Enabling Flexible Software-Defined Energy-Efficient Orchestration in TWDM-PON

Andrew Fernando Pakpahan[1], I-Shyan Hwang[2]

[1] Department of Information Technology, Universitas Advent Indonesia, Indonesia
[2] Department of Computer Science and Engineering, Yuan Ze University, Taiwan
andrew@unai.edu, ishwang@saturn.yzu.edu.tw

Abstract

The emergence of time and wavelength division multiplexed-passive optical network (TWDM-PON) architectures as next-generation access network technologies necessitates the development of new types of network devices and enhanced flexible operations. In this paper, we propose the software-defined (SD) energy-efficient architecture and operations in the TWDM-PON in which legacy PON devices are enriched with SD capabilities. The SD programmable operations deliver a balance between OLT and ONU energy-saving, while still guaranteeing the QoS requirements. We provide system performance and energy-savings trade-off analysis and compare the delay, throughput, and drop probability with the energy-savings performance in the OLT and ONU for various scenarios.

Keywords: TWDM-PON, SDN, Energy-efficiency, QoS

1 Introduction

Energy efficiency is an important issue in developing high-capacity next-generation fixed access network systems that can cope with exponential growth in subscriber traffic. Thus, it is being given serious consideration by government agencies, consortia, and standard bodies concerned about reducing the contribution of information communication technology (ICT) to global energy consumption [1]. Consequently, the next-generation access networks need not only to offer vast capacity, backward compatibility but also low energy consumption. Therefore, to satisfy rapidly evolving and newly emerging services, these devices have to be evolved in order to make them adaptable to the always changing necessities while facilitating energy-saving operations.

Passive optical network (PON) is a prominent access network with fiber-to-the-everything (FTTx) technology that has the least power consumption among the available access network choices [2]. This next-generation PON architecture is called time and wavelength division multiplexed (TWDM)-PON. It offers network operators upgradeable access network technologies that have a vast capacity, larger-geographical coverage, and higher number of clients. However, TWDM-PON consumes more energy and requires more complex resource management [3]. Furthermore, the standard architectures and their working mechanisms are often defined in hardcoded devices and differ in implementation according to their vendors. Thus, a new technology is needed to provide agility and energy-saving operations to the TWDM-PON. The emergence of software-defined networking (SDN) provides a unified programmable architecture with central control, global awareness, and granular resource provisioning. Thus, software-defined (SD) TWDM-PON architecture [4] is a suitable solution to provide more flexible access network and energy-saving operations. This article aims at proposing flexible SD energy-saving operations in the TWDM-PON. We propose to enhance legacy PON devices with programmable SD technology which enable SD granular energy-efficient orchestration that can be rapidly reconfigurable to different requirements.

The remainder of this article is organized as follows. Sections II and III discuss the working mechanism of TWDM-PON and the development of software-defined (SD) PONs, respectively. Section IV discusses the present energy-saving mechanism of the standard PONs and the necessities of SD TWDM-PON. Sections V and VI outline the proposed SD energy-saving architecture that encompasses the SD reinforced TWDM-PON architecture and its operation, respectively. Section VII discusses the system performance and energy-saving in different scenarios. Section VIII analyzes the results and concludes this work.

2 TWDM Passive Optical Network

TWDM-PON standards are described in the next-generation ITU-T NG-PON2 (ITU-T G.989.1) [5] which outlines the stacking of several TDMA-PONs

*Corresponding Author: I-Shyan Hwang; E-mail: ishwang@saturn.yzu.edu.tw
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[2]. TWDM-PON retains the physical topology of TDMA-PON, which comprises an optical line terminal (OLT), placed at the operator's central office (CO) and multiple optical network units (ONUs) located at the locations where the subscribers are. However, the OLT of TWDM-PON requires multiple transceivers in different wavelength pairs, and the ONUs have either a tunable transceiver (NG-PON2). PON is a point-to-multipoint architecture in the downstream direction and multipoint-to-point in the upstream direction. In the downstream direction, each OLT's transceiver broadcasts the packets destined to the ONUs on the same wavelength while all ONUs listen for the broadcasted packets and determine whether to receive or discharge a particular packet based on their type and destination address. To enable ONU access to the shared upstream channel, the OLT deploys a dynamic wavelength and bandwidth allocation (DWBA) mechanism, where it allocates a unique transmission timeslot and wavelength to each ONU based on the reported queue size.

3 Software-Defined TWDM-PON

To provide a flexible TWDM-PON that adapts to the changing necessities, its hardware has to be easily manipulated and programmable [6] which can be realized by enhancing the TWDM-PON architecture with SDN technology. It reduces the network devices' responsibilities and transfers their control functionalities to an external SD-controller to be controlled by high-level language SD applications that are easily programmable and allows the rapid deployment of new services and functionalities. OpenFlow is a notable SDN protocol that enables SD application control of network devices by implementing SD tables in the devices. In TWDM-PON, OpenFlow signals can be used to manage and synchronize the wavelength configuration of OLT and ONU with SD configurable circuit-based digital signal processing transceivers [7]. The reconfiguration capability of SD TWDM-PON is combined with end-to-end SD management of PON elements and core networks may provide fast protection and dynamic wavelength allocation [8]. To achieve a complete SD reconfigurability of a PON system may require virtualizing its components (i.e., dynamic bandwidth allocation (DBA), media access control (MAC) control client, and operations administration and management (OAM)). However, virtualizing all PON components introduces additional delay and degrades the performance of TWDM-PON systems [9]. Therefore, a new approach is needed to enable SD mechanisms and signaling to work in conjunction with the standard PON protocols [10]. Through its optimal SD granular dynamic resource provisioning, SD TWDM-PON has the potential for energy-saving operations while providing a future-ready management platform.

4 TWDM-PON Energy-saving

To reduce its energy consumption, the OLT needs to be dynamically programmed to suppress the number of active transceivers in low traffic conditions. However, the OLT controls the PON system and is considered an ever-ready device. Moreover, each OLT transceiver is associated with some ONUs that work in particular wavelength pairs. Therefore, before an OLT transceiver can be shut down, the connected ONUs need to be migrated to other transceivers' wavelengths [11-12]. If there is only a tunable transceiver in the ONU, it needs to be tuned to the forthcoming working wavelength. An additional means of reducing energy consumption is to apply the adaptive link rate (ALR) mechanism that enables the OLT and ONUs to transmit at different speeds [13].

Table 1 compares the transmitter and receiver working modes and system operations in the available standard ONU energy-saving schemes, IEEE's SIEPON [14], ITU-T GPON [15-16], Watchful Sleep [17], and our proposed mechanisms. To reduce energy consumption, an ONU can turn off its transmitter while keeping the receiver on to receive downstream traffic from the OLT (Tx/Doze/Listen). Further energy-consumption reduction can be achieved by the ONU turning off both the transceiver and the receiver (TRx/Sleep/Asleep). However, keeping the ONU receiver off for an extended period can result in the ONU losing synchronization with the OLT, causing disconnection. This can be avoided by temporarily turning on the receiver (Watch) to maintain the synchronization of the PON system.

TWDM-PON transmission medium sharing mechanism brings a straightforward means for ONU to work in Tx-off. In its upstream transmission, only a single ONU can transmit its data on a specific wavelength at a particular time, and other ONUs are idle during the waiting time. To conserve energy, each inactive ONU could switch its transmitter to Tx-off while buffering its subscribers' packets. Subsequently, when the predetermined transmission timeslot arrives, the ONU could activate the transmitter to transmit the buffered packets. In Rx-off mode, the ONU cannot receive any data from the OLT, and the OLT needs to buffer the downstream packets for a certain period. When an ONU spends more time with fewer components turned on the energy-saving performance increases. ONU energy-saving is achieved by postponing the ONU transmission for a certain amount of time to achieve the desired energy-saving operations. It is important that the energy-saving operation is achieved while still satisfying the QoS requirements and to provide a balance between the energy-saving and to guarantee the QoS.

Table 1. ONU's Energy-Saving Modes and System Operations Comparison of Non-SD and The Proposed SD Architecture

	Non SD architectures			Proposed SD enabled architecture
	SIEPON [14]	GPON [15]	Watchful Sleep [17]	
Transmitter & receiver energy-saving condition				
Transmitter & receiver off	TRx	Sleep	Asleep	Tx-off/Rx-off
Transmitter off & receiver on	Tx	Doze	Listen	Tx-off/Rx-on
Receiver periodic wake up	-	-	Watch	
System operations				
Transmitter & receiver can be independently managed		No		Yes
Energy-saving assignment		OLT		SD application
ONU wake-up decision		OLT		ONU (based on SD-defined threshold)
Programmable/high-level configured		No (Hardcoded/low-level configured)		Yes
Dynamically reconfigurable upon deployment		No		Yes

The previous energy-saving studies [18-20] mostly focused on how to save energy by efficiently turn-off the OLT wavelengths or putting the ONUs to sleep modes for a specified period. They mostly rely on inflexible hard-coded energy-saving algorithms. Thus, when operators are confronted with newly emerging services or changes in policies and requirements, the devices' firmware need to be reprogrammed. This inflexibility adds maintenance time and operation expenditure. Therefore SD technology is being implemented to enhance energy-saving in OLT, where the transceivers activation/deactivated can be controlled by SD controller that is rapidly reconfigurable upon deployment.

5 Proposed Software-defined Architecture Energy-saving For TWDM-PON

Figure 1 depicts the proposed comprehensive SD TWDM-PON architecture, in which the active devices are enriched with OpenFlow technology. The proposed SD TWDM-PON consists of an SD-OLTs, a multiplexer (MUX) /demultiplexer (DEMUX), a power splitter, multiple SD-ONUs, and an SD-platform.

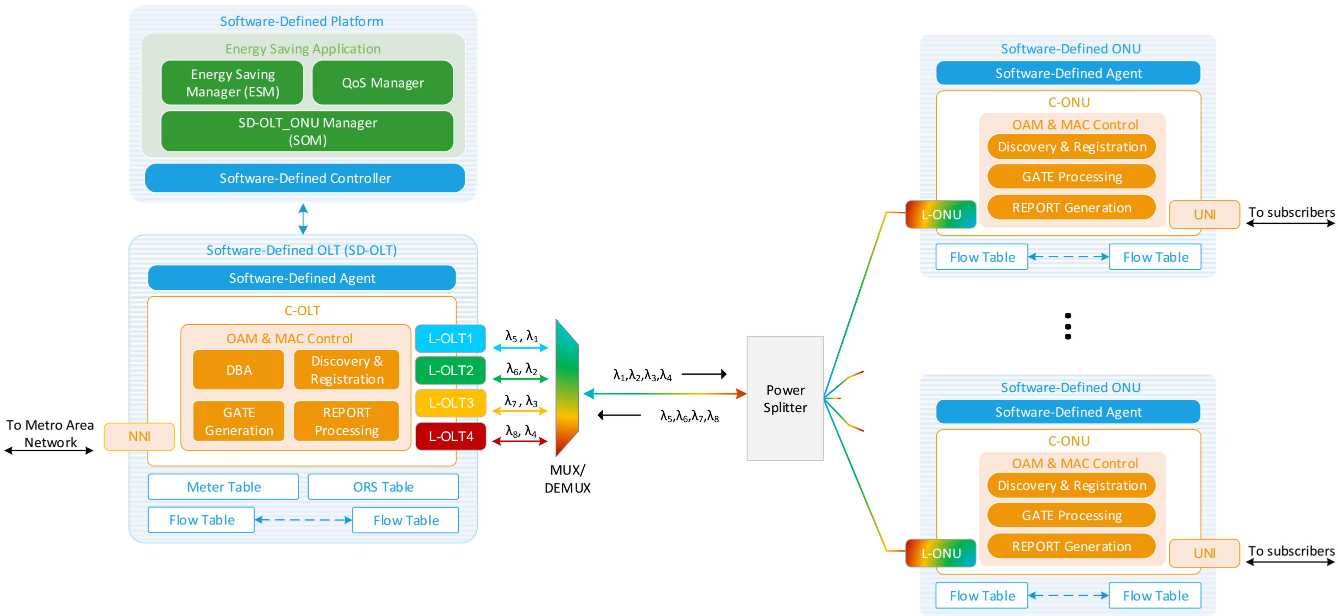


Figure 1. Proposed software-defined TWDM-PON energy-efficient architecture

5.1 SD-OLT & SD-ONU

The SD-OLT and SD-ONU are based on SIEPON [14] C-OLT and C-ONU, respectively, which are enhanced with SD technology to enable programmable SD energy-saving operations. The SD-OLT and SD-ONUs are equipped with an SD-Agent and flow tables. The SD-Agent is responsible for: SD-Agent to SD-Controller communication, transceiver activation/ deactivation, ONU wavelength tuning, and link-rates configuration. The flow tables provide SD packet classification, queueing, and forwarding for all input and output ports.

The SD-OLT connects the TWDM-PON system to the metro network and the SD platform through its network-to-network interface (NNI). The SD-OLT has four transceivers (L-OLTs) that are tuned to different wavelengths and can work in two link-rates, 1 Gb/s and 10 Gb/s. Conversely, the SD-ONU's user-to-network interface (UNI) connects the subscribers to the SD-OLT by a tunable transceiver (L-ONU) that can be tuned to any of the wavelength pairs of the SD-OLT.

The MAC control is responsible for standard EPON multipoint control protocol (MPCP) discovery/ registration process and GATE/REPORT message generation/processing. The dynamic bandwidth allocation (DBA) allocates upstream timeslots allocation for the SD-ONUs. Furthermore, the SD advancements in the SD-OLT are realized by a meter table and an ONU Rx-off (ORS) table. The meter table provides the QoS-based downstream transmission rate-limiting. The ORS table provides the Rx-off duration for the SD-ONUs to be used by the OAM to execute energy-saving signaling to the SD-ONUs.

5.2 SD-Platform

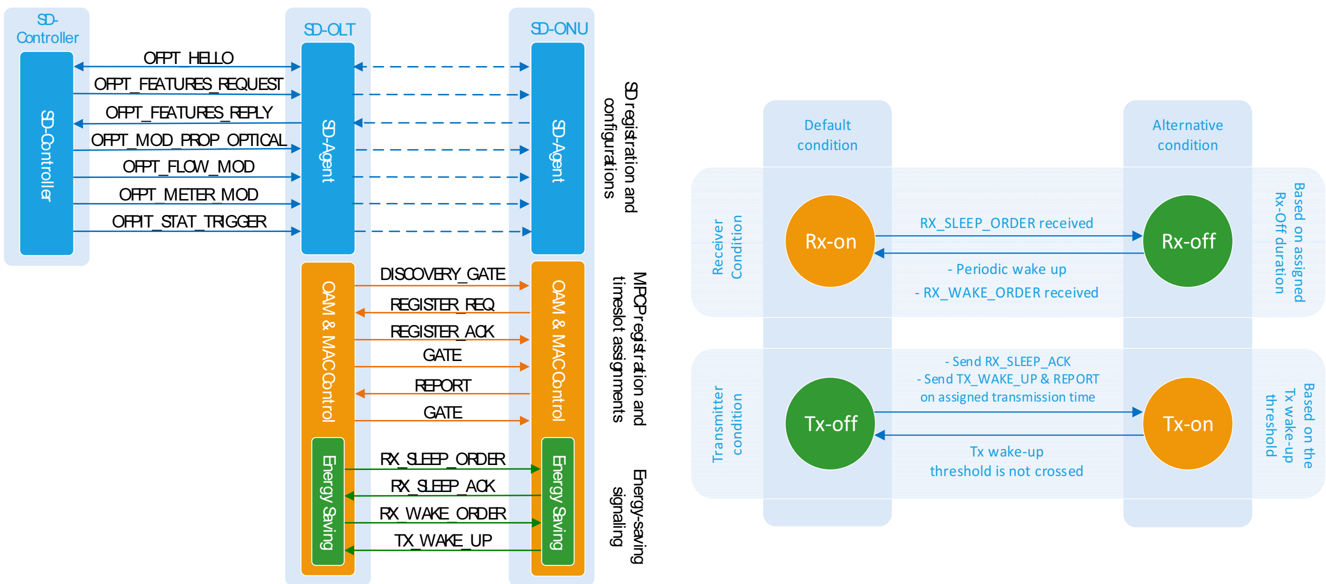
The SD-platform enables the programmability of the proposed SD TWDM-PON which includes an OpenFlow controller (SD-Controller) with multiple energy-saving SD applications on top of it. The SD-Controller interacts with SD energy-saving application using an application programming interface (API). Subsequently, it translates the applications' instructions to device-specific configurations and realizes the changes through the SD-Agents using OpenFlow messages.

The following energy-saving SD applications provide the energy-saving operations orchestration in the SD TWDM-PON:

- Energy-saving manager (ESM): orchestrates the dynamic resource provisioning and energy-efficient operation based on the global knowledge of devices condition and traffic load database.
- QoS manager: defines the QoS of the PON system which collaborates with the ESM and SD-OLT's DBA to define the downstream QoS traffic, energy-saving boundaries, and timeslot allocations for SD-ONUs, respectively.
- SD-OLT_ONU manager (SOM): controls the operation of the SD-OLT and SD-ONU. It has the following responsibilities: Ordering the activation/ deactivation and adjusting the link rate of the L-OLT, initiates the wavelengths tuning of the L-ONU at which the ESM corresponds.

6 Proposed Software-defined Energy-saving Operation for Twdm-pon

Figure 2(a) depicts the proposed SD operation and signaling of the discovery and registration process, and energy-saving signaling of the proposed SD TWDM-PON architecture.



(a) Combined software-defined, MPCP, and OAM signaling

(b) Proposed ONU transmitter and receiver conditions

Figure 2. Signaling and ONU transceiver conditions in the proposed software-defined energy-saving operation for TWDM-PON

6.1 Initialization and Registration

The initialization and registration process starts with the SOM activates the default L-OLT on the pre-configured default wavelength and link rate. Then, it initiates a twofold SD-ONU registration system, which enables the SD-ONU to be managed by both the SD-OLT and SD-Controller. The MPCP based registration is done by the SD-OLT through sending a DISCOVERY_GATE, followed by REGISTER_REQ from the SD-ONU and REGISTER_ACK from the SD-OLT to confirm the registration process. After the MPCP registration is completed, the SD registration is initiated by sending the OFPT_HELLO followed by OFPT_FEATU-RES_REQUEST AND OFPT_FEATU-RES_REPLY by the SD-ONU. After the SD-ONU is registered, the SOM orders the QoS manager to populate the SD-ONU's flow tables for packet-classification and assign the corresponding QoS configuration in the SD-OLT's DBA. Thus, when a packet enters the SD-ONU, it enters a particular queue according to the entries in the flow tables. When a transmission timeslot comes, the SD-ONU sends the occupied queue size using REPORT messages to the SD-OLT. Afterward, the DBA allocates the upstream transmission timeslots to the SD-ONUs according to the QoS manager discretion.

6.2 SD Configurations

The SD-Controller translates the SD application's directions to the device-specific configuration using specific OpenFlow messages.

- Wavelength and link-rate configuration. The OFPT_MOD_PROP_OPTICAL message is used to set the wavelength/link rate configuration.
- Flow and meter tables configuration. OFPT_ FLOW_MOD and OFPT_METER MOD are used to alter the flow and meter tables entries.
- Threshold configuration. The OFPIT_STAT _TRIGGER is used to configure the transmitter (Tx) wake-up queue threshold settings in the SD-ONU.
- ORS table configuration. We propose a new OFPT_ES_MOD to modify the SD-ONU Rx-off duration in the ORS table.

6.3 SD Energy-Saving Operations in the SD-OLT

The SD-OLT energy-saving operation is accomplished by adjusting the number of active L-OLTs and their link-rates based on the overall PON traffic and energy-saving condition of the SD-ONU. The number of the minimum required L-OLT (TR_{num}) is calculated as:

$$TR_{num} = \frac{BW_{request}}{W_{throughput}}, \quad (1)$$

where the $BW_{request}$ and $W_{throughput}$ are the total average bandwidth request of all active SD-ONUs and maximum throughput of an L-OLT in higher link-rate, respectively.

Based on TR_{num}, the foreseeable capacity of each required L-OLT is acquired. If the TR_{num} is less than one, then only one L-OLT is activated. Conversely, if the TR_{num} is more than the number of available L-OLT, all L-OLTs will be activated. Moreover, to achieve more energy-saving performance, the adaptive link-rate capability may be employed to switch the link-rate of the L-OLT to the lower one if the traffic condition may be served by the lower the link rate.

In order to synchronize the SD-OLT energy-saving operation and the SD-ONU one, before an L-OLT could be shut down or switched to lower link-rate, the registered SD-ONUs need to be migrated/switched to the forthcoming active wavelength or link-rate configurations. Moreover, to avoid a sleeping SD-ONU goes out of sync and redo the discovery and registration process, during the migration process, the SOM has to make sure that all affected SD-ONUs are not sleeping and receive the migrating order.

6.4 SD ONU Energy-Saving Parameters

To achieve the desired energy-saving operation, there are several system parameters that need to be determined: the SD-ONU's Rx sleeping duration (Rx-off duration) and Tx wake-up threshold (Tx_threshold).

(1) *Rx-off duration*

The Rx_sleeptime is based on the maximum queue boundary, downstream traffic, link-rate, and the QoS requirements. The SD-controller calculates, $T_{Rx[TT]}$, the maximum time that a traffic type can tolerate for Rx_sleeptime, and is expressed as Eq. (2):

$$T_{RX[TT]} = \frac{Q_{[TT]-threshold}}{R_{[TT]-NNI} - R_{[TT]\text{-}OUT}}, \quad (2)$$

where $Q_{[TT]\text{-}threshold}$, is the maximum queue boundary for a TT, while $R_{[TT]\text{-}NNI}$, and $R_{[TT]\text{-}OUT}$ are incoming and outgoing traffic. Then, to avoid QoS violation, the Rx_sleeptime is chosen from the minimum value of $T_{Rx[TT]}$ of all traffic type.

(2) *Tx wake-up queue threshold*

The Tx_threshold value for each SD-ONU depends on the average recent PON cycle time, $T_{cycle\text{-}avg}$, where the cycle time is a time needed for all SD-ONUs to complete their assigned transmission timeslots and the QoS requirements for the high priority packets. First, the $C_{[TT]wait}$, is calculated as in Eq. (3), which is the number of cycles that the packets spent in the SD-ONU's queue until the QoS requirement for each traffic type, TT_{Qos_req}, is reached.

$$C_{[TT]wait} = \frac{TT_{QoS\_req}}{T_{cycle\_avg}}. \quad (3)$$

Afterward, the SD-controller calculates independent initial Tx_thresholds for each traffic type, $Tx_{inital\_thld_{[TT]}}$, is expressed as Eq. (4):

$$Tx_{inital\_thld_{[TT]}} = V_{offset} \times (P_{in\_avg[TT]}) \times C_{[TT]wait}, \quad (4)$$

where V_{offset} and $P_{in\_avg[TT]}$ are the offset value to achieve the QoS requirement and the average incoming traffic for the TT, respectively.

The $Tx_{inital\_thld[TT]}$ calculation in Eq. (4) determines the initial threshold for the maximum occupancy of each traffic types in ONU's buffer, without violating the QoS requirements as in Eq. (3). Lastly, to avoid buffer overflow the Tx_threshold for each traffic type, $Tx_{thld[TT]}$, is the minimum value of the calculated initial threshold and the maximum buffer capacity of each queue of an SD-ONU, as can be seen in Eq. (5):

$$Tx_{thld_{[TT]}} = \min(Tx_{inital\_thld_{[TT]}}, Q_{max[TT]} - P_{in_{avg[TT]}}), \quad (5)$$

where, $Q_{max[TT]}$ is the maximum queue size for the TT.

After the energy-saving parameters is calculated, the Rx-off duration is stored in the ORS table, while the Tx_threshold is sent to the ONUs.

6.5 SD Energy-Saving DBA (SDES-DBA)

The SD energy-saving DBA (SDES-DBA) is responsible to dynamically allocate the upstream bandwidth for each SD-ONU. The SD-OLT begins the bandwidth allocation computation after collecting the REPORT messages from all SD-ONUs. The SDES-DBA assigns upstream transmission timeslot to the active SD-ONUs and gratuitous grant for SD-ONUs in energy-saving mode. The available timeslots are allocated to the active SD-ONUs and distributed for each TT depending on the traffic priority, where higher priority traffic is satisfied first and the remaining assigned to lower priority traffic. There is two information contains in the gratuitous grant assigned to the SD-ONU in energy-saving: listening time and transmission time. The listening time is the time for SD-ONU to turn on its Rx to receive the next gratuitous grant message. While the gratuitous transmission time is used by SD-ONU's Tx to exit the energy-saving mode and only enough for transmitting a REPORT message.

6.6 SD Energy-Saving Operations in the SD-ONU

Figure 2(b) depicts the proposed SD-ONU transmitter and receiver conditions and the circumstances surrounding the switch to different modes. The SD-ONU's receiver and transmitter condition are decided by the Rx-off duration assignment and the (Tx) wake-up queue threshold, respectively. The Rx-off duration and Tx wake-up queue threshold are decided by the ESM based on the QoS manager information and system traffic condition. The ESM sets the ONU's Rx-off duration in the ORS table, while the Tx wake-up is set directly in the SD-ONUs' flow tables queues. The Rx-off duration and Tx wake-up threshold calculation is based on maximum boundary delay requirements of different types of present traffic.

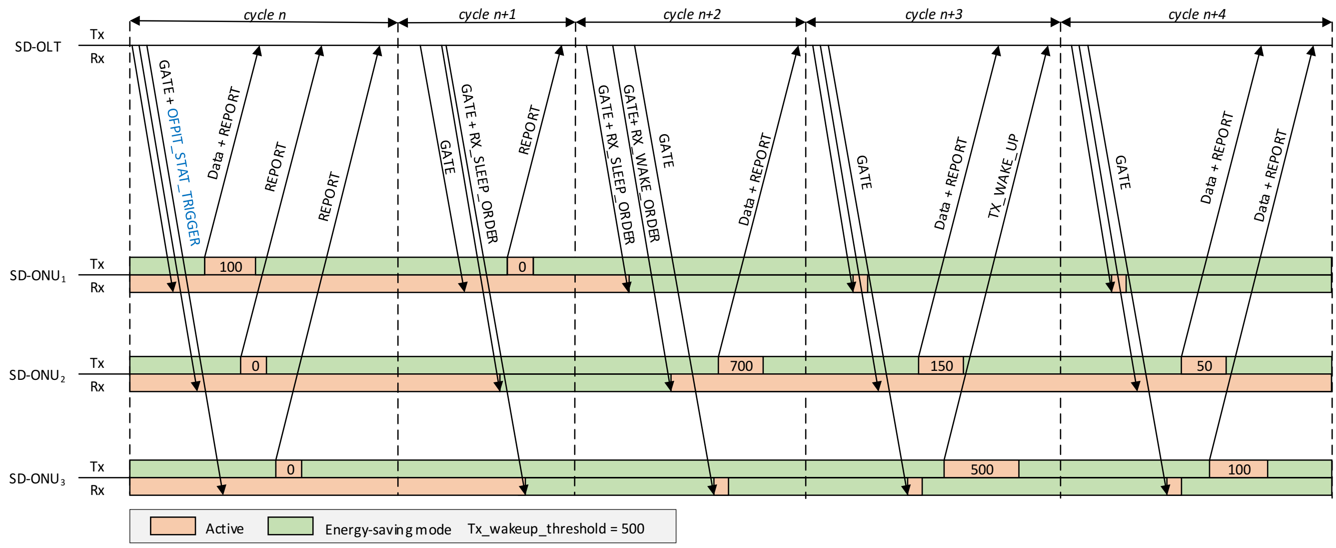


Figure 3. Proposed SD-ONU energy-saving operation

Figure 3 shows the proposed SD-ONU energy-saving operation. In cycle n, the SD-OLT forwards the Tx wake-up threshold configuration assigned by the ESM using OFPIT_STAT_TRIGGER message. Meanwhile, the ESM populates the ORS table with the Rx-off duration of the eligible SD-ONUs. Based on this table, the SD-OLT's OAM generates the RX_SLEEP_ORDER to the SD-ONUs. The default condition of the SD-ONU's receiver is Rx-on: then, upon receiving the RX_SLEEP_ORDER (in cycle n+1), the SD-ONU's switches the receiver to Rx-off during the assigned duration and switches to Rx-on if an RX_WAKE_ORDER is received. However, even when the SD-ONU is in Rx-off, it needs to switch the receiver to Rx-on regularly for a short time. This is done to receive the GATE message (for time synchronization and to determine the gratuitous granted time to submit the TX_WAKE_UP message) and the RX_WAKE_ORDER message. Conversely, the default condition of the SD-ONU transmitter is Tx-off, and it is switched to Tx-on if the Tx wake-up threshold is passed (in cycle n+3), the SD-ONU switches the transceiver to Tx-on at the gratuitous transmission time and sends the TX_WAKE_UP and REPORT concurrently. When the TX_WAKE_UP message is received by the SD-OLT, the ESM is made aware of the buffer condition of the SD-ONU and orders the SDES-DBA to assign the next transmission timeslot according to the latest SD-ONU's REPORT message.

7 System Performance

In this section, we analyze the proposed mechanism regarding system throughput, average delay, packet drop probability, and SD-OLT and SD-ONU energy-saving. The proposed mechanism was modeled using an OPNET simulator with 64 SD-ONUs and an SD-OLT with four L-OLTs. The downstream/upstream channel rate between the SD-OLT and SD-ONU was dynamically assigned as 1 or 10 Gb/s. The SD-OLT and SD-ONUs were uniformly distributed at distances between 10 km and 20 km, and the SD-ONU buffer size was 10 Mb. The L-OLT power consumption of an is 5 W [21]. ONU power consumption in active mode is 3.85 W, 1.7 W in Tx mode and 1W in TRx mode [22]. The maximum transmission cycles were 1.5 ms, and self-similarity and long-range dependence were used as the network traffic model for the AF and BE traffic, respectively. The model generated high-burst AF and BE traffic with a Hurst parameter of 0.7 and a packet size uniformly distributed between 64 and 1,518 bytes. The EF traffic was based on a Poisson distribution with fixed packet size (70 bytes).

To show the energy-saving and system performance trade-off, we compared four system operation cases, as listed in Table 2: Case 1 had no energy-saving configured, Case 2 had the energy-saving functionality available only in the SD-OLT, Case 3 had the energy-saving functionality only in the SD-ONU, and Case 4 had the energy-saving functionality in both the SD-OLT and the SD-ONU. There are two traffic profiles simulated: 136 (EF occupied 10%, AF occupied 30%, BE occupied 60%) and 154 (EF occupied 10%, AF occupied 50%, BE occupied 40%).

Table 2. Simulation scenario

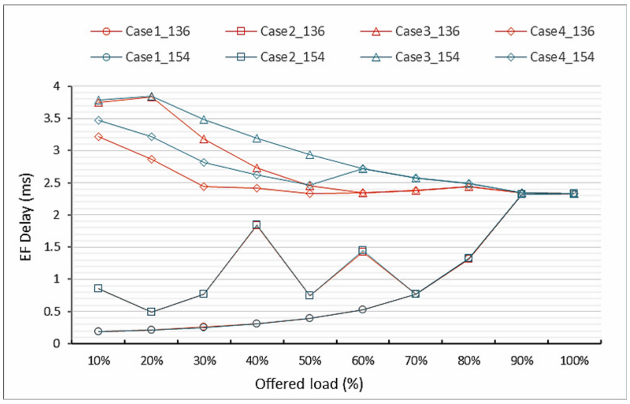
Scenario	OLT Energy Saving	ONU Energy Saving
Case 1	No	No
Case 2	Yes	No
Case 3	No	Yes
Case 4	Yes	Yes

7.1 Mean Packet Delay

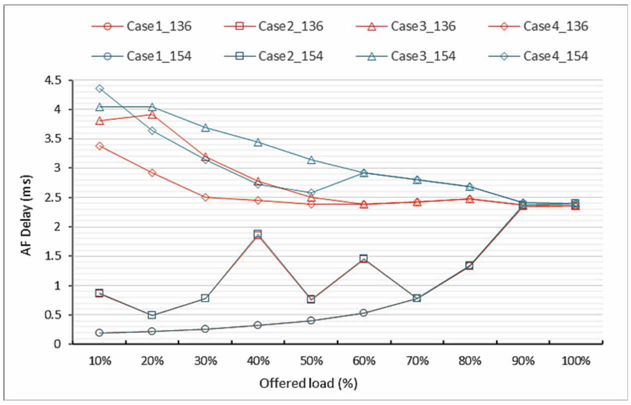
Figure 4(a) and Figure 4(b) show the mean packet EF and AF delays for different simulation cases. Case 1, with no energy-saving operation configured, had the lowest EF delay performance because the packets were transmitted with no additional delay to save energy. Case 2 had higher delay performance that fluctuates depending on the traffic load and the number of active transmitters. If the number of active L-OLTs remained the same, the delay increased along with the traffic load. Conversely, when there were more active L-OLTs, the delay became lower because when there were more active L-OLTs, the number of SD-ONUs sharing the same wavelength decreased and the SD-ONU had more time to transmit its packets. When there is still enough time to transmit the packet the EF and AF experience similar delays, but the BE delays will suffer; when the EF and AF traffic occupy more part of the traffic, the BE delays become higher. In Case 3, the packet transmission was delayed according to the Tx wake-up threshold. When the traffic load was low, the packet transmission could be delayed to save more energy. However, when traffic load increased, the delay decreased, because SD-ONUs Tx wake-up threshold was reached faster and there was less time to spend in energy-saving mode. Case 4 had lower delay compared to Case 3 because to save energy in lower traffic load, there were fewer L-OLTs deployed, and more SD-ONUs shared the same L-OLT, and there was less available transmission timeslot. Moreover, when the traffic load was above 50%, Case 3 and Case 4 had the same performance because the number of active L-OLTs in both cases were the same.

7.2 Throughput

Figure 5(a) shows the system throughput versus the offered load. The system throughput is the PON line rate multiplied by the combined efficiency, which includes the management and encapsulation overheads. In low traffic condition, the throughput of cases with energy-saving configured (Case 2, 3 and 4) was lower than the Case 1 because the packet transmission is delayed to save more energy, resulting in less throughput. However, when the traffic load was above 70%, all of OLT transceivers were activated. Thus Case 3 and Case 4 had the same throughput performance.

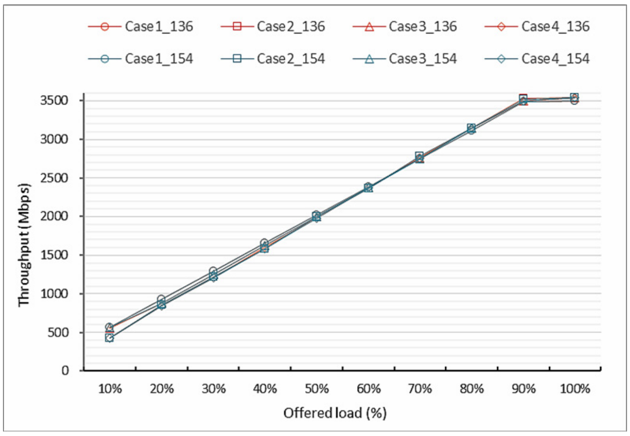


(a) EF traffic

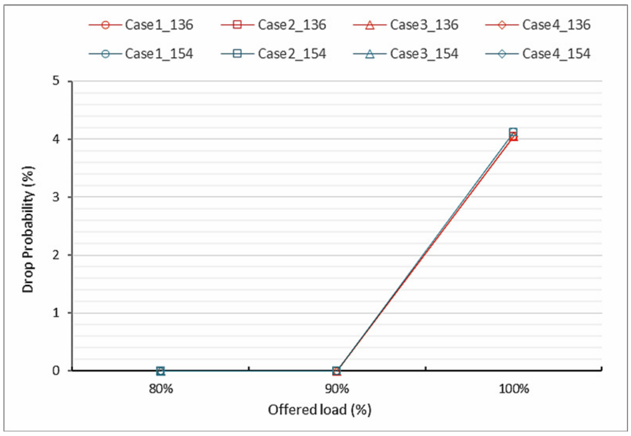


(b) AF traffic

Figure 4. Mean packet delay comparison



(a) System throughput



(b) Packet loss probability

Figure 5. Throughput and packet loss in different traffic scenarios

7.3 Packet Loss Ratio

Figure 5(b) shows the packet loss ratio of different cases. There were no packet losses in the high priority EF and AF packets in all cases with different traffic loads. All cases had no packet loss when the traffic load was less than 90%. However, if the buffer is full when the traffic load was high, the low priority BE packets are dropped to maintain the necessary QoS performance.

7.4 Energy-saving

Figure 6 shows the SD-OLT energy-saving performance of Case 2 and Case 4 in different traffic scenarios. When the traffic is less than 80%, fewer active transceivers were needed, which resulted in a higher SD-OLT energy-saving percentage. Conversely, when the traffic load was more than 70% (for Case 2) and 60% (for Case 4), there was no SD-OLT energy-saving because all of the L-OLT were activated to avoid the excessive delay that violates the QoS requirements. The SD-OLT energy-saving of Case 4 in 40% and 70% traffic load were lower compared to Case 2 because to achieve SD-ONU energy-saving more active wavelengths were required. Figure 7 shows the SD-ONU energy-saving performance in Case 3 and Case 4 in different traffic condition. The SD-ONU energy-saving performance had decreasing trend along with the increment of the traffic load and the number of active wavelengths. When the traffic condition was less than 60%, Case 3 had better SD-ONU energy-saving performance than Case 4 because in Case 3, all wavelength was always active and SD-ONU had more available transmission timeslot and can achieve more energy-saving. Thus, the SD-ONU energy-saving performance of Case 4 depends on not only the SD threshold but also the number of active L-OLTs. Finally, to maintain the necessary QoS requirements, there were no energy-saving achieved when the traffic load is more than 80%.

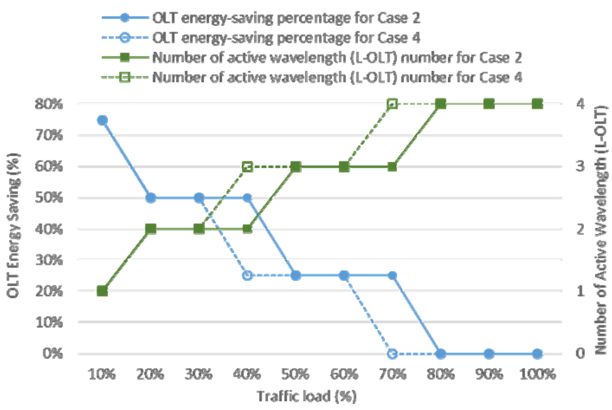


Figure 6. SD-OLT energy-saving in various traffic scenarios

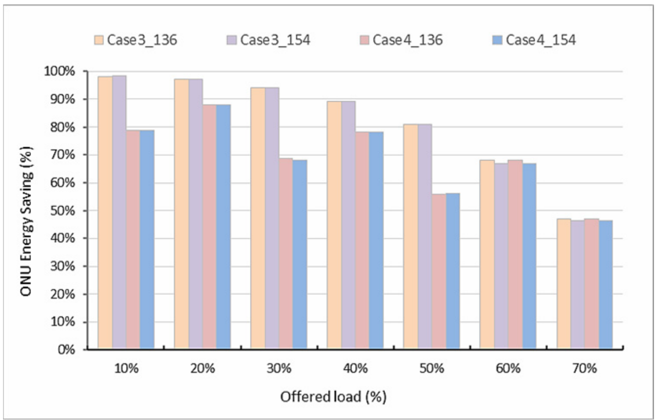


Figure 7. SD-ONU energy-saving in various traffic scenarios

8 Conclusion

In this article, we proposed an SD TWDM-PON architecture, which enables flexible SD energy-efficient orchestration in the PON system. The energy-saving calculation and decision-making are separated into the SD applications that orchestrate the SD-OLT and SD-ONU energy-efficient operations by adjusting the number of active SD-OLT transceivers, link-rates, SD-ONU's Rx sleeping duration, and ONU Tx wake-up threshold. The separation of the energy-saving control to SD applications made the proposed architecture a suitable platform to implement advance mechanisms to automate the energy-efficient operations of the PON system. Nevertheless, the emerging services such as 5G, C-RAN, edge computing, fog computing, and Internet of things push the requirement of advanced and agile first mile devices.

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Biographies

Andrew Fernando Pakpahan received a B.S. degree in computer science from Universitas Advent Indonesia, Bandung, Indonesia and M.S. in Informatics from Institut Teknologi Bandung, Indonesia, and received a Ph.D. degree in Computer Science & Engineering at Yuan Ze University, Taiwan in 2018. Andrew Fernando Pakpahan is with the Department of Information Technology, Universitas Advent Indonesia, Bandung 40559, Indonesia. His current research interests are in passive optical network, software-defined networking, and network function virtualization.

I-Shyan Hwang received B.S. and M.S. degrees in Electrical Engineering and Electronic Engineering from Chung-Yuan Christian University, Chung-Li, Taiwan, in 1982 and 1984, respectively, and M.S. and Ph.D. degrees in Electrical and Computer Engineering from the State University of New York at Buffalo, NY, in 1991 and 1994, respectively. In Feb. 2007, he was promoted to Full Professor in the Department of Computer Science & Engineering at the Yuan Ze University, Chung-Li, Taiwan. His current research interests are fault-tolerant computing, high-speed networks, fixed mobile convergence, heterogeneous multimedia services over fiber optic networks, NGN, green computing and optical-network based infrastructure over cloud computing. He serves as a member of the Editorial Board for the Springer *Photonic Network Communications* Journal.