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Software-defined dynamic bandwidth optimization (SD-DBO) algorithm for optical access and aggregation networks

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Abstract The optical access networks and aggregation networks are necessary to be controlled together to improve the bandwidth resource availability globally. Unified control architecture for optical access networks and aggregation networks is designed based on software-defined networking controller, the function modules of which have been described and the related extended protocol solution has been given. A software-defined dynamic bandwidth optimization (SD-DBO) algorithm is first proposed for optical access and aggregation networks, which can support unified optimizations and efficient scheduling by allocating bandwidth resources from a global network view in real time. The performance of the proposed algorithm has been verified and compared with traditional DBA algorithm in terms of resource utilization rate and average delay time. Simulation result shows that SD-DBO algorithm performs better.

Keywords Software-defined network · Optical access network · Bandwidth optimization

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1 Introduction

The access networks are always considered as the last mile of information superhighway, which can provide the customers with broadband internet services. Today, intelligent terminal equipment is becoming more and more diversified, promoting the growth of network scale and traffic load greatly. On the one hand, the increasing complexity of networking puts forward higher requirements for network control and resource scheduling. On the other hand, a variety of traffic models promote the development of access network in the intelligent, flexible and highly customizable direction.

Among various access network technologies, passive optical network (PON) has become the main technology choice because of the advantage of high transmission capacity, long transmission distance, and good performance of anti-jamming. PON typically consists of optical line termination (OLT) and optical network unit (ONU) [1]. The requirements of efficient use of network resources and configuration optimization lead to the appearance of the dynamic bandwidth allocation (DBA) directly. Traditional optical access networks use DBA algorithm to realize flexible and efficient bandwidth allocation between the single OLT and its affiliated ONU nodes, according to terminal bandwidth requirements and pre-established policies. Classic DBA algorithm is represented by Interleaved Polling with Adaptive Cycle Time (IPACT) [2], which takes first-come-first-service (FCFS) as the core idea with built-in control signal processing algorithm. Based on this algorithm, the researchers put forward more complex DBA algorithm according to relative requirement and IPACT's shortcomings. For the problem about large message time delay on heavy load ONUs, the literature [3] proposes an algorithm called Per-slot DBA. For the problem of delay time deterioration, the literature [4] proposes a service level agreement (SLA)-based DBA algorithm providing quantity of service (QoS) guarantee according to different services.

Although there has been much work on DBA, it is still difficult for DBA algorithm to meet the rapidly increasing requirement of flexible bandwidth configuration throughout the whole optical access networks. On the one hand, the current DBA algorithm is on the basis of manual pre-established parameter policies with little consideration of network traffic changes. Thus it can hardly satisfy the terminals' bandwidth requirements in real time. On the other hand, the resource managements of access networks and aggregation networks are separated [5], which accounts that DBA is usually used inside a single OLT, lacking flexible bandwidth configurations among multiple OLTs. In fact, the use of point-to-point protocol over ethernet (PPPOE) is always limiting the bandwidth resource assigned to broadband users, which is allocated by the management system in metropolitan area network (MAN). The network management system of PON can only allocate the bandwidth resources from one OLT. There is no communication between different OLTs. As a result, there may emerge a mismatch between bandwidth resource and traffic requirement. For instance, a huge waste of network resources exists in idle areas, while the quality of user experience may be very poor in busy areas by contrast. Therefore, it is meaningful to realize global intelligent bandwidth allocation, by which network bandwidth resources can be managed and controlled dynamically and flexibly, providing a high improvement of the bandwidth efficiency.

Recently, the software-defined networking (SDN) has attracted much attention. It is a novel centralized control network architecture, which can implement the management of network resources, provide programmable interfaces for underlying devices, and then achieve the goal of open and flexible network architecture [6]. Due to the advantages of unified control and resource virtualization, the application of SDN paradigm to optical access and aggregation networks is foreseen to solve the challenges that the current networks face, then leading to the realization of next-generation intelligent optical access and aggregation networks [7]. There have some research works of SDN application in optical access networks. For example, software-defined transceivers have been introduced into optical access networks [8], and the concept of virtual passive optical networks is proposed [9].

In this paper, a software-defined dynamic bandwidth optimization (SD-DBO) algorithm is first proposed for the whole optical access and aggregation networks under SDN control architecture. It enforces allocating network bandwidth resources from a global network view by taking the changes of network traffic in real time into account. Additionally, it offers new opportunities to improve the network resources utilization, optimize user quality-of-experience (QoE) and reduce network operation costs. The efficiency and feasibility of the proposed SD-DBO algorithm has been proved through numeric simulation. The rest of the paper is organized as follows. Section 2 presents the framework of software-defined optical access/aggregation networks (SDOAN). In Sect. 3, SD-DBO algorithm is described in detail. Section 4 presents the simulation results and discussion. And Sect. 5 concludes the work.

2 SDOAN framework

2.1 Architecture of SDOAN

The SDOAN architecture is illustrated in Fig. 1, consisting of infrastructure layer, control layer and application layer.

The infrastructure layer refers as the underlying network devices including aggregation switch (AGS) in IP metro networks and OLT/ONU in optical access networks. These 'goofier' hardware only need to transmit data and execute strategies, with the control layer implementing the traditional analysis and management about network strategies instead. But ONUs are still controlled directly by OLT considering the requirements and cost of control granularity. The infrastructure layer provides the control layer with programmable interfaces based on OpenFlow Protocol, which is the standard communication protocol between infrastructure layer and control layer.

The application layer can gain real-time network state by the north application programming interface (API) provided by controllers, and participate in online decision, so it can realize more complex functions, such as network resource optimization, QoS management, smart energy-saving, resource authentication, security and so on.

The control layer mainly includes network operating system which can support the co-existence of heterogeneous networks and equip the application layer with abstract network view. Given the differences between IP metro and optical access networks, we propose the scheme of multi-controller containing the metro controller and the access controller, and those two controllers can communicate with each other through east–west interactive interface which can avoid exposing internal details.

2.2 Architecture of SDOAN controller

The internal architectures of both metro controller and access controller are almost the same. It is shown as Fig. 2.

The controller of SDOAN is a complex software system, which can be built from some open-source project, such as OpenDaylight and FloodLight. The detailed modules of SDOAN controller can be found in Fig. 2, which are described as follows.

Fig. 1 SDOAN architecture

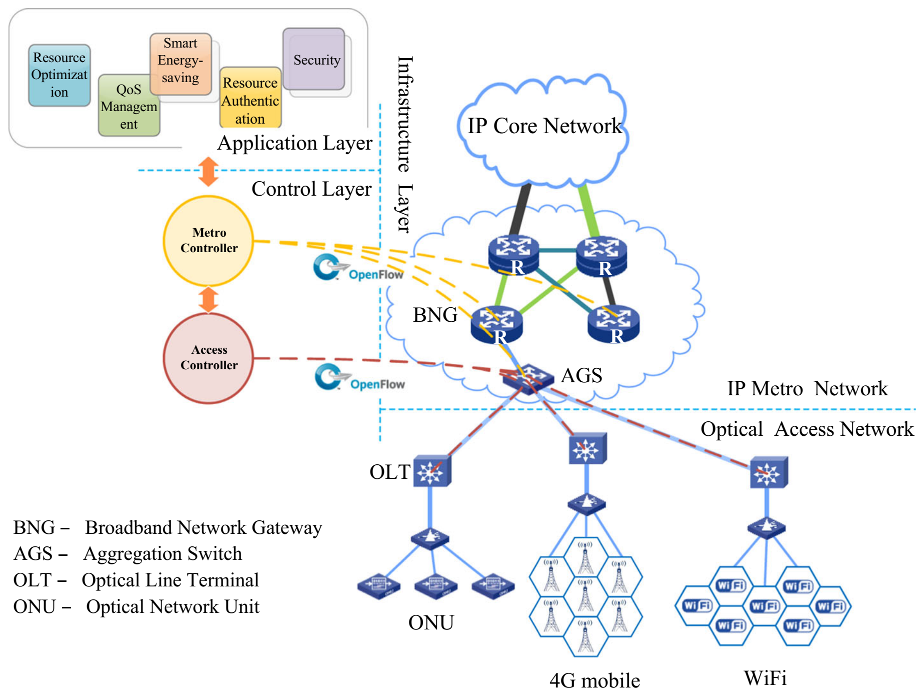
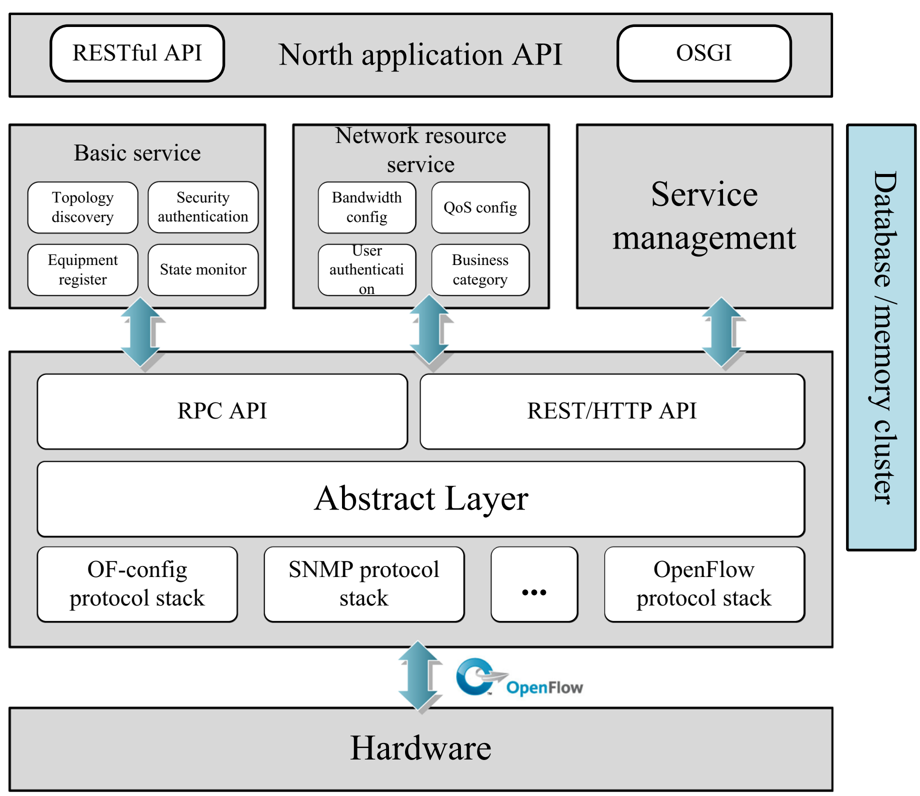


Fig. 2 Internal architecture of SDOAN controller



Firstly, there are protocol stacks connecting with hardware, which can establish the security channel, code/decode message provided by protocols. The controller can not only support OpenFlow protocol in different official versions and extended private versions, but also support network management protocols (SNMP and others) for forward compatibility with widely deployed PON devices until now.

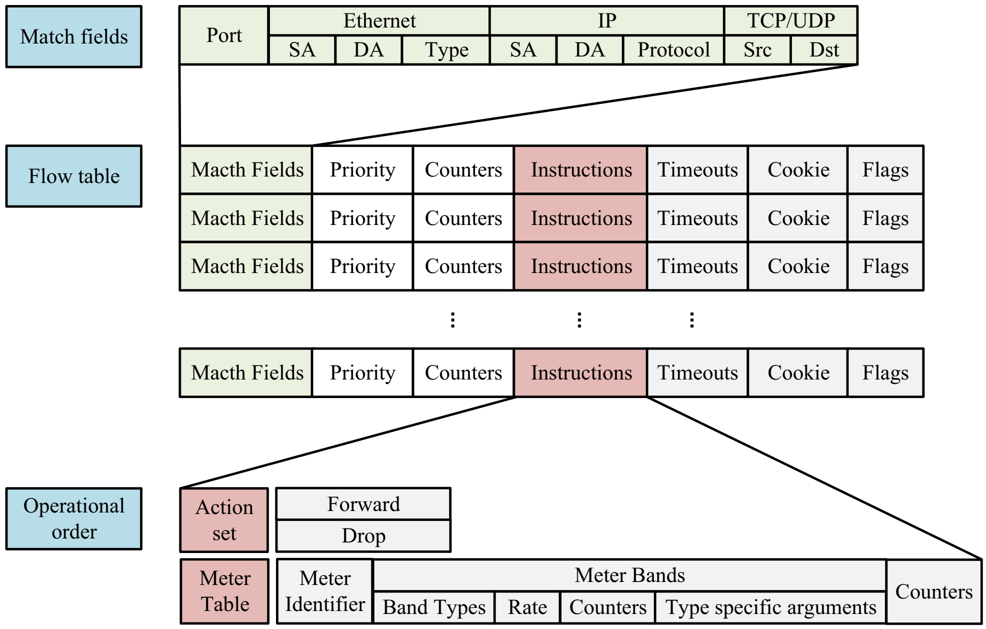


Fig. 3 Flow table extension

Secondly, parsed OpenFlow message would be translated to high-level data model by Yang modeling language [10] for description of resource and strategy. The translating procedure is also called abstract procedure of network events.

Thirdly, heterogeneous network resources descripted by Yang language can provide information for basic network service modules (topology discovery, security authentication, equipment register, state monitor, user authentication, bandwidth configuration, QoS configuration, and business category) through RPC API, REST API, and HTTP API. Besides, the information about network state, configuration, topology, and network session is usually stored in database/memory cluster.

2.3 Extension of protocols

For realizing SDOAN programmable hardware interface, the OpenFlow protocol has been extended as shows in Fig. 3.

The standard OpenFlow message consists of Controller-to-Switch message, Asynchronous message, and Symmetric message. In the extended message interactive process, controller and hardware equipment (switch or router) connect with each other through HELLO message and then initialize session through FEATURES message. Configuring network and querying state operation can be done through CONFIGURE message, which contains a lot of segments about optical access network equipment, such as OLT MAC address, ONU MAC address, ONU logical ID, and so on. When OLT receive data packages which do not match the flow table, it will report to controller through PACKAGE-OUT message and the controller reply to it after make decision.

3 SD-DBO algorithm description

3.1 Parameter symbol descriptions

The parameter symbols which will be used in the paper are described in Table 1.

3.2 SD-DBO Algorithm

The basic principle of the proposed SD-DBO algorithm is to collect and analyze the real-time traffic information of the whole network and then generate global bandwidth optimization strategy. Furthermore, we introduce the prediction strategy to reduce the effect of processing delay on QoE and offer better compatibility with traditional non-OpenFlow PON. Moreover, in order to cope with different conditions, the proposed SD-DBO algorithm mainly consists of four stages, which can be referred as OLT internal bandwidth allocation strategy, global bandwidth allocation strategy, global bandwidth recovery strategy and OLT internal bandwidth recovery strategy, respectively.

At the very beginning, metro controller and access controller initialize OLTs and ONUs bandwidth according to resource authentication applications which generate each terminal's authorized bandwidth and initial bandwidth through

Table 1 Basic notation

Symbol	Description
M	Total number of OLT
N	Total number of ONU
p	OLT ID of required optimized ONU
q	Required optimized ONU ID
B_q	ONU_q's bandwidth requirement
A_m	Allocation bandwidth of OLT_m
A_n	Allocation bandwidth of ONU_n
Au_m	Authorized bandwidth of OLT_m
Au_n	Authorized bandwidth of ONU_n
Av_n	Residual available bandwidth of ONU_n
T_m	Traffic of OLT_m
T_n	Traffic of ONU_n
P_m	Fluctuation probability of OLT_m's bandwidth requirement in next moment
P_n	Fluctuation probability of ONU_n's bandwidth requirement in next moment
I_m	Idle bandwidth of OLT_m
I_n	Idle bandwidth of ONU_n
F_m	Unfair bandwidth of OLT_m
F_n	Unfair bandwidth of ONU_n
IT	Idle threshold (%)
BT	Busy threshold (%)
C_n	Polling cycle of ONU_n

SLA. Then OLT allocates bandwidth resources to ONUs depending on their initialization parameters and under the rules like traditional DBA policy. The main difference about initial bandwidth allocation between traditional DBA and SD-DBO is that the latter one considers the difference in load condition between different areas to maximize the use of resources. And the principle behind it is that allocated bandwidth should be changed with the movement of population. While access controller monitors Av_n following the variable polling cycle C_n, which can be expressed as:

$$C_n = \mathrm{e}^{-P_n} \cdot \left(e - \mathrm{e}^{-A_n/T_n}\right) \quad n = 1, 2, \ldots, N \tag{1}$$

$$\mathrm{Av}_n = \max\left\{A_n \cdot BT^{(1+P_n^3)} - T_n, 0\right\} \quad n = 1, 2, \ldots, N \tag{2}$$

when Av_n is zero, our proposed SD-DBO algorithm will be touched off.

As mentioned above, the first stage is OLT internal bandwidth allocation strategy. On this condition, access controller calculates idle bandwidth of all ONUs under the OLT_p as follows:

$$I_n = (A_n - T_n) \cdot \min\{\mathrm{IT} \cdot (1 - P_n), 1\}$$
$$n = 1, 2, \ldots, N, n \neq q \tag{3}$$

where P_n ranges from -1 to 1 representing the fluctuation probability of ONU_n's bandwidth requirement, which can be calculated by the NeuroFuzzy model (α_SNF) [11]. After that, access controller will reduce the allocated bandwidth of idle ONUs to meet ONU_p's bandwidth requirement considering the priority of ONUs and the value of I_n. If B_q become zero which indicates bandwidth optimization has been done, access controller will gather this optimization results and issue bandwidth allocation message to the affected OLTs. Afterward underlying devices allocate bandwidth according to the new DBA parameters. However, if B_q is still greater than zero after this stage, access controller will send global bandwidth optimization request message to metro controller to start the global bandwidth allocation strategy, including p and the new B_q.

Then metro controller calculates I_m, which can be written as:

$$I_m = (A_m - T_m) \cdot \min\{\mathrm{IT} \cdot (1 - P_m), 1\}$$
$$m = 1, 2, \ldots, M, m \neq p \tag{4}$$

where m is the number of OLTs under AGS corresponding to OLT_p. In this stage, metro controller will optimize bandwidth allocation among multi OLTs according to the comprehensive ranking of I_m and the priority of OLTs. That is the allocated bandwidth of idle OLTs will be cut down in order while that of OLT_p will be increased at the mean time. As above, if B_q become zero, the optimization will stop. However, if B_q is still greater than zero after this stage, metro controller need to make sure whether the current allocated bandwidth of OLT_p is smaller than the authorization value. If it is true, it means there is unfair situation in OLT bandwidth allocation which will account to the enablement of global bandwidth recovery strategy.

In this case, metro controller will calculate all the unfair bandwidth of OLTs, and the sum is given by:

$$F_m = \max\{\mathrm{Au}_m - A_m, 0\} \quad m = 1, 2, \ldots, M, m \neq p \tag{5}$$

SD-DBO Algorithm

1: Controllers initialize OLTs and ONUs bandwidth according to resource authentication;
2: **While** Av_n is zero by Eq.2 following the polling cycle C_n by Eq.1 **do;**
3: **for** each positive I_n by Eq.3 **do;**
4: reduce the allocated bandwidth of idle ONUs in order to meet the ONU_q's bandwidth requirement;
5: **if** B_q is zero **do goto step** 22 **end if;**
6: **end for;**
7: **for** each positive I_m by Eq.4 **do;**
8: reduce the allocated bandwidth of idle OLTs in order to meet the OLT_p's bandwidth requirement;
9: **if** B_q is zero **do goto step** 22 **end if;**
10: **end for;**
11: **if** current allocated bandwidth of OLT_p is smaller than Au_p **do;**
12: **for** each positive F_m by Eq.5 **do;**
13: reduce the allocated bandwidth of unfair OLTs in order to ensure fairness;
14: **if** the fairness is satisfied **do goto** 22 **end if;**
15: **end for;**
16: **end if;**
17: **if** current allocated bandwidth of ONU_q is smaller than Au_q **do;**
18: **for** each positive F_n by Eq.6 **do;**
19: reduce the allocated bandwidth of unfair ONUs in order to ensure fairness;
20: **end for;**
21: **end if;**
22: access controller handles the all optimization results, and reallocates bandwidth;
23: **end while.**

Only on the condition of light network loads, the OLT_m's allocated bandwidth can exceed Au_m to improve network resources utilization rate. However, if the network is busy, the fairness will be a significant property we need to guarantee at first. To recover the fairness of bandwidth allocation, metro controller will consider the value of F_m and the priority of OLTs, then reduce those F_m which is greater than zero to the equal of Au_m following this comprehensive order. After metro controller implements all the dynamic bandwidth optimizations, it will send the optimization result message to access controller including updated OLTs bandwidth allocation parameters. In addition, the access controller will re-update ONUs bandwidth allocations under the adjusted OLT. At this point, if A_q is still less than Au_q, the last stage, i.e., OLT internal bandwidth recovery strategy will be performed. Access controller will calculate F_n under the OLT_p as follows:

$$F_n = \max\{\mathrm{Au}_n - A_n, 0\} \quad n = 1, 2, \ldots, N, n \neq q \tag{6}$$

According to the value of F_n and the priority of OLTs, access controller can get the comprehensive order to cut down those ONUs' allocated bandwidth which F_n is greater than zero. Thus the fairness of bandwidth allocation will be recovered. Finally, all the steps of our proposed SD-DBO will have been done, and the updated bandwidth allocation configurations will be sent to underlying device. From the stages described above, we can see that SD-DBO algorithm is implemented based on DBA algorithm. The time complexity of DBA algorithm, i.e., IPACT is O (N), while the time complexity of SD-DBO algorithm can be described as O (MN), where N is the number of ONUs and M is the number of OLT.

4 Simulation results and discussion

A simulation is performed to evaluate the proposed SD-DBO algorithm. We make comparison of the performances between the proposed SD-DBO algorithm and traditional DBA algorithm [12] in terms of resource utilization rate, average delay and delay of a single mobile user. Moreover, we also investigate the influence of prediction strategy as mentioned in last section on our proposed algorithm by using SD-DBO without prediction as a contrast. The only difference between SD-DBO and SD-DBO without prediction is that P_m and P_n in SD-DBO without prediction equal zero. The total aggregate uplink rate of AGS with 40 OLTs is 50 Gbps, and the total uplink rate of each OLT with 1:64 splitting ratio is 1.25 Gbps. The average processing delay of controller is about 2 ms.

Figure 4 shows the average delay of different services, while resources utilization rate versus different average loads is shown in Fig. 5. From Figs. 4 and 5, we can see that there is a relationship between average delay and resource utilization. When the loads are light, maybe less than 50 %, the average delay of DBA is much higher than SD-DBO, which makes more network resources under DBA algorithm are used for the services. When the network is deployed with heavy load (more than 60 %), the resource utilization of DBA changes little even though the average delay still increase sharply. SD-DBO has higher resource utilization, because they can complete the resource allocation globally. So there is a point of transition at about 55 % traffic load of for DBA band SD-DBO algorithms.

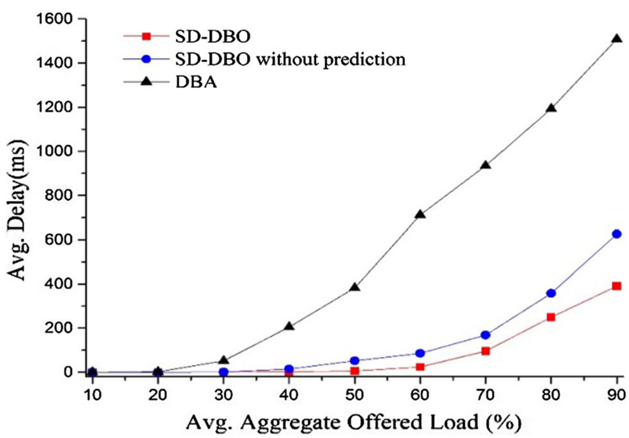


Fig. 4 Average delay for three algorithms

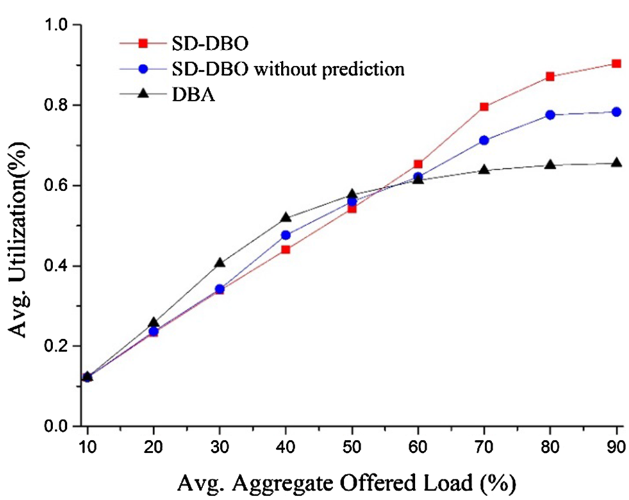


Fig. 5 Average utilization for three algorithms

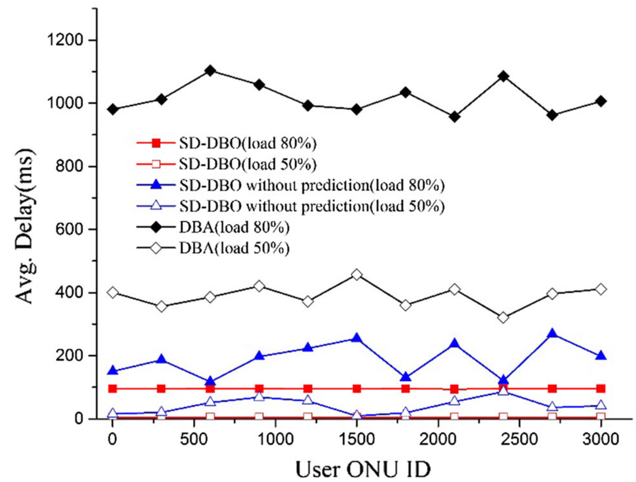


Fig. 6 Average delay of a single mobile user for three algorithms

From the simulation results as shown in Figs. 4 and 5, we can also see that the prediction policy can always reduce the user serving time and improve the quality of service. But in the aspect of resource utilization, the effects of prediction policy are very small when the traffic load is light (less than 50 %). For the network with heavy load, prediction policy will play a much more important role in the resource utilization. Overall, it follows the rule that more network resources are consumed, shorter average delay can be gained.

The changes of services average delay during one ONU user terminal's move are shown in Fig. 6 (assuming the user access to the network via Wi-Fi or 3G ONU under), and the network average load is 50 and 80 %, respectively. In Fig. 6, DBA shows the largest amplitude fluctuation which illustrates that user experience is badly affected by local network load. The reason why SD-DBO without prediction shows small amplitude fluctuation is that the extreme scenario that user keeps roam requires high flexibility, and the system time delay of control loop results in time delay of adjustment. After considering prediction, delay time looks like linear result, which means that SD-DBO with prediction can implement unified user experience with excellent quality. Except small amplitude fluctuations in the network switching process, the user delay is very small, keeping in 400 μs or less.

5 Conclusions

In this article, we first present a global dynamic bandwidth optimization algorithm for software-defined optical access and aggregation networks in order to meet the requirements of effective and flexible resources scheduling of next-generation intelligent optical access networks. With global perspective of the whole network and prediction strategy based on historical data, the proposed SD-DBO algorithm can get more exact bandwidth requirements in advance, which enables optimal and efficient bandwidth allocations in real time. Additionally, we make evaluation and comparison of the performances among the proposed SD-BDO algorithm and traditional DBA algorithm in terms of resource utilization rate, average delay, and delay of a single mobile user. It turns out that our proposed SD-DBO algorithm always shows a better performance than DBA. Further, the simulation results verify SD-DBO can dynamically adjust bandwidth optimization configurations and utilize optical network resource effectively.

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