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Software defined passive optical networks with energy-efficient control strategy

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ABSTRACT

With the rapid growth of new broadband services and traffic flows, Passive Optical Network (PON) is facing the challenge of bandwidth crunch and energy consumption. There are a huge number of optical network elements, such as Optical Line Terminal (OLT) and Optical Network Units (ONU), which can be controlled flexibly and efficiently to improve the performance of PON. Then, software defined networking (SDN) is considered as the optimal choice for the next generation PON because of its advantages of flexible and centralized control capability. Software defined passive optical network (SPON) architecture is designed with OpenFlow protocol extension in this paper, based on which a novel energy-efficient control strategy is proposed and evaluated on SPON testbed. Also, theoretical analysis work for the energy consumption of this architecture has been conducted. Numeric results show that the proposed energy-efficient control strategy can reduce the energy consumption of optical access networks and efficiently facilitate the integration of access and metro networks resources.

1. Introduction

With the fast development of Internet of Things (IoT) and edge computing in recent years, 4G/5G mobile networks have attracted more and more attentions from academic and industry. A lot of issues in mobile access networks have been researched up to now. For example, optical-access-enabled Cloud RAN (CRAN) has been recently proposed as a next-generation access network, where the digital unit (DU) of a conventional cell site is separated from the radio unit (RU), by an optical access network (fronthaul), and moved to the “cloud” (DU pool) for centralized signal processing and management [1]. Also novel energy-saving schemes exploiting virtual base station formation (VBF) are proposed for both the network planning stage and traffic engineering stage [2]. On the other hand, as one of the most important broadband access network technologies, Passive Optical Network (PON) plays very important role in 4G/5G mobile franthaul networks [3], especially with the emergence of high-bitrate applications over the Internet in the edge side [4].

Then, in order to meet the requirement of different application scenarios, the configuration of PON equipment, such as optical line termination (OLT) and optical network unit (ONU), is needed to be modified manually and periodically in the local area. However, the geographical distribution and huge quantity of equipment will increase the cost of operation and

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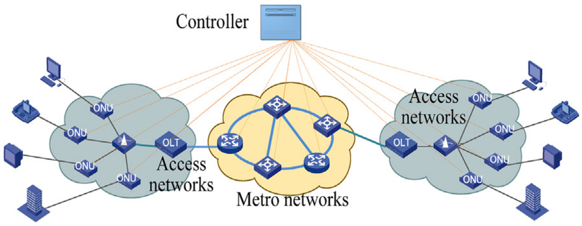

Fig. 1. SDN based passive optical networks.

maintenance greatly. Therefore, how to improve the performance of PON in terms of cost, bandwidth utilization and energy consumption makes the intelligent control technology beneficial and necessary for PON.

Recently, as a novel control technology, software defined networking (SDN) enabled by OpenFlow protocol has gained popularity in metro and backbone networks [5,6] due to its programmability of network protocols and functionalities, which can provide a unified and efficient control over various resources with a global view [7]. Due to the diversity and flexibility of desired data flow in the edge side, the demand for dynamic control is more urgent in access network than the core and convergence sides [8]. Therefore, SDN/OpenFlow technique promoted into customer side in the “first mile” is a promising scenario to remotely control and allocate the resource converged from various PONs in a dynamic, programmable and unified manner [9]. For example, remote unified control architecture is demonstrated for OpenFlow-based software defined access optical networks [10], and bandwidth allocation method is presented for virtualized PON [11]. The work presented in [12] focuses only on the SDN control plane aspects of a TDM-DWDM LR-PON and does not include integration with a realistic physical layer. End-to-end software defined networking (SDN) management of the access and core network elements is also implemented and integrated with the PON physical layer in order to demonstrate fast protection mechanism and dynamic wavelength allocation (DWA) [13].

On the other hand, energy consumption has become an important challenge for the information and communication technology (ICT) area. According to statistics, in 2010, the energy consumption of fixed communication network of the Internet portion is 20 GW, accounting for 1% of global energy consumption. To 2025, energy consumption will be increased to 1.5T W, accounting for 75% of the world’s total energy consumption in 2010 [14]. The major component of internet energy consumption is the access network, which accounts for about 70% of the total energy consumption of the Internet [15]. Therefore, how to effectively reduce the energy consumption of the access network has become a key task with top priority. Some approaches are described to save energy in TWDM-PON [16]. Some relevant standardization work has been started. For example, IEEE has released 802.3az EEE energy efficiency standards in EPON networks. And ITU has published ITU-T G.sup45 GPON energy efficiency standards. Equipment manufacturers launched some equipment supporting those standards, such as Huawei S1700 series switches, HP E5400 and E8200 switch and so on. There are also some research works about energy saving. For example, an adaptive handshake protocol is proposed to shut down ONU [17], and an energy saving method is proposed to switch an ONU working and sleeping mode according to the change of the ONU traffic [18]. However, few works have been done on the topic of energy saving with software defined passive optical networks.

The main contribution of this paper is described as follows. In order to reduce the energy consumption of PON, software defined passive optical network (SPON) architecture is designed with OpenFlow protocol extension in this paper. A novel energy-efficient control strategy is proposed based on SPON architecture. Some related theoretical analysis work for the energy consumption has been conducted. Numeric results show that the proposed energy-efficient control strategy can reduce energy consumption of optical access networks.

The paper is organized as follows. In Section 2, SPON architecture is described with OpenFlow protocol extension. An energy-efficient control strategy is proposed based on SPON, and some theoretical analysis work is given in Section 3. In Section 4, the implementation process of the mechanism is described. Numeric results and analysis are given in Section 5, and Section 6 is the conclusion.

2. Software defined passive optical networks

As shown in Fig. 1, the distributed ONUs are interconnected and converged into metro networks. Similar with some SDN enabled optical access networks architecture [13], all the network resources can be controlled by SDN controller in a unified manner. To control the PON through extended OpenFlow protocol (OFP), OpenFlow-enabled OLT node with OFP agent is required, which is referred to as OF-OLT. Many optical network units (ONU) can be controlled through OFP by the controller. The motivations of SPON architecture are twofold. Firstly, the centralized SDN controller located in central side is used by the operator to maintain and control multiple PON domains remotely. Secondly, the dynamic bandwidth assignment (DBA) in line side of OLT among multiple domains can be scheduled with metro and core networks in a unified manner, so as to implement large-scale resource optimization.

The control architecture of SPON is described as Fig. 2, which includes data plane, control plane and application plane. The data plane consists of underlying network devices in optical access networks and metro networks. The metro networks in the architecture are considered as optical transparent networks, and different PON systems are connected through the

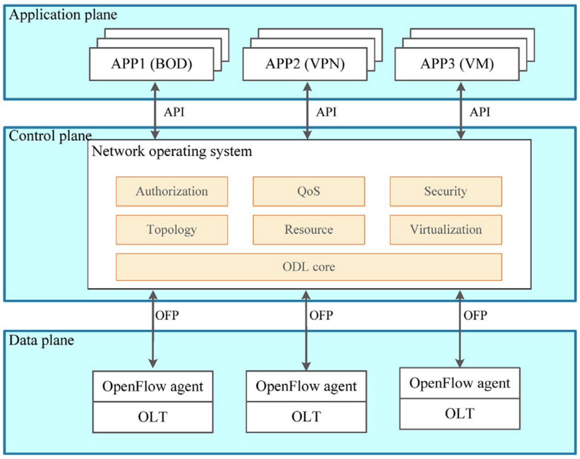

Fig. 2. SPON implementation architecture.

metro networks. These equipment in the data plane only need to transmit data and execute strategies, while the control plane implements the traditional analysis and management about network strategies with the help of Open Daylight (ODL) controller. There are programmable interfaces between the data plane and control plane, which are designed based on one of the standard communication protocols, i.e., OFP. Some other protocols, such as PCEP and TL1 can also be adopted here. The control plane mainly includes network operating system, which can be located in metro networks or at the edge of metro networks to control the PON equipment efficiently. It can also support the co-existence of heterogeneous networks and equip the application layer with abstract network view. The core control functions of control plane mainly consist of network topology discovery, network status information collection, heterogeneous network virtualization, user authentication, QoS guarantee and security. The application plane can provide some application services, such as Bandwidth on Demand (BOD), Virtual Private Network (VPN), and Virtual machine Migration (VM) for the customer through the north application programming interface (API) on the control plane.

3. Energy-efficient control strategy in SPON

Different actions can be conducted to reduce the energy consumption of PON system. First, ONUs can be controlled to enter energy-saving mode. What's more, there are enormous opportunities for energy-saving in the OLT. For example, SPON detaches control functions from OLTs, so it can reduce the energy consumption of the master control board at OLTs directly. On the other hand, we can also shut down the idle ports in the uplink/downlink board and idle boards to reduce energy consumption in the OLT.

An EPON energy-saving strategy has been proposed, i.e., EMM-UCS (Energy Management Mechanism-Upstream Centric Scheduling), which takes bandwidth allocation over the upstream to the center [19]. In this strategy, the upstream and downstream data will be transmitted only when the particular ONU is in wake mode. At other time, the ONU is in sleep mode. The same conception is also suitable for OLT [20]. UCS-based strategy is relatively simple, because the sleep cycle is only determined by the upstream traffic. OLT assigns different time slots in sleep mode for downstream ONUs by using DBA algorithm.

On this basis, we propose a quasi-periodic bi-directional energy-efficient control strategy based on a modification of IPACT [21], which is called EMM-UDS. There are mainly two different points between EMM-UCS and EMM-UDS. First of all, the sleep cycle in EMM-UCS is only determined by the upstream traffic, which could limit the speed of downstream traffic. While in EMM-UDS, the sleep cycle is determined by the upstream traffic and downstream traffic together, which can provide critical sleep cycle for bi-directional traffic demand. Secondly, the division of EMM-UDS is more reasonable than EMM-UCS. In EMM-UDS, we distinguish the ONUs and OLTs, and separately define three modes for them. In this strategy, the three modes are awake mode (called So_1), sleep mode (called So_2), and critical mode (called So_3). The state of OLT is divided into three types also, i.e., awake mode (called Sl_1), port sleep mode (called Sl_2), and board sleep mode (called Sl_3).

There are three tables about OLT's and ONU's energy consumption in different modes [22,23], which are listed as follows. Table 1 introduces ONU modules' power diagram, Table 2 introduces energy consumption by shutting down idle port in OLT, and Table 3 introduces energy consumption by shutting idle board in OLT.

In Sl_1, OLT's several modules operate as usual. In $\mathrm{S1}_2$, idle port is turned off, and in $\mathrm{S1}_3$, marching board is turned off. There are several boards inserted into general OLTs, each board will be in three modes. Therefore, the state of OLT mentioned below represents the state of a board on the OLT.

Notably, mode Sl_3 is different from Sl_1 and Sl_2. There are some pre-configured but actually unused user boards in the existing network equipment. For those boards where all ports are not open, we can use board-off energy-saving technologies,

Table 1
ONU modules and power diagram.

Mode	Optical transceiver module	System-level processing chip	Cache and cache management	User side interface circuit	Total energy consumption
Wake	3.5 W	2 W	0.7 W	0.15 W	6.35 W
Sleep	0 W	0.4 W	0.02 W	0.15 W	0.57 W
Critical	3.5 W	2 W	0.7 W	0.15 W	6.35 W

Table 2
Energy conservation by shutting down idle port.

Equipment manufacturers	Work mode	Port energy consumption in $S1_2$ (W)	Saving energy consumption in $S1_2$ (W)	The proportion of savings
Manufacturer 1	GPON	5.45	1.17	21.52%
Manufacturer 1	EPON	7.91	0.40	5.00%
Manufacturer 2	EPON	9.05	0.23	2.57%
Manufacturer 3	GPON	6.93	0.13	1.82%
Manufacturer 4	GPON	3.67	0.73	19.92%
Manufacturer 4	EPON	2.10	0.67	31.99%

Table 3
Energy conservation by idle board.

Equipment manufacturers	Work mode	board energy consumption in $S1_1$ (W)	Saving energy consumption in $S1_3$ (W)	Savings proportion
Manufacturer 1	GPON	43.63	43.6	about 100%
Manufacturer 1	EPON	31.62	31.6	about 100%
Manufacturer 2	EPON	36.21	7	19.33%
Manufacturer 3	GPON	55.41	5.78	10.43%
Manufacturer 4	GPON	29.37	28.84	about 100%
Manufacturer 4	EPON	33.64	33.64	about 100%

allowing those boards to enter a deep sleep state to maximize power savings. If the controller detects no traffic, it will shut down the board, and cut the connection between board and backplane. Theoretically, when the board runs in $S1_3$, it consumes nearly 0 W. The board needs little time to be restarted, but there is no influence on the traffic [24].

The reason why ONU needs critical mode and OLT needs port sleep mode is that the two modes are transition, which can keep balance between sleep mode and awake mode with little cost.

There is a simple EPON system with only one OLT and two ONUs (ONU1 and ONU2). In the cycle time when OLT polls over the downstream ONUs, ONU1 is allocated with length of T_1, while ONU2 is allocated with length of T_2. For ONU1, upstream bit rate is $BRup_1$, upstream data is Qup_1, downstream bit rate is $BRdn_1$, and downstream data is Qdn_1, and for ONU2, upstream bit rate is $BRup_2$, upstream data is Qup_2, downstream bit rate is $BRdn_2$, and downstream data is Qdn_2.

In fact, the required time to complete data transmission for ONU1 is T_1'.

$$T_1' = \max\left\{\left(\frac{Qup1}{BRup1}\right), \left(\frac{Qdn1}{BRdn1}\right)\right\} \le T_1 \quad (1)$$

Similarly, the required time to complete data transmission for ONU2 is T_2'.

$$T_2' = \max\left\{\left(\frac{Qup2}{BRup2}\right), \left(\frac{Qdn2}{BRdn2}\right)\right\} \le T_2 \quad (2)$$

And the actual time to complete a polling cycle is $Tcycle'$.

$$Tcycle' = T_1' + T_2' \le Tcycle \quad (3)$$

The difference between $Tcycle$ and $Tcycle'$ is Delta.

$$Delta = Tcycle - Tcycle' \quad (4)$$

Obviously, it will be a waste of energy when there is no upstream and downstream data in Delta. In this paper, the strategy based on EMM-UCS considers both upstream and downstream data to make OLT enter Sl_2, and ONUs enter So_2.

In order to avoid the possible disturbance of low data flow in sleep mode, we use traffic shaping technology [23], to translate the continuous low flow of business traffic into high burst traffic.

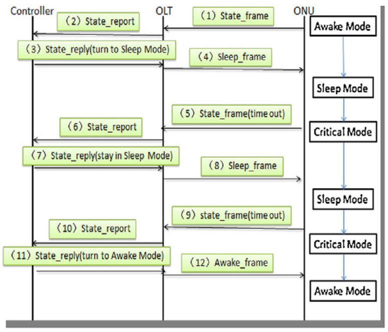

Fig. 3. Implementation procedure of energy-efficient control strategy.

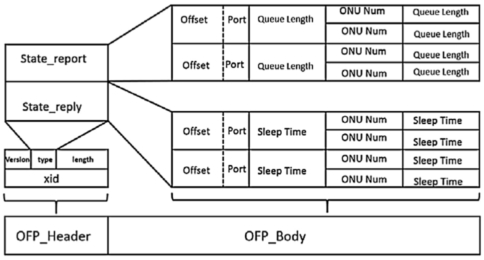

Fig. 4. The structure of extended OFP messages.

4. Implementation procedure of energy-efficient control strategy in SPON

Fig. 3 shows implementation procedure of energy-efficient control strategy in SPON, the details of which are described as follows.

1) At the end of assigned time slot, ONU sends State_frame status frame to OLT, which contains the ONU upstream queue length information;
2) After receiving the frame State_frame, OLT sends State_report message to the controller. The message contains the queue length of each OLT's port and each ONU upstream queue length information;
3) According to the obtained information, the controller executes energy-saving algorithm to determine whether to make OLT or ONU enter the sleep mode. If so, State_reply message will be sent to the OLT, making the appropriate ONU and OLT's port enter sleep mode. The message contains the sleep time T, OLT port number and other necessary information.
4) OLT receives the sleep command, and transmits the Sleep_frame to the specified ONU. And then, OLT makes the specified port enter Sl_2.
5) ONU enters So_2, and starts the countdown, whose value is configured by SDN controller. At the end of timing, ONU enters So_3, and OLT's port linked to this ONU has been changed into Sl_1 as well. ONU recalculates the buffer queue length, and send State_frame state frame to OLT again.
6) OLT summaries new data, which comes from ONU and carries state information, and sends State_report message to the controller again.
7) If the controller confirms that there is no need to be awake at this time, it will send State_reply message to the OLT, making the appropriate ONU and OLT's port enter sleep mode. In this message, all parameters are passed to be recalculated.
8) OLT sends new Sleep_frame to ONU, and makes its own port enter Sl_2 again.
9) Similar with step 5, ONU enters So_2, and starts the countdown. At the end of timing, ONU enters So_3, and OLT's port linked to this ONU will enter Sl_1 at the same time. ONU recalculates the buffer queue length, and send State_frame state frame to OLT again.
10) OLT summaries information and sends State_report message to the SDN controller.
11) If the controller confirms that it is time to make ONU and OLT's port work normally, it will send State_reply message to the OLT, making the appropriate ONU enter So_1, OLT's port enter Sl_1. Then, all the parameters are passed to be recalculated.
12) OLT sends Awake_frame frame to the specified ONU. And ONU enters So_1 from So_3.

For the sake of implementing such controller, the OpenFlow protocol needs to be extended. We add a pair of symmetric message called State_report and State_reply. Fig. 4 shows the structure of these two messages.

As shown in Fig. 4, the equipment can distinguish the message by the type field in OFP_Header, which can be State_report or State_reply. There are five parts in State_report message as shown in Fig. 4. And every entry composed of those five parts

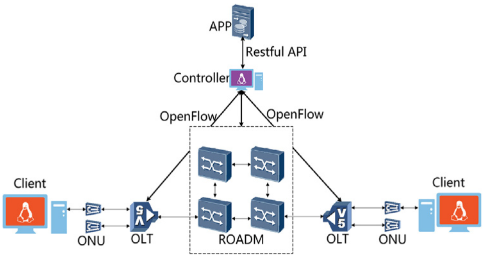

Fig. 5. Experimental testbed.

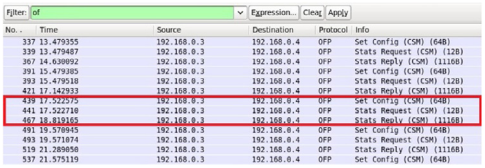

Fig. 6. Wireshark capture of the OF message.

means one configuration command for specific OLT port. The "port" field with 5 bits length can appoint the port number, the "offset" field with 11 bits length appoints the length of this entry, the "Queue Length" field with 16 bits length means the queue length at this port in OLT, the "ONU Num" field with 16 bits length means the specific ONU's serial number, and the "Queue Length" field after "ONU Num" field with 16 bits means the queue length of that ONU. Every State_report message can configure all ports of one OLT and all ONU connected to this OLT. The structure of State_reply is similar to the structure of State_report message. And the "Sleep Time" in the former means the sleep time of specific OLT port or specific ONU.

5. Experimental demonstration and numeric results

5.1. Experimental testbed

To evaluate the proposed architecture, we set up testbed including the access and metro networks equipment as shown in Fig. 5. In data plane, four convergence network nodes are equipped with ROADMs supporting multi-granularity client side interfaces. Two groups of 10GE PON equipment are deployed in the access side, and connected through the metro network. In each 10GE PON group, two ONUs are connected to OF-OLT by optical splitter. Due to the limitation of OLT equipment in the lab, we mainly extended the Openflow protocol based on the SNMP APIs to control its hardware through OFP. For OpenFlow-based SPON control plane, the SDN controller based on ODL is assigned in core side to support the proposed architecture, while the database server is responsible for maintaining management information and configuring the database and network resources. The operator can monitor and configure the system through remote interfaces.

We have experimentally verified remote unified control in SPON architecture. The service is provided according to ONU requirements at client side and adjusted based on variation of user's QoS demands. Fig. 6 illustrates the Wireshark capture of the OpenFlow message between the controller and OLT agent. From the time information in the figure, we can see that the time interval between set configure message and status reply message is about 1.3s. Because two groups of 10GE PON equipment are controlled by the controller in parallel and the connection creation latency in the local metro domain is less than 100 ms [24], the setup latency of an end-to-end path from one client to another client through metro networks under the control of SDN is about 1.3 s. Fig. 7 shows the video from four terminals. The priorities of them are A < B < C < D. When terminal C is shut down, the bandwidth resources are reallocated, and the quality of A and B degrade heavily. Because A, B, C and D are connected with two different OLTs, we can obtain that the controller can schedule the bandwidth resource of the entire network. The bandwidth is assumed to be equal to the value of bit rate for each ONU.

5.2. Numeric results

EMM-UDS in the paper is a modification of algorithm in literature [19] which is suitable for SPON platform. According to the literature [19], if we just detect upstream traffic, it will not detect its own OLT downstream traffic, so there is no way to save the energy of OLT.

The power consumption of ONU is typically at ten-watt level in the market today, and an OLT can be linked to 64 or 128 ONUs. So the total power consumption of the entire ONUs is at kilowatt level, while the energy consumption of OLT is also at kilowatt level. Because OLT adopts the TDM strategy in the downstream direction, its working time is the sum of all ONUs' working time, and the sleep time is shorter than ONU. But it can be expected that, when traffic load is not heavy, OLT working hours can have a considerable reduction. In this situation, energy saving of OLT becomes quite promising.

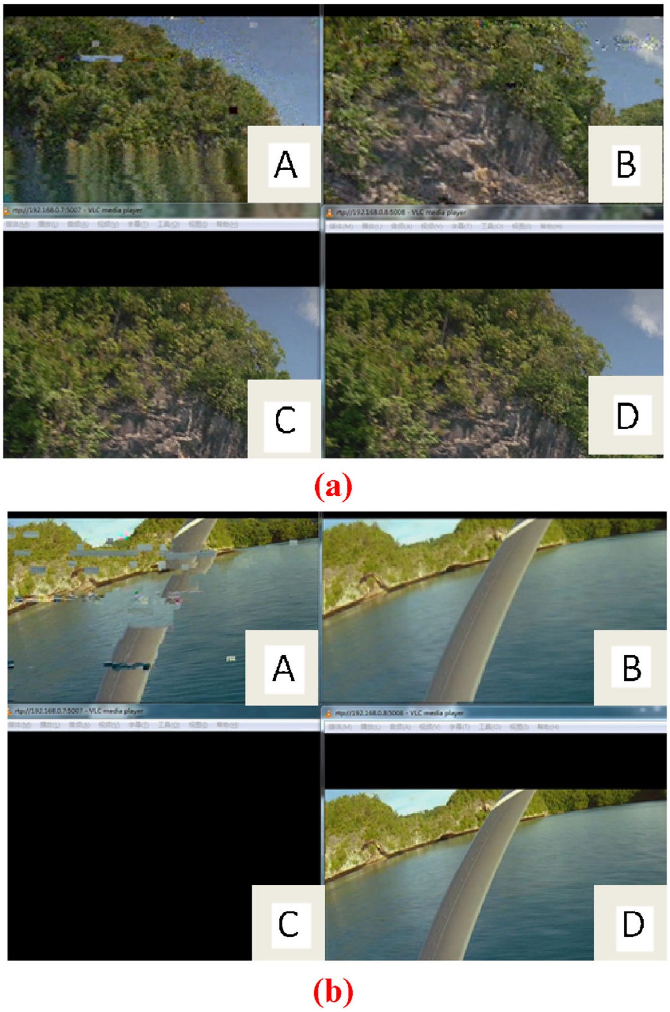

Fig. 7. (a) Video from four terminals, (b) video after terminal C is shut down.

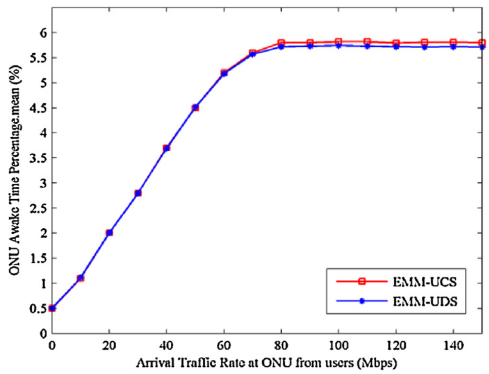

Fig. 8. ONU wave-up time.

To verify the results, we conducted the simulation under the same condition as in literature [19]. Due to the hardware limitation, some virtual machines are used here to act as the OLT and ONU nodes, which are connected with the controller node. EPON and GPON systems are both considered in the simulation work. Then we get Figs. 7 and 8, which describe ONUs and OLT awake time in different upstream traffic rates.

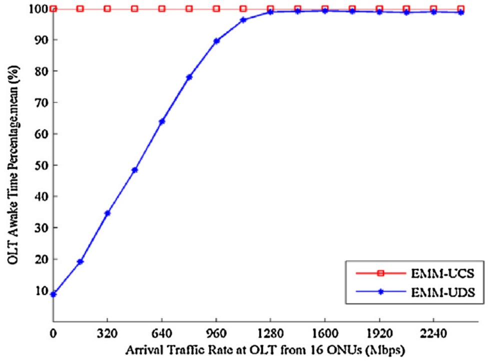

Fig. 9. OLT wake-up time.

Fig. 8 shows the influence of two algorithms on the ONUs' wake-up time. We can find that, without considering the effects of downstream flow, EMM-UDS's efficiency is about the same as EMM-UCS. And ONUs' awake time is just a little shorter when the access network is under high traffic load, because of its complicated process.

Fig. 9 shows the influence of two algorithms on the OLT's wake-up time. We can find that, OLT's awake time with EMM-UDS strategy is obviously shorter when network traffic is low, and when network traffic is high, awake time with either EMM-UCS or EMM-UDS is nearly zero.

6. Conclusions

In order to optimize the performance of PON, especially the energy consumption, software defined passive optical network (SPON) architecture is designed with OpenFlow protocol extension in this paper. A novel energy-efficient control strategy is proposed based on SPON architecture. Some theoretical analysis work for the energy consumption of this architecture has been described. Numeric results show that the proposed energy-efficient control strategy based on SPON architecture can reduce energy consumption of passive optical networks.

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