ITU TWDM-PON Module for ns-3 Network Simulator

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Abstract. Optical fiber access systems are one of the driving forces behind the success of the Internet. Time- and wavelength- division multiplexing passive optical network (TWDM-PON) is regarded as the key technology for future Internet access networks. In this paper, we propose an ITU TWDM-PON module for the ns-3 network simulator and describe its concept and design specifications. The proposed module is developed based on the XG-PON module for ns-3. It can simulate G.989 standard-compliant data packet transmission in the upstream and down- stream directions using multiple wavelength channels. It enables us to evaluate the performance issues that arise with the TWDM-PON development, including various dynamic bandwidth allocation (DBA) and dynamic wavelength allocation (DWA) algorithms. The proposed module is expected to become a good platform for studying future access networks composed of TWDM-PON and mobile networks by enabling us to simulate dynamic wavelength and bandwidth allocation (DWBA).

Keywords: ns-3 · TWDM-PON · Wavelength allocation · Bandwidth allocation

1 Introduction

During the last few decades, the numbers of both fixed and mobile broadband subscribers and their data consumption have increased greatly. Optical fiber access systems are one of the driving forces behind the success of the Internet. Passive optical networks (PONs) are the key technology for providing low-cost access services.

The architecture of PON based access networks is shown in Fig. 1. The optical line terminal (OLT) is usually located in a central office. The optical net- work units (ONUs) are located on the subscriber's premises. They are connected through the optical distribution network (ODN), which consists of optical fiber and power splitters located in the outside plant. As the next step in relation to optical access systems, the standardization and development of time- and wavelength- division multiplexing passive optical network (TWDM-PON) including next generation-PON2 (NG-PON2) [12], which is a 40 Gb/s capacity PON system [6, 7], are under way. TWDM-PON is expected to be a multi- service platform that includes residential, business, mobile, machine to machine (M2M), and Internet of things (IoT) services as shown in Fig. 1.

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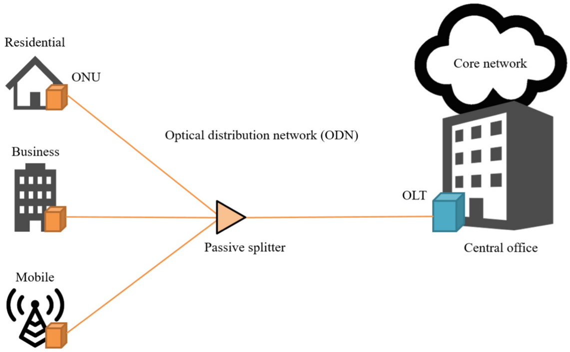

Fig. 1. Access network architecture.

The bandwidth and power consumption of TWDM-PON must be scalable, flexible, and efficient to provide various services. Since work on TWDM-PON is still in its early stages, a simulation of TWDM-PON would be useful and effective in terms of its development and deployment. In this paper, we present an ITU TWDM-PON module for the ns-3 [8] network simulator, which is a state of the art open source network simulator. The proposed module is expected to become a good platform for studying future access networks composed of TWDM-PON and mobile networks by enabling us to simulate dynamic wavelength and band- width allocation (DWBA).

This paper is organized as follows. Section 2 describes the background and related work. Section 3 introduces the concept of the proposed ITU TWDM-PON module. Section 4 describes the design specification of the developed module. Section 5 provides the conclusion.

2 Related Work

The ns-3 [8] simulator is an open source based network simulator. It has been pointed out that ns-3 uses less CPU and memory and the simulation speed is higher than other network simulators [5, 11]. For ns-3, an XG-PON module was developed, which is based on G.987 recommendations [14]. The XG-PON module focuses on the physical medium dependent (PMD) and transmission convergence (TC) layers, including frame structure, resource allocation, quality of service (QoS) management, and dynamic bandwidth allocation (DBA) algorithms. To improve the simulation speed, the ODN and the operations of physical layers are simplified. With this module, the XG-PON performance can be evaluated using existing ns-3 modules, including a realistic Internet protocol stack and various wireless networks (LTE, WiFi, WiMAX, etc.).

Several studies simulated XG-PON with this module. The need for an im- proved DBA algorithm and scheduling mechanism was revealed from the performance evaluation of three TCP variants (Reno, CUBIC, and H-TCP) [2]. The X-GIANT DBA algorithm was proposed and implemented in the XG-PON module to evaluate the delay and throughput for different classes of traffic [3]. The group-GIANT DBA algorithm was developed to assign group assured bandwidth to backhauling base stations with PON [1].

There have been some cases where a TWDM-PON simulation was performed. These include for a digital radio over fiber (DRoF) system [9], for a WDM-PON downstream physical link evaluation using an optical transmission simulator [10], and for a K-out-of-N scheduling technique for DBA with a discrete event simulation model [4]. However, there has been no simulator to evaluate packet level data transmission for TWDM-PON using various protocol stacks. The development of an ITU TWDM-PON compatible module for ns-3 is useful for studying various DBA and DWA algorithms and evaluating the integration of TWDM- PON and wireless networks. To develop the module, we need to implement WDM transmission by stacking wavelength channels based on the XG-PON module. In addition to WDM, we require ONU assignment to a wavelength and an ONU wavelength channel handover sequence, which include PLOAM message transfer and the ONU state transition. In addition, there have been limitations as regards the XG-PON module. To evaluate various DBA algorithms such as multi-thread polling and multi-cycle allocation, the DBA functions need to be redesigned. To improve the delay measurement accuracy, we need to employ differential propagation delays for the ONUs and calculate the start time of upstream traffic at each ONU should be implemented.

3 ITU TWDM-PON Module Concept

We describe the concept of the proposed ITU TWDM-PON module for the ns-3. The overall purpose of the module is to simulate the data packet transmission in G.989 recommendations and evaluate the throughput and delay using various DBA and DWA algorithms.

3.1 Overview

Basic Idea. We developed the ITU TWDM-PON module based on the XG-PON module [14], because the concept of the XG-PON module matches the purpose of the proposed module. Therefore, the features of the module are inherited from the XG-PON module. This module performs stand-alone and packet-level simulation. The physical layer is simplified, and the ODN is modeled as a simple channel. The optical transmission is assumed to work well, and the propagation delay and line rates are simulated. Line coding, payload encryption, cyclic redundancy check (CRC), and header error correction (HEC) are not implemented. The bandwidth overhead and the effect of forward error correction (FEC) are implemented, but the FEC procedure is not. To evaluate the performance of the TWDM-PON system during normal operation, PLOAM and OMCI channels are not fully implemented. The activation or ranging procedure in operating TWDM-PON is also not implemented.

DWBA Simulation. To simulate the time- and wavelength- division multiplexing (TWDM) packet transmission in the upstream and downstream directions, we decided to employ multiple PON channels, which represent individual wave- length channels between an OLT and ONUs. ONU assignment to a wavelength and ONU wavelength channel handover are performed by enabling one channel from the set of PON channels. The sequence of ONU wavelength channel handover, including the PLOAM message transfer and the ONU state transition, is implemented to evaluate and compare DWA algorithms.

For accurate measurement of the data packet transmission in each channel, the DBA functions are redesigned and the accuracy of data transmission is improved compared with the XG-PON module. We can use various DBA algorithms, including multi-thread polling and multi-cycle allocation. The delay measurement accuracy is improved by calculating the start time of the upstream traffic at an ONU, the propagation delay between an OLT and each ONU, and their frame-processing delay.

3.2 Channel Model

In the following, we explain the concept of major implemented functions. And, we describe the channel model. To simulate the multiple wavelength channels provided by TWDM-PON, OLT and ONU devices are connected to multiple PON channel classes. Each of the PON channel classes corresponds to a wavelength channel. ONUs are assigned and handed over using these PON channel classes.

There is one PON channel between an OLT and the ONUs in the XG-PON module. All the ONUs always use the PON channel and the bandwidth is allocated to all the ONUs by the DBA engine of the OLT. In the TWDM-PON module, there are multiple channels between an OLT and the ONUs. Each channel is connected to the OLT and all the ONUs. An ONU enables one channel and disables the other channels. We assumed that an ONU uses only one channel at a time, and the same channel is used for upstream and downstream data transmission for simplicity. The downstream frame transmission and DBA are performed at each channel considering the ONU wavelength allocation.

3.3 ONU Channel Handover

The implemented ONU wavelength channel handover sequence basically follows G.989 recommendations. The implemented ONU state transition is shown in Fig. 2a, which is the normal operation part of the ONU state diagram. Figure 2b shows the OLT wavelength handover states for each ONU. Simulation of the normal handover sequence does not require the implementation of inter-channel- termination protocol (ICTP) and rollback process.

The handover sequence is as follows. First, an ONU is operating in the Associated state in a specific channel. The OLT is in the *Hosting* state at a source channel termination (CT) and in the *Unaware* state at the target CT. The source OLT CT sends *Tuning Control* specifying the target ONU, target channel, and scheduled SFC. The OLT state transits to the *Redirecting* state at the source OLT CT and the *Expecting* state at the target OLT CT. After that, a PLOAMu grant is allocated to the ONU in both the source and target channels. If the ONU can start the handover, it sends *Tuning Response (ACK)* and transits to the *Pending* state. When the source OLT CT receives *Tuning Response (ACK)*, the state becomes *Seeing-off*. The ONU starts the tuning procedure at the scheduled SFC. The state transition order in the tuning is *Off-sync*, *Profile learning*, and *US tuning state*. When the tuning is finished, the ONU sends *Tuning Response (Complete u)*. When the target OLT CT receives the message, it sends *Tuning Control (Complete d)* and downstream data. The OLT state transits to *Hosting* in the target CT and *Unaware* in the source CT. The ONU receives *Tuning Control (Complete d)* and transits to the *Associated* state.

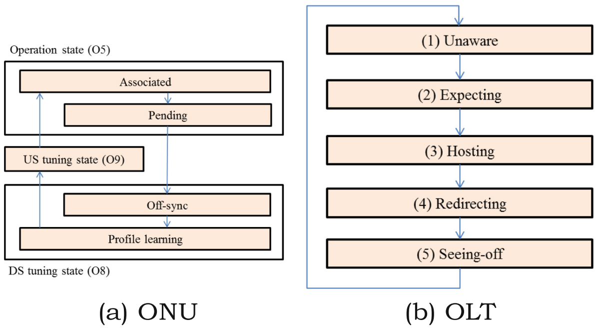

Fig. 2. Wavelength handover state transition.

3.4 DBA

DBA Procedure. Figure 3 shows the DBA procedure assumed in this paper. An ONU sends its buffer occupancy to an OLT when it sends uplink data. We call it a request message in this paper. The OLT calls the DBA engine in order to calculate the bandwidth allocation for ONUs based on their requests. Then, the OLT sends the bandwidth allocation to each ONU, which is sent using the BW map in ITU TWDM-PON. We call it a grant message in this paper. The grant message includes the start time and the data size assigned for each ONU. The ONU sends uplink data in accordance with the grant. The DBA procedure described above enables ONUs to share the uplink bandwidth flexibly.

Multi-cycle Allocation. The OLT sends a grant to ONUs every 125 μs, and this is called the grant cycle in this paper. The DBA engine does not need to calculate the bandwidth allocation to all the ONUs in one grant cycle as regards the reduction in the processing time in a real machine. We call the time period between DBA calculations a DBA cycle. A DBA cycle is *k* times a grant cycle, where *k* is a natural number. We enabled the DBA engine to carry over its calculation result over *k*–1 grant cycles in the

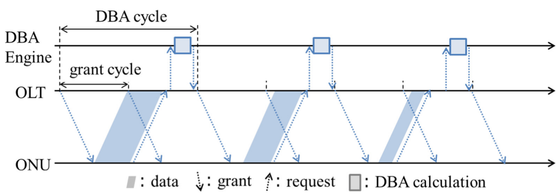

Fig. 3. DBA procedure.

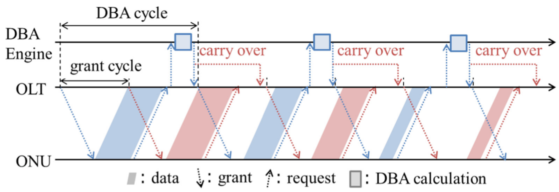

Fig. 4. Multi-cycle allocation.

TWDM-PON module. We call this multi-cycle allocation. Multi-cycle allocation is a natural extension of the usual DBA process (single-cycle allocation). Multi-cycle allocation can improve bandwidth utilization efficiency as shown in Fig. 4.

Multi-thread Polling. The sequence including a request, a DBA calculation, and a grant is called a thread in this paper. We enabled the OLT to poll multiple threads in parallel as shown in Fig. 5, which is called multi-thread polling [13]. Multi-thread polling is a natural extension of the usual DBA procedure (single- thread polling). The OLT can poll *k* threads in parallel when the DBA cycle of a single-thread is *k* times of the grant cycle. Multi-thread polling can reduce the time between packet arrival and the next request sent by that ONU. However, since the DBA cycle of *k*-thread polling is a *k*-th of that of single-thread polling, multi-thread polling can place a high load on a CPU in a real machine. The difference between multi-cycle allocation and multi-thread polling is the frequency of the DBA calculation.

Start Time. For simplicity, the XG-PON module assumes that the propagation delays of all ONUs are same, the equalization delays (EqD in Fig. 6) of all ONUs are zero, and the response time of all ONUs is zero. To improve the accuracy of the delay measurement, we implemented differential propagation delays for the ONUs and the calculation of start time of upstream traffic at each ONU. Figure 6 shows the timing relationships stated in G.989.3 [12]. The TWDM-PON module calculates the equalization delays with [12]:

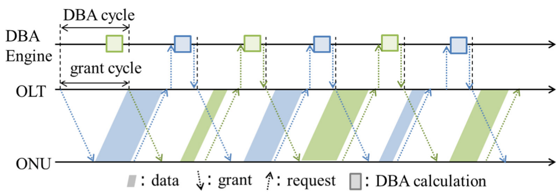

Fig. 5. Multi-thread polling.

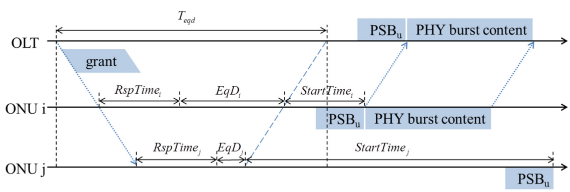

Fig. 6. Timing relationships.

$$EqD_i = RTD_i - T_{eqd} = RTT_i + RspTime_i - T_{eqd}. \quad (1)$$

EqDi represents the equalization delay of ONUi, RTD_i represents the round-trip delay of ONUi, RTT_i represents the round-trip time of ONUi, $RspTime_i$ represents the response time of ONUi, and T_{eqd} represents the zero-distance equalization delay. $RspTime_i$ is set at 35 μs in this module, since it is required to be 35 ± 1 μs. We can set T_{eqd} based on the ODN design parameters [12].

4 Design Specifications

This section describes the design specifications of the ITU TWDM-PON module in detail.

4.1 Channel and Network Devices

An OLT and an ONU are represented as *ItutwdmponOltNetDevice* and *ItutwdmponOnuNetDevice* attached to *Node*. Four *ItutwdmponChannel* instances are attached to them, each of which represents a wavelength channel in the ODN.

ItutwdmponOltNetDevice sends and receives the PON frames of each *ItutwdmponChannel* using per channel *ItutwdmponOltEngine*s, *ItutwdmponOltPhyAdapter*, and *ItutwdmponOltDsScheduler*. The processes related to multiple *ItutwdmponChannel*, including ONU channel handover, are managed by *ItutwdmponOltDwaEngine*.

ItutwdmponOnuNetDevice produces and parses PON frames with *ItutwdmponOnuEngine*s. It sends and receives them through enabled *ItutwdmponChannel* using *ItutwdmponOnuPhyAdapter* of each channel. The enabling and disabling of *ItutwdmponChannel* is controlled by *ItutwdmponOnuDwaEngine*.

4.2 DWA Engine

OltDwaEngine performs the DWA procedure and manages the enabled channel of each ONU and the state transition of each channel in the OLT. The common functions for the DWA procedure are implemented in *OltDwaEngine* and DWA algorithms are implemented in subclasses. The functions of a DWA algorithm include deciding whether or not to start channel handover, and, if it decides to start the handover, selecting the target ONU and target channel. Various DWA algorithms can be easily implemented and compared with this implementation. *OnuDwaEngine* manages the enabled channel and state transition in the ONU.

OltDwaEngine and *OnuDwaEngine* cooperates with *OltPloamEngine* and *OnuPloamEngine* to exchange PLOAM messages. We implemented PLOAM messages, which are used for ONU wavelength channel handover signaling, namely message type ID 0 × 15 *Tuning Control* and message type ID 0 × 1A *Tuning Response*. The generation of a PLOAM message is driven by *OltDwaEngine* and *OnuDwaEngine* in the DWA sequence. *OnuPloamEngine* processes a received PLOAMd message in 750 μs.

OltDwaEngineFixedRroundRobin is implemented as a default DWA algorithm. With this algorithm, when a new ONU is added, it is assigned to one of multiple wavelength channels in a round-robin manner. The wavelength assignment is static and ONUs are not handed over to another channel.

4.3 State Transition

Here we describe the operation of an OLT and an ONU in each state as shown in Fig. 2.

OLT Operation. In the *Hosting* and *Redirecting* states, downstream Tx and upstream bandwidth allocation are enabled. In the *Redirecting* and *Expecting* states, PLOAMu is always granted. Because an ONU is limited to one enabled channel in this module, the enabled channel list is updated at the end of the *Redirecting* state and waits to receive *Tuning Response* message at the target channel. As a consequence, in the *Seeing-off* state, the frame forwarding and DBA grant are disabled. Although this operation is a slight modification of the standard approach, it has little effect on the frame transaction.

ONU Operation. In the *Pending* state, frames are not fragmented. A connection whose amount of data exceeds the available payload length is not selected by *ItutwdmponOnuUsScheduler*. In the *Off-sync* and *Profile learning* state, Tx and Rx are disabled. When the state becomes *Us tuning*, only Tx is disabled.

4.4 DBA Engine

Overview. *ItutwdmponOltDbaEngine* and *ItutwdmponOnuDbaEngine* are responsible for the DBA procedure described in Sect. 3.4. Because their design is basically the same as that in the XG-PON module, here we focus on updates from the XG-PON module. *ItutwdmponOltDbaEngine* calculates the bandwidth allocation for T-CONTs based on the enabled channel, and the state of the ONUs, which are obtained by calling *ItutwdmponOltDwaEngine*. *ItutwdmponOnuDbaEngine* calculates the start time of the upstream traffic based on the equalization delay and the response time of the ONU. Because the ranging procedure is not implemented in the proposed module, the propagation delay and the equalization delay are calculated before starting the data transmission.

Basic Algorithms. Here we introduce the basic DBA algorithms that we employed. These subclasses will help users to understand the basic concepts of the cycle and thread of DBA.

ItutwdmponOltDbaEngineProportional allocates bandwidth to all T-CONTs at each DBA cycle in proportion to their request size, as shown in Fig. 3. To allot transmission opportunity fairly and reduce upstream delay, the total slot size (125 μs) is proportionally assigned in a round-robin manner. The following algorithms are developed based on *ItutwdmponOltDbaEngineProportional*.

ItutwdmponOltDbaEngineMultiCycle employs the multi-cycle allocation shown in Fig. 4 by keeping a grant cycle counter and a grant log. Let k ($1 \leq k$) denote the initial value of the grant cycle counter, which can be set as a variable. k represents that the DBA cycle length is how many times of the grant cycle length, for example, $k = 2$ in Fig. 4. Let c denote the counter value, and c is decremented in each grant cycle and is reset to k when it reaches zero. If c is equal to k, *Ng-pon2OltDbaEngineMultiCycle* allocates bandwidth to all T-CONTs in proportion to the latest request size in the same way as *ItutwdmponOltDbaEngineProportional*, and stores the result in the grant log. Otherwise, it copies the grant log and the bandwidth allocation is the same as the last cycle.

ItutwdmponOltDbaEngineMultiThread employs the multi-thread polling shown in Fig. 5. Let K $(1 \leq K)$ denote the maximum value of the grant cycle counters.

Let n $(1 \leq n \leq K)$ denote the number of threads, and i $(0 \leq i \leq n-1)$ denote the thread identifier. The user can set n and K. k_i denotes the initial value of the grant cycle counter of i-th thread. k_i is set at $k_i = n - i$. Let c_i denote the counter value of i-th thread. c_i is decremented in each grant cycle and is reset to K when it reaches zero. If c_i is equal to K, *ItutwdmponOltDbaEngineMultiCycle* allocates bandwidth to all T-CONTs in proportion to the latest request size. Otherwise, it allocates no bandwidth. When $n = 1$, *ItutwdmponOltDbaEngineMultiThread* acts just like *ItutwdmponOltDbaEngineProportional*.

5 Conclusion

In this paper, we presented an ITU TWDM-PON module for the ns-3 network simulator and described its concept and design specifications. The proposed mod- ule is implemented based on the XG-PON module and can simulate the data packet transmission described in G.989 recommendations. TWDM packet trans- mission in the upstream and downstream directions is simulated using multiple PON channels. It enabled us to evaluate the performance issues that arise during TWDM-PON development, including various DBA and DWA algorithms. The proposed module currently implements the normal operation part of the state diagram. In the future, we will develop the activation and ranging procedure using PLOAM messages to evaluate the performance in more realistic situations.

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