gain of the algorithm):

$$Imp_{DGA} = \frac{TG_{DRA} - TG_{DGA}}{TG_{DGA}} \tag{4}$$

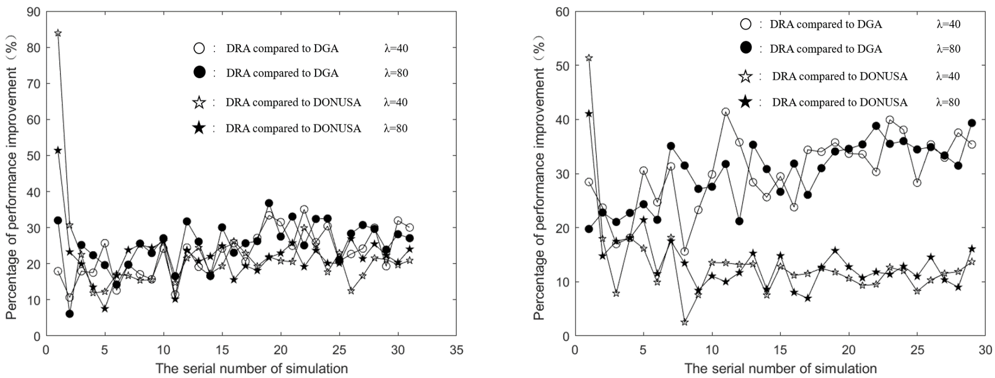
$$Imp_{DONUSA} = \frac{TG_{DRA} - TG_{DONUSA}}{TG_{DONUSA}} \tag{5}$$

Figure 4 shows the traffic gain of 3 algorithms with 8 and 16 OLTs, and Figure 5 shows the improved performance of DRA compared to DGA and DONUSA with 8 and 16 OLTs. Hollow nodes are results at λ = 40 Mbs, and the solid nodes are results at λ = 80 Mbs.



(**a**) (**b**)

Figure 4. (**a**) Traffic gain of three algorithms with 8 OLTs; (**b**) traffic gain of three algorithms with 16 OLTs.



(**a**) (**b**)

Figure 5. (**a**) Improved performance of DRA compared to DGA and DONUSA with 8 OLTs; (**b**) improved performance of DRA compared to DGA and DONUSA with 16 OLTs.

In Figure 4, the circle nodes represent the traffic gain of DGA, the square nodes represent the traffic gain of DONUSA, and the pentagram nodes represent the traffic gain of DRA. In Figure 5, the circle nodes are the improved performance of DRA compared to DGA, and the pentagram nodes are the improved performance of DRA compared to DONUSA. It can be seen that under the above simulation conditions, DRA has achieved the highest traffic gain. When there are 8 OLTs, the improved performance of DRA compared to DGA and DONUSA are similar, which are roughly between 10% and 30%. When there are 16 OLTs, the performance of DRA is about 30% higher than that of DGA, and about 10% higher than that of DONUSA. You might notice that DRA achieves a much higher performance than DONUSA in the first experiment, this is because when N = 32, M = 8 or N = 64, M = 16, the number of nodes in each subgraph (*K*) is only 4 and DONUSA is greatly affected by the randomness of initialization when the number of nodes in each subgraph is small. Only with the increase in the number of ONUs can the performance of DONUSA be gradually stabilized [21].

In addition, in order to test the influence of the number of subgraphs on the performance of the algorithms, the number of ONUs is set at 512 and the simulation is carried out for the case of a varying number of OLTs (4, 8, 16, 32, 64, 128, 256). As shown in Figure 6, DRA also achieves better performance than DGA and DONUSA under different OLT numbers.

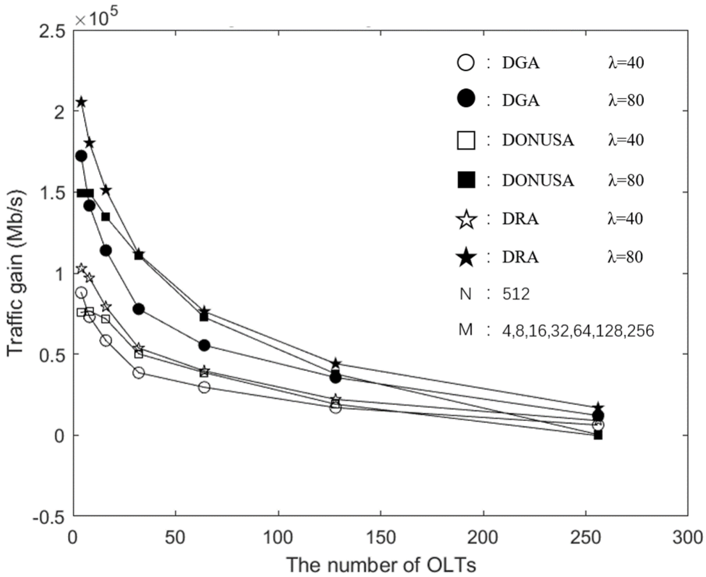


Figure 6. The traffic gain of 3 algorithms with 512 ONUs.

5. Discussion

The reason why the DRA algorithm can achieve a high performance is that DGA only divides the graph into two subgraphs in each iteration, and deletes a subgraph after calculation and exchange is completed. The initial graph of each dichotomy is the remaining node after deleting the subgraph in the previous step, which ignores the effect of the results of previous partitions on subsequent partitions. (For example, assuming that the node switch gain of two nodes *i* and *j* is 0, the initial graph with *i* or *j* in the next iteration will yield different results). Therefore, the result of each iteration is a locally optimal solution rather than a globally optimal solution. Reviewing the DRA, it divides the whole graph into M subgraphs at the beginning, and then calculates for all nodes. At the same time, the changes of traffic by exchanging two nodes of two subgraphs are reflected on at the global level, and will be taken into account in the next calculation of exchange gain. During the whole process, there is no need to delete the subgraph and all nodes are considered in each calculation. In this way, not only is the problem of ignoring the influence of previous steps in multiple partitions solved, but also the global optimal solution is obtained. Therefore, DRA algorithm can achieve a higher performance than DGA. Compared with DONUSA, the result of DRA is the optimal solution at the global level, which is not affected by randomness of initialization. Therefore, DRA has better performance and is more stable than the DONUSA algorithm.

As can be seen from Figure 4, the DRA algorithm still achieves higher performance as the number of ONUs increases. In addition, it can also be seen from Figure 5 that with the increase in the number of ONUs, the improved performance of DRA algorithm compared to the existing algorithm is maintained between 10% and 30%. These results indicate that the proposed DRA algorithm has good expansibility and stability. With the deepening and popularization of 5G technology in the future, the expansion of the network will require more network terminals. In this case, the proposed DRA algorithm with strong scalability and stability will have better application value.

In addition, the DRA algorithm is implemented on the SDN controller, and the calculated results need to be transmitted to the basic network infrastructure through the southbound interface and make some corresponding adjustments. So the whole communication process is based on software-defined network technology, which is the core technology of 5G. Therefore, the proposed DRA algorithm is applicable to all multi-OLT-based access networks that support software-defined technology, and has a very broad application prospects and scope.

Considering that there may be some differences between the simulation conditions and the actual scene, we will deploy the algorithm on the actual optical access network experiment platform for real scene verification in the subsequent research, so as to ensure the effectiveness of the algorithm in practice. We will also add more different scenarios and factors during the verification process. In addition, the algorithm is deployed in the SDN controller at the local end, which may cause the communication compatibility issues between the SDN controller and the existing network infrastructure. For example, in the actual application process of the algorithm, the existing network infrastructure needs to be upgraded to support the Openflow protocol. At the same time, the existing Openflow protocol should be extended to include instructions that can control the dynamic slicing process of the existing network infrastructure. Therefore, how to extend the Openflow protocol based on the results of this algorithm is also one of the future research directions. Furthermore, we will also consider adding the corresponding authorization mechanism in the SDN controller.

6. Conclusions

In this paper, a dynamic PON slice restructuring algorithm based on flexible PON architecture is proposed. The proposed algorithm avoids the influence of previous steps on subsequent steps by directly dividing the graph into subgraphs of the target number and regrouping them at the global level. In addition, since the decision condition is that the exchange gain of any two nodes in all subgraphs is less than 0, DRA is less affected by the randomness of initialization and has more stable performance. The simulation results show that compared with DGA and DONUSA, the proposed DRA has better performance and stability. Specifically, the performance of the proposed algorithm is about 10∼30% higher than that of DGA and DONUSA in the case of 8 OLTs. Furthermore, in the case of 16 OLTs, the performance of the proposed algorithm is about 30% higher than that of DGA and 10% higher than that of DONUSA.

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Abbreviations

The following abbreviations are used in this manuscript:

PON	Passive Optical Network
TWDM-PON	Time- and Wavelength-Division Multiplexing Passive Optical Network
ONU	Optical Network Units
OLT	Optical Line Terminal
DRA	Dynamic PON Slice Restructuring Algorithm
DGA	Dynamic ONU Grouping Algorithm
DONUSA	Dynamic ONU Slicing Algorithm
IoT	Internet of Things
IoUT	Internet of Underwater Things
eMBB	Enhanced Mobile Broadband
mMTC	Massive Machine Type Communication
uRLLC	Ultra-Reliable Low-latency Communication
QoS	Quality of Service
VNF	Virtual Network Function
RAN	Radio Access Network
LSTM	Long-Short Term Memory
ODN	Optical Distribution Network
SDN	Software Defined Network
CC	Clustering Coefficient

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