Energy Saving Scheme Based on Multi-modes Hybrid Dynamic Bandwidth Optimization for Software Defined Distribution Optical Networks

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Abstract — As the increasing number of access devices, and the complex and changeful of access site and the media, energy consumption of power distribution communication access networks is expected to further grow in the future, energy saving has become a key issue with the development of Passive Optical Networks (PONs). In this paper, we propose a Software Defined Distribution Optical Network (SD-DON) architecture, design an energy saving aware control strategy which support unified optimization and efficient scheduling from multi-domain perspective. Additionally, a Multi-Modes Hybrid Dynamic Bandwidth Allocation (MH-DBA) scheme are proposed and evaluated under SD-DON, in which, 4-saving modes and multi-period mixed adaptive dormancy method is designed to maximize energy saving of Optical Network Units (ONUs).

Simulation results show that MH-DBA can significantly save energy under different traffic loads, and clearly outperform the conventional scheme.

Index Terms—SD-DON, energy saving, multi-domain, MH-DBA, ONU, dormancy

I. INTRODUCTION

A. Background and Motivation

As the increase of power telecommunication network and bandwidth, the power distribution network has gained unprecedented development. Passive Optical Networks (PONs) have been widely considered as the most favorable power distribution network architecture to cater for the growing demand of bandwidth-hungry applications. Even though PONs are considered more energy-efficient compared to other wired access technologies, such as xDSL, due to their massive deployment nowadays and even more in the future, it is desirable to further reduce their energy consumption [1].

Software Defined Networking (SDN) is an emerging technology used to provide more flexible controls on networks by abstracting lower-level switch functionality [2], [3]. By separating the control and data planes and logically centralizing the traffic management intelligence, the controller directly manages SDN aware devices via a well-defined interface and control protocol. The central control paradigm of SDN enables the controller to utilize network resources efficiently and facilitate QoS differentiation for services through network-wide optimization [4].

B. Prior Art and Limitation

Many successful efforts have used SDN to improve access network performance [5]-[8]. Reference [9] presented an architectural design and system implementation for a GPON based OpenFlow - enabled SDN virtual switch. By combining the DBA and bandwidth control of the add-on OpenFlow switch, their virtual switch can control bandwidth usage accurately and dynamically. Reference [10] proposed possibilities for integrating OpenFlow in GPON, in which an OpenFlow controller directly performs the DBA function. In addition, ONUs would have to be enhanced to provide OpenFlow-like matching and processing functions. A detailed implementation of the system is not addressed in that work.

Furthermore, a variety of technologies have been proposed for improving the energy efficiency of PONs [11]-[15]. Enabling Optical Network Units (ONUs) to enter sleep mode for energy saving is considered one of the most effective methods [16]-[22]. In particular, Reference [11] proposes a parametric extension allowing the unified power management mode, in which an ONU periodically turns off both its receiver and transmitter, as in the cyclic sleep mode, and performs infrequent bidirectional handshakes, as in the doze mode. The timely reaction to an external stimulus is ensured by periodic unidirectional handshakes when only the ONU receiver is turned on. The unified mode thus combines the advantages of the two standardized power saving modes, and a system that supports the unified mode can emulate either the cyclic sleep or doze behavior as a special case. Simulation results show the energy efficiency superiority of the unified mode over either of the two standardized...
modes in general. Reference [18] presents an energy efficient medium access control protocol exhibiting intelligent switching among ONU transceiver power levels. This is implemented by introducing a new methodology at the ONU active free state of NG-PONs based on the adaptation of standard local sleep and local doze queue indicators to a more comprehensive grated mode selection policy. Computer simulations have shown the superiority energy efficiency of this study. Reference [23] proposed a QL (queue length) -based proportional and proportional-derivative controllers, effectively reduce the power consumption of ONUs while maintaining the downstream queuing delay at a constant level. Besides, many Dynamic Bandwidth Allocation (DBA) were usually just used inside a single Optical Line Terminal (OLT), lacking flexible bandwidth configurations among multiple OLTs. As a result, a huge waste of network resources exists in idle areas in all working devices. What’s more, the majority of traditional schemes realize bandwidth allocation according to terminal bandwidth requirements and pre-established 3-saving mode (active, doze and sleep) switching policies [24], [25]. However, in the current 3-saving mode DBA method (3M-DBA), when the end point of the DBA period is reached, regardless of whether there is a large data traffic, ONU will always be awakened. So a 4-saving modes (active, doze, light sleep, deep sleep) and multi-periods mixed adaptive dormancy method is needed to maximum energy saving efficiency.

C. Proposed Approach and Key Contributions

This paper designs a Software Defined Distribution Optical Network (SD-DON) framework. Control mechanism includes multi-domain scheduling, dormancy awareness and bandwidth allocation. It is beneficial to simplify the control process, improve network management and maintenance level, and promote the greenization of the distribution networks. Besides, a novel multi-modes hybrid dynamic bandwidth allocation algorithm (MH-DBA) is first proposed under SD-DON architecture. One of the challenges is to specify a scheduling order in which data transmission, light/deep sleep period, and doze period are scheduled. Moreover, ONU sleep/doze time should be carefully determined so that energy-savings can be achieved whilst maintaining the required Quality of Service. Simulation results show that MH-DBA under SD-DON can significantly save ONU energy, provide lower latency under high traffic loads, and can ensure the communication quality of the power system.

The next sections arranged as follows. Section II describes the SD-DON architecture. Section III describes our definition for four kinds of ONU energy saving mode, and the MH-DBA scheme in detail. Section IV gives our simulation results and analysis. In Section V, we will conclude the paper.

II. SD-DON ARCHITECTURE

EPON have been widely considered as the most favorable access network technology of its low cost, easy to use and easy to update to cater for the growing demand of bandwidth-hungry applications. Combine PON technology, architecture of SD-DON from perspective of multi domain convergence and integration control is illustrated in Fig. 1. Consisting of control layer, 4-level backbone communication network layer and access layer. The distribution optical access network refers as underlying network devices including OLT, splitter and ONU. These ‘goofier’ hardware only need to transmit data and execute strategies, with the controller implementing the analysis and management about network strategies instead. The access layer provides the control layer with programmable interfaces based on OpenFlow protocol, which is the standard communication protocol. Domain controller can be integrated into the OF-OLT. Convergence occurs in gateways on 4-level electric power backbone network layer between control layer and access layer, achieve the information intelligent collection and gathering. The application layer can realize more complex functions using the north application programming interface (API) on the control layer. Based on the proposed SD-DON architecture, the key technologies of ONU sleep and energy saving are proposed in this paper.

Based on the proposed SD-DON architecture, the function and the mutual cooperation relationship of each control module are shown in Fig. 2. The innovation lies in adding the Adaptive Dormancy Control Module (ADCM) and the Multi Domain Control Module (MDCM) to realize the multi domain ONU energy saving strategy. In control plane, the Traffic Monitoring Module (TMM) collects the statistics of services’ traffic. MDCM balanced the allocation of the whole network OLTs bandwidth/traffic. On receiving the flow state, the traffic scheduling policy of the Dynamic Bandwidth Allocation Module (DBAM) will allocate bandwidth according to the
required time slot of different services. According to the dormancy strategy, the slot calculation unit of ADCM calculate each ONU’s slot distribution and slot energy-saving state (active/ doze/ light sleep/ deep sleep). Operation Administration and Maintenance (OAM) module feedback to DBAM to adjust each ONU bandwidth slot allocation in order to meet the requirements of energy saving effect. Particularly, operators will deploy this energy-saving policy module into controller in the form of plug-in, and it will make convenient for control strategy expansion and customization.

Data/ forwarding plane describes the exchange process of OLT and ONU. In OF-OLT, the downstream (DS) traffic is generated by the receiver in the Tx/Rx module and broadcast to all connected ONU. For the upstream (US), the Tx/Rx module can be used to receive traffic and allocate bandwidth slots with different granularity for the corresponding ONU. OpenFlow protocol agent is Embedded in the OF-OLT maintaining the information flow table, and simulate OLT related control information (e.g. ONU sleep state), the software content is mapped as the hardware (transmitter and receiver internal switchgear) control and adaptation. Therefore, the US and DS link can be virtualized as a logical flow. Similarly, OpenFlow protocol agent is also embedded in the ONU, ONU interact with OF-OLT through signaling, directly control transmitter and receiver internal switchgear.

light sleep mode. If after 2nd Thr_{time}, data cache is still less than Thr_{cache}, ONU may enter deep sleep mode.

2) Sleep command
OLT assign ONU to enter sleep mode with this kind of GATE.

3) Awake state
An interim mode, when the clock (ONU_{clk}) of sleep control achieves sleep interval, ONU enters this mode spontaneously receiving the trigger from the sleep control.

4) Active interval
The periods ONU in active mode. In active interval, all models of ONU are active. It receives normal gate and DS data from OLT and transmits data according to the normal gate’s start time and length.

5) Doze interval
The time ONU in doze mode. In doze interval, ONU transmitter close off, and stops transmitting data. ONU also maintains a timer to calculate the doze period which is specified by OLT. Keep the part function active of the receiver. The data which arrives during the doze period will be temporally stored in ONU’s buffer. When ONU_{clk} sleep control arrives a DBA cycle, T, ONU will always be awaked.

6) Light sleep interval
The time ONU in light sleep mode. Stop all function of user interface, optical receiver and transmitter. ONU cannot receive or send any traffic. Similar to doze state. When ONU_{clk} arrives T, ONU will always be awaked, and start to transmit data stored in buffer.

7) Deep sleep interval
The same as light sleep interval, ONU cannot receive or send any traffic, but ONU may sleep for a polling period which is 2T. When ONU_{clk} sleep control arrives polling periods, 2T, ONU will always be awaked, and start to transmit data stored in buffer according to the sleep gate’s start time and length.

B. MH-DBA Scheme Operation
The MH-DBA protocol operation for intra-domain is illustrated in Fig. 3. For US, OLT calculate the time and US bandwidth when the US data begin to transmit in the next cycle. Then, OLT bond the time and the bandwidth together to constitute a GATE, and put it into the GATE queue. For DS, The MH-DBA performs dynamic scheduling where the OLT waits for all the report messages from ONUs before computing grants for the next cycle. Before assign the bandwidth for an ONU, OLT should check the GATE queue. If there is GATE waiting to transmit, OLT assign the time slot for all GATE first, then calculate the start time and bandwidth for the ONU.

Meanwhile, ONU could not sent Report package utilizing SDN, in order to compact time slots to reduce bandwidth resource occupancy of OLT. OLT allocates data slot duration as the minimum between US and DS buffer backlogs. The OLT first sends a GATE to an ONU. When the ONU receives the GATE, both US and DS data transmissions take place. When the data slot duration
ensures that both OLT and ONU have sufficient bandwidth for both transmission directions.

When incorporating four energy saving modes into the operations of a PON system, a scheduling scheme must specify where to insert the doze period and/or light, deep sleep period into an existing order of data transmission, and GATE message. Therefore, the scheduling order becomes a challenge.

This paper implements MH-DBA schemes as shown in Fig. 4. If monitoring large bandwidth requests, all models of ONU remain active. Otherwise, according to $\text{Thr}_{\text{time}}$ that set by controller, judge ONU’s energy saving state. We assume two DBA cycle as a polling period. If the data in report and cache is smaller than the $\text{Thr}_{\text{cache}}$ within the time, ONU may enter doze mode. If exceeding $\text{Thr}_{\text{time}}$, there are still little data requests or smaller uplink traffic, ONU may enter light sleep mode, and the sleep interval is $T$. Otherwise, inactive state exceeding a DBA period $T$, ONU may enter deep sleep mode of the sleep interval $2T$. When the timer reaches the sleep interval, ONU spontaneously goes to wake mode. ONUs in state doze or light sleep will judge again whether remain the original mode. When the timer reaches polling period ($2T$), ONUs start to transmit data stored in buffer according to the sleep gate’s start time and length.

C. MH-DBA under SD-DON

DBA algorithm is one of key technologies of EPON. The MH-DBA algorithm we propose, means adopting multi-periodic polling to assign bandwidth in both upstream and downstream direction. When power service trigger, ONU mapping as service request. The flow chart of MH-DBA under SD-DON Implement and definitions of some parameters are described in Table I. We take DS DBA for instants.

In general, MH-DBA is divided into two types, inter-domain and intra-domain, which are described as step 2 and step 3. For inter-domain. Each domain OLTs gathering ONU service requests and ONU network status report to multi domain controller. According to the OLT queues cache in per domain and prediction results, controller evaluate the traffic demand in next $T$ cycle. Then it allocate OLT bandwidth as principle of reduce free domain OLTs bandwidth, as well as prior to occupy busy domain. In each domain, the OLT has to store downstream data to separate cache for each ONU first, and then poll every ONU and assign the bandwidth according to the caches. Take instants, OLT collect all

Fig. 3. Scheduling order of MH-DBA scheme operation

Fig. 4. Illustration of MH-DBA scheme operation
ONUs report in advance according to the different types of ONU request in the OLT feedback and the length of the reported message (caches). Weighting and convergence, calculate the length of time slot and the upstream bandwidth for each ONU, and then return to the domain controller. For intra-domain. An upstream or downstream DBA cycle means the summation of transmission timeslot for each ONU when OLT has polled all ONUs once. Because the time slot for each ONU is related to the report in upstream, the cache in downstream, the cycles are different. The calculation of upstream and downstream transmit time slot is associated to each other. Particularly, step 4 utilizes the dormancy strategy we presented above, the slot calculation unit of ADCM calculate each ONU’s slot distribution and slot energy-saving state (active/ doze/ light sleep/ deep sleep). In step 5, 6 and step 7, OF-OLT function module receive OF south interface message, maintain the information flow table. ONU interact with OF-OLT through signaling, and start ONU sleep-state-switch module to make the corresponding action, due to the active period, doze period and/or light, deep sleep period, directly control transmitter and receiver internal switchgear. Do the bandwidth allocation according to the scheduling order of data transmission. Besides, maximum allowable delay $TD_{max}$ is derived directly through controller which is alterable in step8. If $TD_{set}>TD_{max}$ then service block. Else, service succeed.

<table>
<thead>
<tr>
<th>TABLE I: FLOW CHART OF MH-DBA UNDER SD-DON</th>
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<tr>
<td>$TD_{max}$ denotes the maximum allowable delay set by controller; $TD_{req}$ denotes the retransmission latency; $TB_{active}$ denotes the US available bandwidth of OLT; $UB_{request}$ denotes the US bandwidth request of ONU;</td>
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<tr>
<td><strong>Step1</strong>: ONU mapping as service request.</td>
</tr>
<tr>
<td><strong>Step2</strong>: For inter-domain. Each domain OLT gathering ONU service requests and network status report to multi domain controller. Controller evaluate the traffic in next T cycle due to the OLT queue cache and prediction results per domain, then allocate OLT bandwidth as principle of reducing free domain OLT bandwidth, and prior to occupy busy domain. If $TB_{active}&gt;UB_{request}$ then go to step 3, else, jump to step 6.</td>
</tr>
<tr>
<td><strong>Step3</strong>: For intra-domain. OLT collect all ONUs report in advance according to the different types of ONU request in the OLT feedback and the length of the reported message. Weighing and convergence, calculate the length of time slot and the US bandwidth for each ONU, and then feedback to multi domain controller.</td>
</tr>
<tr>
<td><strong>Step4</strong>: According to currently network-wide energy saving state, DBAM start the sleep slot calculation unit of ADCM to calculate the next time slot saving state.</td>
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<td><strong>Step5</strong>: OF-OLT function module receive of south interface message, open/close OLT transceiver due to the calculated energy saving state.</td>
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<td><strong>Step6</strong>: OLT and ONU interact by signaling, start ONU sleep-state-switch module to make the corresponding action.</td>
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<td><strong>Step7</strong>: Bandwidth allocation. If succeed, then jump to step9, else return null.</td>
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<td><strong>Step8</strong>: Start latency retransmission mechanism, controller update $TD_{max}$. If $TD_{set}&gt;TD_{max}$ then service block, jump to Step 9, else, jump to Step 2.</td>
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<tr>
<td><strong>Step9</strong>: Service processing end.</td>
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### IV. EXPERIMENTAL RESULTS AND ANALYSIS

We evaluate the effectiveness of the proposed MH-DBA by means of extensive simulations of a PON with one OLT and eight ONUs per domain using C-based discrete-event simulator OPNET 14.5. More values of evaluation parameters are shown in Table II. The physical distance between the OLT and ONUs is set randomly following a uniform distribution between 15km and 20km. Both US and DS channels operate at a data rate of 1Gbit/s. The energy consumption of an ONU in the active mode, doze mode, light sleep mode and deep sleep mode are equal to 3.75W, 1.70W, 1.08W and 0.40W, respectively. Upon bandwidth allocation, the OLT sets the length of a given cycle based on the allocated bandwidth and the start time, which may be adjusted dynamically by controller within a permissible range.

<table>
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<th>TABLE II: VALUES OF EVALUATION PARAMETERS</th>
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<tr>
<td>Parameters</td>
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<td>-------------------------------------------</td>
</tr>
<tr>
<td>DS and US data rate</td>
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<tr>
<td>Data frame size</td>
</tr>
<tr>
<td>Data buffer size</td>
</tr>
<tr>
<td>Number of domains (N)</td>
</tr>
<tr>
<td>Number of ONUs (N) per domain</td>
</tr>
<tr>
<td>ONU power consumption(Pa, Pd, Pols and Pds)</td>
</tr>
<tr>
<td>physical distance between the OLT and ONUs</td>
</tr>
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</table>

In the following, the performance metric used in the evaluation is average energy-savings.

$$
\mathcal{G} = \frac{(P_{f_d} + P_{f_d} + P_{f_d})}{(P_{f_d} + P_{f_d} + P_{f_d} + P_{f_d})} \tag{2}
$$

where $P_{f_d}$, $P_{f_d}$, $P_{f_d}$, $P_{f_d}$ are the ONU power consumption in active, doze, light sleep, and deep sleep states; $t_{f_d}$, $t_{f_d}$, $t_{f_d}$, $t_{f_d}$ are the average time an ONU sojourns in each state within an operating cycle.

In the case of limited cache, the system will appear the packet loss. Firstly, we consider packet loss in the simulation to evaluate the performance of all algorithms in terms of average energy saving ratio, average latency and packet loss ratio.

By comparing the proposed MH-DBA and conventional 3M-DBA scheme in Fig. 5, the presented results clearly show that MH-DBA has a superior performance in terms of energy saving of ONUs. For 3M-DBA, when the end point of the DBA period is reached, ONU will always be awakened. But for MH-DBA, one more sleep state implies more waiting packets and extended sleep time which could greatly improve the energy efficiency. As we can see from Fig. 5, the average energy saving ratio is 0.85 of MH-DBA and 0.28 of 3M-DBA when network load under 50 Mbit/s. Thus, MH-DBA could reduce the energy consumed by about 32.9% compared with 3M-DBA under low network load. ONU’s
energy-savings of both two schemes encounter significant decline at light traffic loads. Since higher delays implies more waiting packets and longer sleep time. The extended sleep time also helps improve the energy efficiency of the ONU. At medium and high traffic loads, MH-DBA is able to offer a lower delay, resulting in a higher energy consumption of the ONU transmitter. Hence, the lower cycle time leads to a lower energy saving rate of ONUs. When network load exceed 300 Mbit’s, it starts to level off. It also because MH-DBA considering one more energy saving mode than 3M-DBA, and the ONU sleep time can be adjusted as much as possible to maximize energy efficiency.

![Fig. 5. Average energy saving ratio](image)

![Fig. 6. Average latency](image)

US average latency of two schemes is demonstrated in Fig. 6. In most cases, latency of 3M-DBA is lower than MH-DBA scheme because of the smaller cache in channel. However, for increasing traffic loads, dynamic sleep polling cycle plays a main role. This advantage helps the transmission system adapt to real access environments, where traffic is mostly large or bursty. What’s more, the efficient utilization of bandwidth also improves the maximum available channel capacity. MH-DBA shows its superiority by providing similar delay under mid- and heavy-load conditions compare with 3M-DBA. Since an adjusted shorter DBA cycle can reduces the occupation of cache. The channel capacity is not occupied fully and all the traffics can be serviced without more delay.

Fig. 7 shows that the packet loss ratio is increasing as the growth of traffic. For the reason that higher delays for increasing traffic loads lead to a large number of data packets waiting in the buffer. In most cases, packet loss ratio of 3M-DBA is lower than MH-DBA scheme because of the smaller cache in channel. Due to the longer sleep time during deep sleep state, there may be large data cache store in the queue, and the total cache is easy to exceed $Thr_{cache}$, which may lead to the packet loss. In this situation, controller will adjust $Thr_{cache}$ shorter automatically, so as to guarantee the QoS of service.

![Fig. 7. Packet loss ratio](image)

Secondly, in order to reflect the superiority of improved energy-saving mechanism than the traditional mechanism more directly, we make the simulation without any packet loss for all algorithms by increasing the queue buffer and to further evaluate the performance in terms of average energy saving ratio and average latency.

![Fig. 8. Average energy saving ratio](image)

![Fig. 9. Average latency](image)
When the throughput tends to be stable, we conclude the results of energy efficiency that can be seen from Fig. 8. With the increase of traffic load, energy saving ratio of the two mechanisms is reduced, for the reason that the probability of the system to trigger a sleep mechanism is reduced as the load increases. But the presented results still clearly show that MH-DBA has a superior performance in terms of energy saving of ONUs in all scenarios. In Fig. 9, MH-DBA shows its superiority by providing similar lower delay under heavy-load conditions compare with 3M-DBA. Since an adjusted shorter DBA cycle can also reduce the packet waiting time.

V. CONCLUSIONS

This paper proposes a SD-DON architecture that aims to incorporate ONU’s four dormancy modes into DBA algorithms to reduce ONU energy consumption. Meanwhile, though MH-DBA, ONU energy saving time are maximized as differentiable four modes for any given network condition to maximize energy efficiency. Results show that MH-DBA achieves a good energy saving efficiency, lower delay and can significantly ensure the quality of the distribution optical networks.

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