An XG-PON Module for the NS-3 Network Simulator: the Manual

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Abstract

10-Gigabit-capable Passive Optical Network (XG-PON), one of the latest standards of optical access networks, is regarded as one of the key technologies for future Internet access networks. This report presents our XG-PON module for the NS-3 network simulator. This module is designed and implemented with aim to provide a standards-compliant, configurable, and extensible module that can simulate XG-PON with reasonable speed and can support a wide range of research topics. These include analyzing and improving the performance of XG-PON, studying the interactions between XG-PON and the upper-layer protocols, and investigating its integration with various wireless networks. In this report, we will introduce PON and XG-PON, discuss design principles and trade-offs made during the course, describe the design and implementation details, and present the preliminary evaluation results.

I. Introduction

During the last few decades, we have witnessed the huge success of the Internet, which has changed our daily life significantly and has become one of the main economy engines. In these years, the infrastructure of the Internet kept evolving to provide better performance, and optical communication is one of its driving forces.

Transmission links in the network core are already based on optical fiber technology, which provides huge amount of bandwidth through the matured DWDM (Dense Wavelength Division Multiplexing) technology. More recently, optical fibers have also found their application in access networks to provide high speed Internet access to end users. FTTx (Fiber To The Home/Building/Curb, etc.) networks based on Passive Optical Network (PON) technologies, such as Gigabit-capable PON (GPON) standardized by the Full Service Access Network (FSAN) group of the International Telecommunications Union (ITU) [1] and Ethernet PON (EPON) standardized by the Ethernet in the First Mile (EFM) task force of the Institute of Electrical and Electronics Engineers (IEEE) [2], have been widely deployed in many countries such as the US, Korea and Japan.

10-Gigabit-capable Passive Optical Network (XG-PON) is a new standard released by the FSAN that improves G-PON, by increasing the default downstream data rate to 10 Gb/s, while increasing the upstream data rate to 2.5 or 10 Gb/s. Also, the maximum number of users per wavelength is increased from 64 to 256, and amendments are being defined for extending the physical reach up to 60 Km.

Since XG-PON could pave the way for many bandwidth-intensive applications (IPTV, Video On Demand, Video Conference, etc.), it is very important to study the performance issues arising with the deployment of XG-PON. For instance, it is valuable to study the impacts on the performance of XG-PON, when the propagation delay is much longer than that of the current PON networks [3]. It is also important to investigate the interactions between XG-PON and the upper-layer protocols (TCP [4], etc.) for improving user experience [5]. In addition, XG-PON has been proposed for Fiber To The Cell, in which XG-PON acts as the backhaul for multiple base stations of a cellular network [6]. Under this scenario, it is also very valuable to study its integration with various wireless networks (LTE [7], WiMAX [8], etc.) for providing high speed mobile Internet access.

Considering that XG-PON is still in its early stage, the above research topics should be first studied through simulation since it is too expensive to setup one XG-PON testbed and it is too complex to model the above scenarios to be studied with enough details. In this report, we present an XG-PON module for NS-3 [9], a state of the art open-source network simulator. Our XG-PON module is based on a series of G.987 Recommendations from the FSAN group of ITU. These recommendations mainly define the specifications of Physical Media Dependent (PMD) and Transmission Convergence (TC) layers of XG-PON. To study the above research topics with reasonable simulation speed, the optical distribution network and the operations of physical layer are simplified significantly. This XG-PON module focuses on the issues of TC layer, such as frame structure, resource allocation, Quality of Service (QoS) management, and Dynamic Bandwidth Assignment (DBA) algorithms for the upstream wavelength. During the design and implementation of this module, we have also paid a lot of attention on its extensibility and configurability. Since this XG-PON module needs to simulate a 10Gbps network and hundreds of ONUs, its performance (the speed of simulation and the overhead of memory) has also been given a high priority when designing and implementing these components.

This XG-PON module is built completely in C++ with 72 classes and approximately 22,000 lines of code. These code are under the GNU General Public License and can be downloaded from our websites (CTVR[1] and MISL[2]). To the best of our knowledge, it is the first XG-PON module for NS-3. We believe that this work is a significant contribution to the scientific community as it allows to simulate XG-PON, the next generation optical access network, and study the performance issues that arise with the deployment of XG-PON.

This report is organized as follows. Section II briefly introduces PON, NS-3, and related works. The details of XG-PON are then presented in section III. The design principles and key decisions are discussed in section IV. The important trade-offs made by us in terms of simulation accuracy and simulation speed are also discussed

[1]www.ctvr.ie

[2]http://www.ucc.ie/en/misl/

throughout. Section V presents the details of the design and implementation of our XG-PON module for NS-3. The preliminary evaluation results are then presented in section VI. Finally, section VII concludes this report with several directions for future work. At the end of this report, three appendices are also attached for introducing the installation with NS-3, the source files, and one example of XG-PON simulation.

II. Background and Related Work

A. Passive Optical Network (PON)

Compared to copper, optical fiber can provide higher bandwidth over a longer distance. However, the deployment of optical fiber in access networks is severely hindered by the cost issue. In fact, optical fiber was seriously considered for access networks only after the emergence of PON technology.

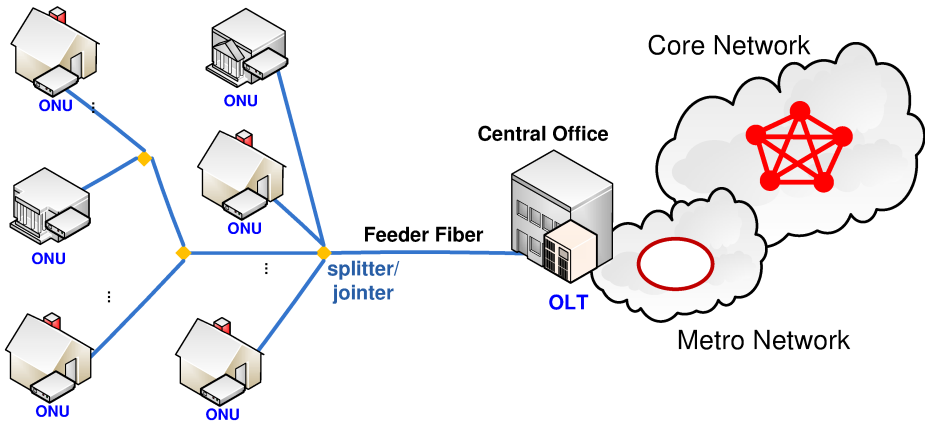


Fig. 1: An Illustration of PON

As shown in Figure 1, PON is a point-to-multipoint fiber network and there are three kinds of equipment: the OLT (Optical Line Terminal) in central office, ONUs (Optical Network Unit) in/near customer premise, and passive optical splitters/jointers in the middle. Through splitter/jointer, OLT and the feeder fiber are shared by multiple users. Compared with the point to point architecture, PON can significantly reduce the amount of required optical fibers and the central office equipments. Since the passive optical splitters/jointers do not need power supply, the cost of deployment, maintenance and operation can also be reduced. Thus, PON could reduce both capital expenditure and operational expenditure significantly.

In a classical TDMA (Time Division Multiple Access) based PON network, downstream traffic is broadcast by the OLT to all ONUs that share the same optical fiber and encryption is used to prevent eavesdropping. Upstream traffic from ONUs is interleaved by OLT for using the optical fiber in a TDMA-like manner. Since ONUs normally have different distances to the OLT, the data bursts from these ONUs must be scheduled carefully for providing a collision-free and efficient upstream data communication. To accommodate the dynamics in bandwidth demands from users and exploit the gain of statistical multiplexing, dynamic bandwidth assignment (DBA) is normally used

for managing the upstream bandwidth. More specifically, ONUs will report their buffer occupancy to OLT, which will then allocate the upstream bandwidth to ONUs based on their bandwidth demands and their Service Level Agreement (SLA).

Some standards have been developed for PONs by both EFM of IEEE (EPON) and FSAN of ITU-T (GPON). EPON is designed for carrying Ethernet frames and GPON can carry various traffics through encapsulation, such as Ethernet frames and ATM cells. Although EPON and GPON have different frame structures, they share the same network architecture and data communication follows the same principles described above. One important difference between EPON and GPON is that GPON is well standardized for QoS management. Hence, GPON can provide full service with the same network and it is highly preferred by ISPs. XG-PON is the new standard developed by FSAN based on GPON. Its details will be introduced in section III.

B. NS-3 Network Simulator

NS-3 [9] is a state of the art open-source network simulator. Based on many lessons from the well-known NS-2 simulator [10], NS-3 is written from the scratch and it is a completely new network simulator. NS-3 has many attractive features, such as high emphasis on conformance to real networks, good support for testbeds, a novel attribute system for configuring simulation parameters, automatic memory management, and a configurable tracing system [11]. It has also been reported that NS-3 performs much better than other simulators in terms of simulation speed and memory overhead [12]. The first release of NS-3 was made in June 2008 with support for a number of modules including CSMA, Point-to-Point, WiFi (IEEE 802.11), TCP, UDP and IPv4. Figure 2 shows the organization of NS-3 modules.

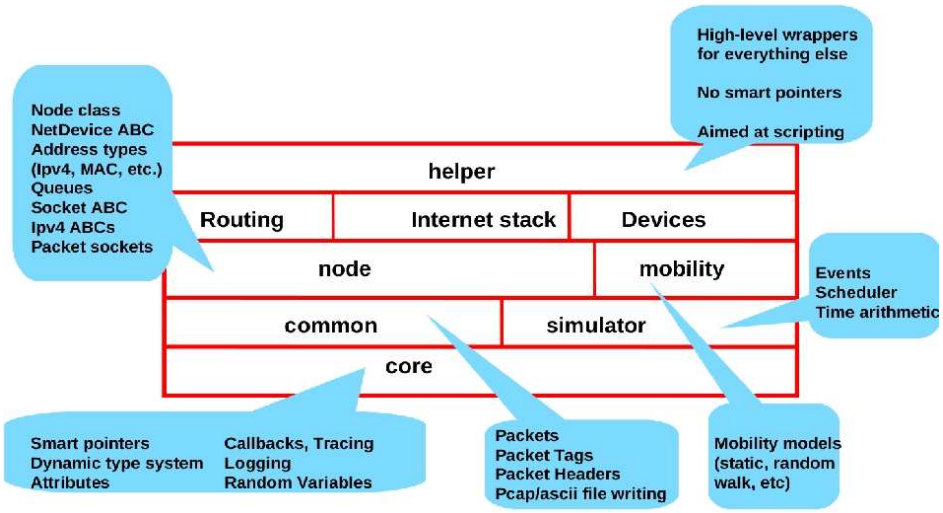


Fig. 2: The Organization of NS-3 Modules

In the last few years, many new modules have been developed and added into NS-3, such as WiMAX module from Inria [13] and LTE module from CTTC [14]. Thus, through implementing one XG-PON module in NS-3, we

can get a very good research platform for studying the issues arisen with the deployment of XG-PON.

C. Related Work

Although simulation has been used to study PON, the existing work cannot be used directly or extended easily to study the performance issues arising with the deployment of XG-PON.

In [3], the authors developed their own simulator to study dynamic bandwidth assignment (DBA) algorithms when the physical reach is much longer than the current PON networks. This simulator has limited functions and there is no Internet protocol stack, which is needed to study many research topics.

EPON and GPON had also been studied with OPNET [15] and several models have been implemented by different groups [16][17]. However, these EPON/GPON models are not available to the public. Furthermore, OPNET simulates too many details (CPU of a router, etc.) and the simulation speed is slow even when the simulated network bandwidth is lower than 1 Gb/s. Since OPNET is not an open-source simulator, we cannot change its core to simulate a 10 Gb/s XG-PON network with a reasonable simulation speed.

In addition, one simple EPON module has been developed for OMNeT++ [18] and the code is available to the public. Since there are a lot of difference between EPON and XG-PON, the code of this EPON module may not be very helpful to implement one XG-PON module for OMNeT++. Considering the good points of NS-3 discussed above, it should be better to develop one XG-PON module from the scratch for the NS-3 network simulator.

Hence, an XG-PON module is designed and implemented in this report for NS-3. With such an XG-PON module, we can simulate XG-PON and study its own performance. With the more realistic Internet protocol stack of NS-3, we can study the performance experienced by users/applications in XG-PON networks. With the existing NS-3 modules for various wireless networks (WiFi, WiMAX, LTE, etc.), we can also study the integration between XG-PON and wireless networks, which is the trend of the future Internet access networks. In summary, with this XG-PON module, NS-3 will become a good platform for studying the next generation Internet access networks composed by XG-PON and wireless networks.

Not only XG-PON, we can also extend this XG-PON module to study Long-Reach PON (LR-PON), an evolution of XG-PON with a larger number of users, symmetric data rate (10 Gb/s in both upstream and downstream), and longer reach (100+ km) [19][20]. The aim of our LR-PON research group is to initially build LR-PON from the XG-PON standard, while identifying the required modifications and improvements.

III. XG-PON Details

The XG-PON standard has many similarities with GPON, such as its TDMA scheme used to share the medium, the mechanism to provide QoS, and the DBA scheme used for the upstream wavelength. However, some changes are required in order to support a larger number of users, higher data rate, and extended physical reach. In this section, we will present the details of XG-PON.

A. Overview of XG-PON

A series of recommendations has been released by FSAN of ITU-T for XG-PON. ITU-T G.987 explains several important concepts of XG-PON and ITU-T G.987.1 presents the general requirements, such as network architecture, migration and coexistence with GPON, services to be supported, hardware specifications, protocol stack, etc. ITU-T G.987.2 focuses on issues of the physical media dependent (PMD) layer, such as the used wavelength and the supported data rates. ITU-T G.987.3 presents the details of transmission convergence (TC) layer. Not only the protocols for data communication, it also covers QoS management and Dynamic Bandwidth Assignment (DBA) scheme for the upstream wavelength. Another related recommendation is ITU-T G.988, which specifies ONU management and control interface (OMCI) for both GPON and XG-PON. Figure 3 illustrates XG-PON common functions and the recommendations in which they are specified.

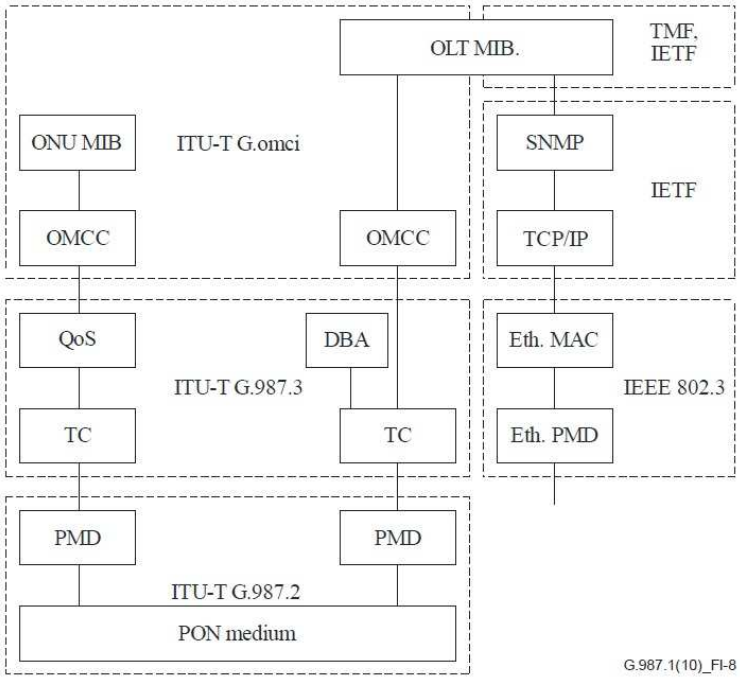


Fig. 3: XG-PON common functions

B. Network Architecture

XG-PON has been proposed for various deployment scenarios to serve different customers, such as residential, business, and cell site. To serve these customers, XG-PON lists the services to be provided, such as Telephony, high speed Internet access, mobile back-haul, etc. XG-PON also introduces many ONU variants that provide different functions and interfaces. In summary, XG-PON has been well standardized for providing full services to various users with one optical network.

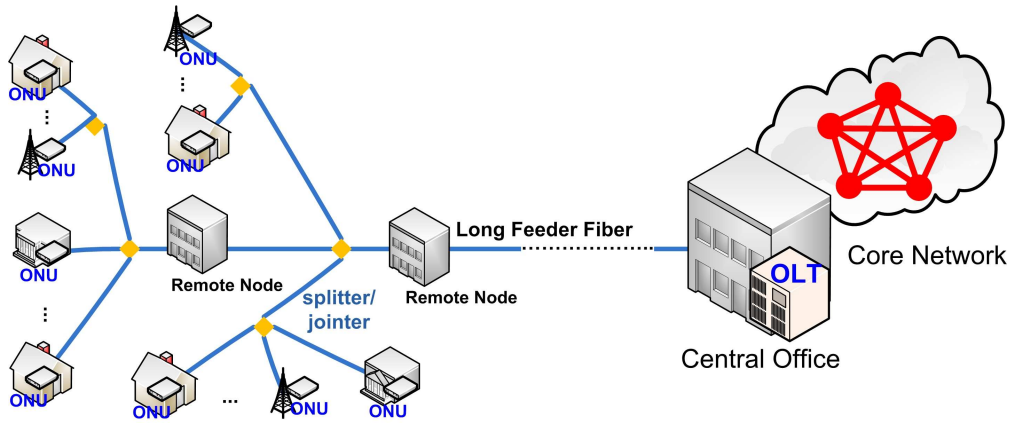


Fig. 4: XG-PON Network Architecture

As for optical distribution network, XG-PON can be deployed as a classical PON, but mechanisms to extend its reach up to 60 km are currently being defined. As illustrated in Figure 4, to support this longer physical reach, active component (Reach Extender) can be applied in remote nodes and one XG-PON can be composed of multiple passive segments connected through REs. These REs can be optical amplifiers or optical-electrical-optical regenerators that could fulfill the necessary optical link budget.

C. PMD Layer

There are two flavours of XG-PONs based on the upstream line rate: XG-PON1, featuring a 2.5 Gb/s upstream path, and XG-PON2, featuring a 10 Gb/s one. The downstream line rate is 10 Gb/s in both XG-PON1 and XG-PON2. ITU-T G.987.2 focuses on the PMD layer for XG-PON1. XG-PON2 hasn't been standardized yet.

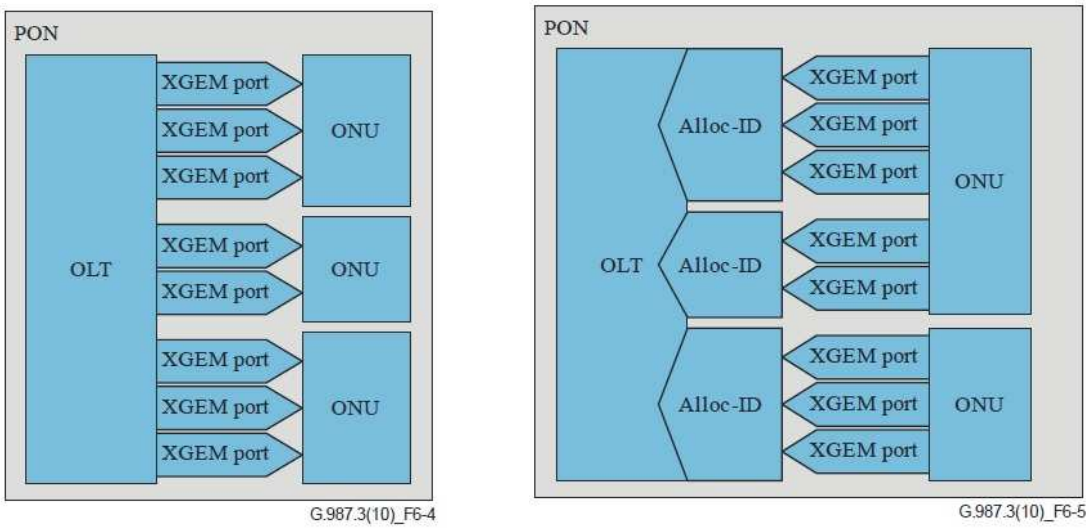
In XG-PON1, the used wavelengths are 1575-1580nm (downstream) and 1260-1280nm (upstream). The exact downstream line rate is 9.95328 Gb/s and the upstream one is 2.48832 Gb/s. For line coding, NRZ (Non-Return to Zero)is used for both directions. ITU-T G.987.2 also specifies the requirements for hardwares, such as optical fiber, transmitter/receiver, etc.

D. Transmission Convergence Layer

The XG-PON Transmission Convergence (XGTC) layer is where the Medium Access Control (MAC) protocol of XG-PON are defined.

To carry traffic between the OLT and the ONUs, the XGTC layer maintains logical connections between these two entities, designated XGEM Ports. Each connection is identified by a unique XGEM Port-Id, which enables to send a packet to the correct ONU and associate a connection to a certain Quality of Service (QoS) agreement. Note that one connection is configured to carry downstream or upstream traffics. It's impossible for two connections in the same direction (downstream or upstream) to have the same XGEM Port-Id, but one downstream connection may use the same XGEM Port-Id with one upstream connection. To reduce the overhead of the DBA scheme,

upstream bandwidth is allocated to groups of connections belonging to a single ONU. These groups are designated as Transmission Containers (T-CONT) and each group/T-CONT is identified by a unique identifier, the Alloc-Id. Figure 5 shows the multiplexing in XG-PON for both directions.



(a) Downstream (b) Upstream

Fig. 5: Multiplexing in XG-PON

XGTC comprises three sublayers: service adaptation, framing, and PHY adaptation, from top to bottom. Following these sublayers, XGTC is introduced below.

1) Service Adaptation Sublayer: The service adaptation sublayer is responsible to adapt the upper layer traffic to the transmission mechanisms of XG-PON. It will do this by mapping upper layer traffic to the corresponding connections, encapsulating/decapsulating data, segmenting/reassembling SDUs when necessary and inserting padding when there is not enough data to fill an XGTC frame. If needed, it is also this sublayer's responsibility to encrypt/decrypt SDUs.

To map upper layer data to and from the connections of XGTC layer, the OLT will maintain all connections and the ONU will maintain the connections that belong to itself.

When the upper layer has something to transmit, it is also the service adaptation sublayer's responsibility to select the connections to be served according to their QoS parameters. When a connection is scheduled to be served, the service adaptation sublayer will then get data from its queue and insert an XGEM header to create an XGEM frame. The XGEM header will contain an XGEM Port-Id and some other information related to segmentation, padding, encryption, etc.

When receiving an XGEM frame, the service adaptation sublayer will get the XGEM Port-Id from the XGEM header. If the corresponding connection exists in the connections maintained by the OLT/ONU, this sublayer will carry out reassembly (if necessary) and pass the data to upper layer. Otherwise, this XGEM frame will be discarded.

2) Framing Sublayer: In XG-PON, the OLT will send downstream XGTC frames every 125 μs, to broadcast traffic to all ONUs. In the upstream, ONUs send variable length XGTC bursts to the OLT for their upstream traffic. The length and start time of these upstream bursts are determined by the OLT through a DBA algorithm.

The framing sublayer is responsible to generate and parse these XGTC frames/bursts. When generating one downstream XGTC frame at the OLT, the framing sublayer gets XGEM frames from service adaptation sublayer and joins them together into an XGTC payload. To create an upstream XGTC burst at ONU side, the framing sublayer may create multiple XGTC payloads, where each payload will carry XGEM frames from a single T-CONT. When parsing an XGTC frame/burst, the framing sublayer will send its payloads to the service adaptation sublayer for further processing.

In the header of the upstream XGTC burst generated by an ONU, there might be queue occupancy reports for the T-CONTs of this ONU. For each downstream XGTC frame, its header contains one BW$_{map}$, which instructs ONUs to share the upstream wavelength in a TDMA-like manner. More specifically, BW$_{map}$ specifies the size of bandwidth allocations for T-CONTs, the used burst profile (the length of preamble, the length of delimiter, forward error correction or not, etc.), and the time to start to transmit. Since the OLT-ONU physical distance could be quite different for ONUs, each ONU should adjust the start time for avoiding collision in the upstream direction. Note that when one ONU is activated, the ranging procedure is carried out between the OLT and this ONU to determine how to adjust the start time of its upstream bursts. Figure 6 illustrates the time-lines in XG-PON. The OLT and ONUs have a common view of the logic one-way delay of the optical distribution network (the largest one-way propagation delay plus various processing delay) and each ONU uses its own equalization delay (EqD calculated in ranging procedure) to avoid collisions in upstream direction.

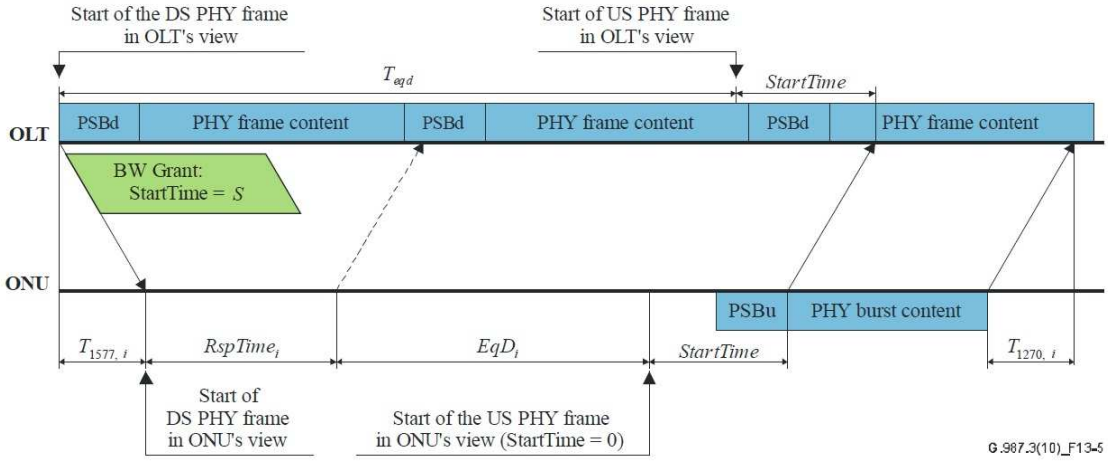


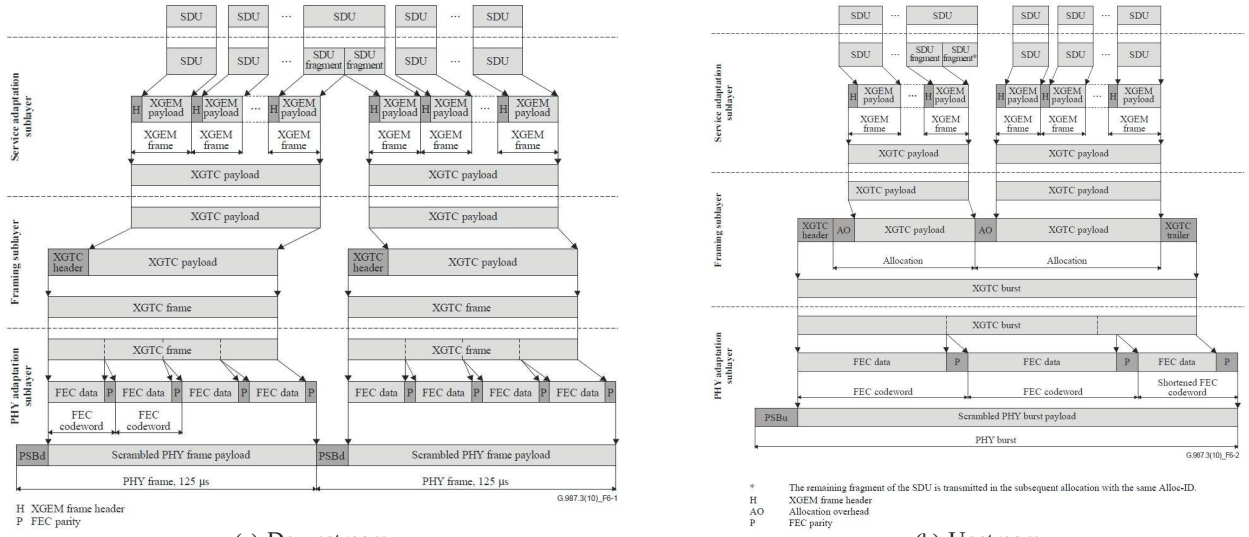
Fig. 6: Time-line in XG-PON

In the header of one upstream XGTC burst, the ONU can send one PLOAM (Physical Layer Operations, Administration and Maintenance) message to the OLT. As for one downstream XGTC frame, the OLT can send multiple PLOAM messages to multiple ONUs. Through exchanging PLOAM messages, many XGTC functions

(key management, ONU power management etc.) can be fulfilled.

3) PHY Adaptation Sublayer: PHY adaptation sublayer interacts with PMD layer directly. Its main functions are forward error correction (FEC), scrambling, and frame delineation through a Physical Synchronization Block (PSB). In the downstream, the PHY adaptation sublayer will get an XGTC frame to create a PHY frame. These PHY frames are sent continuously every 125 μs. In the upstream, the PHY adaptation sublayer will get the XGTC burst and create a PHY burst. These PHY bursts have variable length due to the variable-length XGTC bursts. In the PHY burst, the PSB is determined by a burst profile selected by the OLT (through the BW$_{map}$) among the burst profiles, that are configured through PLOAM messages.

Figure 7 illustrates how these sublayers encapsulate the SDUs of XG-PON into 125μs the downstream frames or the variable-length upstream bursts.



(a) Downstream (b) Upstream

Fig. 7: SDU Mapping in XG-PON

E. Scheduling and DBA

To decide the data to be transmitted in a downstream XGTC frame, a downstream scheduler is used by the OLT. Based on QoS parameters and service history of these downstream connections, the downstream scheduler will decide the connections to be served and the amount of data to be transmitted for each of them.

As for the upstream scheduling, the OLT uses a DBA algorithm to allocate the upstream bandwidth to T-CONTs. The DBA algorithm makes decisions based on queue occupancy reports, QoS parameters, and service history of these T-CONTs. The DBA algorithm needs to select the T-CONTs to be served, reserve a short gap time between the consecutive XGTC bursts for tolerating clock synchronization errors, determine the size of each bandwidth allocation, and calculate the start time for each bandwidth allocation. These decisions are broadcast to ONUs through BW$_{map}$. Since the upstream bandwidth is allocated to T-CONTs and each T-CONT may have multiple

upstream connections, the ONU also needs one upstream scheduler to determine the upstream connections to be served during one transmission opportunity assigned to one T-CONT.

These scheduling algorithms, especially the DBA algorithm, are very important to network performance and QoS management. To allow competition and encourage research, these algorithms were intentionally left out of the standard. Indeed, it has been a very hot topic to study DBA algorithms for EPON and GPON [21][22][3]. Hence, there should be many research opportunities for XG-PON too.

IV. Design Principles and Key Decisions

When designing and implementing XG-PON module, there are many issues to be considered and many tradeoffs must be made when the goals conflict with each other. This section will present the design principles followed by us and the key decisions make during the course.

A. Design Principles

- Standard Compliance:

  The ultimate goal of our research is to improve the performance issues arisen with the deployment of XG-PON. It is highly desirable that the simulated XG-PON is close to the real XG-PON networks that will appear in the future. We can then identify the real problems and provide solutions that can be directly applied in the real world. Hence, we will follow G.987 Recommendations from the FSAN group of ITU when designing this XG-PON module.
- Simplicity:

  Considering that XG-PON is a quite complex standard, it will take a very long time to simulate the whole network, from physical layer to network management. For instance, the document for ONU Management and Control Interface (G.988) is more than 500 pages. Hence, we must decide the functions to be simulated in current phase. We will only simulate the functions needed by our research. Other functions will be left alone or designed as some stub classes for the future extension. For instance, since we are mainly interested in XGTC layer and upper layer issues, we can simulate the physical layer in a very simple way. We can assume that power budget for the optical distribution network has been satisfied through various techniques. The reach extenders and passive optical splitters/jointers need not be simulated. The channel, that simulates the optical distribution network of XG-PON, can simply pass downstream frames to all ONUs and pass upstream bursts to the OLT. As for Forward Error Correction (FEC), instead of the algorithm itself, we can simulate only its effect, i.e., the bandwidth overhead and the much lower packet corruption rate.
- Extensibility:

  When designing the XG-PON module for NS-3, we should also consider its extensibility since many other research topics might also be studied using this module. Hence, the extensibility is very important. When designing the class architecture of the XG-PON module, abstract class should be used appropriately and the interface should be well designed for the future implementation that simulates more details. Of course, we will

only provide a much simpler implementation for the components that we are not interested in current phase. For instance, when designing the class interface for the channel that simulates the optical distribution network of XG-PON, we should enable researchers to specify the tree structure of fibers, reach extenders, and splitters. When adding one ONU, they can also specify the splitter that it will be attached and the physical distance between them. With this interface, it is possible to simulate the optical signal propagation and the possible packet corruption. However, for the current phase, we can let the channel store a list of ONUs and pass the downstream frames to all of them (without any error)[3]. Since DBA algorithm is one hot research topic, the classes for DBA should be well designed to allow the easy implementation of various DBA algorithms.

- Configurability:

  In one simulated XG-PON network, there could be thousands of nodes, such as the OLT, hundreds of ONUs, and hundreds of data traffic generators/sinks in core networks. Many nodes will also be attached to ONUs through various networks and act as traffic generators/sinks. We should export many configurable parameters, but provide default parameters for most of them. Other methods should also be considered to easy the researcher's task for configuring the XG-PON network to be simulated.

- Simulation Speed:

  Considering the XG-PON to be simulated is a 10Gbps network, simulation speed must be considered in all times. One module, that can simulate XG-PON accurately (but very slowly), is useless for our research in which extensive simulations are needed. We should select the data structures and algorithms carefully for saving CPU and memory. For instance, when XG-PON is fully loaded and the size of each packet is 1KBytes, the simulator need process around one million packets per second. Since XG-PON could have hundreds of ONUs (1023 at most), the simulator must run the procedure used by ONU to judge whether it is the destination of one XGEM frame one billion times per second. This procedure must be implemented high-efficiently. Straightforwardly, we can add one vector at each ONU whose index is XGEM Port-Id. When configuring XGEM Ports for this ONU, this vector can be marked correspondingly. Consequently, this vector can be used to filter out the traffic for this ONU quickly. However, XGEM Port-Id is a 16-bit number and this vector can consume a lot of memory when the number of ONU is large. Due to the same reason, hash map in which GEM Port-Id acts as the key is not adopted by us too. In our XG-PON module, we impose some simple relationship among XGEM Port-Id, Alloc-Id, ONU-ID, and IP address of the computer that this XGEM Port belongs to. Consequently, we consume a small amount of memory in total and achieve $O(1)$ time complexity when mapping IP address/XGEM Port-Id to the corresponding data structure.

  During the implementation, many useful features of C++ language should be exploited and some black-holes of CPU cycles should be avoided. First, we should pass parameters by reference whenever it is possible and const reference is preferred. We should also know that the smart pointer provided by NS-3 is fundamentally

[3]Depending on the situation, it may be worthwhile to simulate a likely packet corruption rate, which should be very low with considering the effects of FEC.

a small object. When the function is called frequently and some of its parameters are smart pointers, we should replace them with the reference of that smart pointer. Second, since C++ allows one class to override its *new* and *delete* operators, we should exploit this feature for data structures that are created and destroyed dynamically and frequently. Through overriding the two operators, we can avoid to call the expensive *malloc* too many times and CPU cycles can be saved. Third, when we select the data structure for a sequence of objects, *vector* should be considered due to its efficiency. However, when too many objects are added into one vector, reallocation may occur and the simulation can be slowed down significantly. Thus, we should reserve enough memory if the largest vector size can be pre-determined. Otherwise, *deque* should be considered as the container. Fourth, although virtual function and inheritance are very attractive, they should be used when absolutely necessary since virtual function is much slower than the common function. Class downcast should also be avoid in the implementation since it is unsafe and consumes a lot of CPU cycles. For instance, for each function of XGPON (DBA, etc.), there should be two classes designed for OLT and ONU, respectively, and it is attractive to let them inherit from the same parent. However, the logic at OLT is totally different with that of ONU, the amount of reused code is limited, the interface of the parent becomes more complex, and simulation speed is slowed down. Thus, these classes are designed independently and the inheritance is not used.

B. Key Decisions

Below are several key decisions made by us when designing and implementing this XG-PON module.

- Stand-alone Simulation: Since XG-PON is a 10Gbps network with hundreds of ONUs, it is very attractive to use distributed simulation to speed up XG-PON simulation. However, although NS-3 supports distributed simulation through MPI, this feature only works for point-to-point links and XG-PON is fundamentally a point-to-multipoint network. Many works are necessary to enable distributed simulation for XG-PON and we need also study how to allocate ONUs to different computers. Furthermore, many researchers may not have the access to some clusters and these clusters may not support MPI well. Thus, in the current phase, this XG-PON module works as a stand-alone simulator. It uses only one core even when one computer has multiple processors or cores. In the future, distributed simulation will be considered for this XG-PON module.
- Packet-level Simulation: Due to the high bandwidth of XG-PON (10Gbps) and the frequency of state-of-the-art processor (several GHz), it is hopeless to simulate the details in byte or bit level. For flow-level simulation, it's too complex to model both XG-PON and TCP/IP protocol stack, and We cannot study the potential subtle interactions between TCP/IP and XG-PON. Considering that NS-3 is fundamentally a packet-level simulator, this XG-PON module should simulate XG-PON in packet level. Furthermore, when passing traffic between OLT and ONU, all XGEM frames in the downstream frame or upstream burst should be handled together, and the number of simulation events can be reduced significantly. Due to the short XG-PON frame size (125μs), the upper layer protocols won't be affected if we keep the order of XGEM frames in the downstream frame or the upstream burst. Based on this decision, many physical layer operations, such as line coding and Forward

Error Correction, will not be implemented in this module. However, the bandwidth overhead of FEC must be considered. Payload encryption/decryption will not be implemented too. The logic used for key management will be implemented for future extensions.

- XG-PON in Operation: Since we are mainly interested in the performance issues of one XG-PON network in operation, many aspects of XG-PON can be simplified. For instance, the activation procedure that uses PLOAM messages to add one ONU to one operating XG-PON need not be implemented. We can simply add all ONUs to the network before starting the simulation through one helper class. Instead of the ranging procedure that uses PLOAM messages to measure the one-way propagation delay of each ONU, we can set the same value to both the OLT and this ONU when configuring the XG-PON to be simulated. In XG-PON, XGEM Port and T-CONT configuration is carried out through OMCI (ONU Management and Control Interface: G.988). However, this standard document (more than 500 pages) is very complex and it will take a lot of time to implement OMCI for XG-PON. Thus, instead of configuring XGEM Port and T-CONT dynamically through OMCI, we will configure all XGEM Ports and T-CONTs before starting the simulation through one helper class. In summary, PLOAM and OMCI channels will not be fully implemented in this XG-PON module. Stub classes will be designed for the future extensions.
- Simple Optical Distribution Network and Reliable Data Transfer: In XG-PON, the optical distribution network is quite complex and is comprised of many optical fibers, splitters/jointers, and reach extenders. Although they are important to network architecture and optical device research, they are irrelevant to the research topics that we plan to study. Thus, the optical distribution network will be modeled as one simple channel and we only simulate the propagation delay and line rates. We assume that the link power budget has been ensured through various techniques (reach extenders, etc.) and the laser receiver can work well. Thus, we won't simulate optical signal propagation (wavelength-dependent) and assume that all downstream frames and upstream bursts can arrive to their recipients correctly. In another word, transmission errors are not simulated in our XG-PON module. This is reasonable since FEC is normally applied to hide transmission errors. Based on this decision, CRC and HEC (header error correction) are not executed in the simulation.

  In the future, transmission error might be simulated. At the recipient, the downstream frame or upstream burst will be dropped with a distance-dependent probability. This is reasonable since FEC is normally used and there is no XGEM frame delimitation. Once the transmission error cannot be handled by FEC, all of the following data cannot be decoded by the recipient.
- Serialization Avoidance and Meta-data in Data Structures: Since this XG-PON module is designed for stand-alone simulation, (de)serialization is unnecessary and should be avoided[4]. This is why XgponXgemFrame is added into this XG-PON module to represent XGEM frame. At the first glance, we can use Packet provided by NS-3 directly. XGEM frame header can be added into and extracted from Packet easily. Packet also supports

[4]Of course, all data structures should provide one function to return its Serialized size for composing the downstream frame and upstream burst correctly.

fragmentation and reassembly which is needed by XGEM encapsulation. However, when XGEM frame header is added into Packet, the header is serialized and put into one byte array. When one XGEM frame is received, the recipient needs to extract the XGEM frame header from the byte array, i.e., create one XgponXgemHeader and carry out de-serialization. Considering that one XGEM frame in downstream direction will be processed by hundreds of ONUs, the above operations may consume too much CPU. To solve this issue, XgponXgemFrame is designed to have one smart pointer of XgponXgemHeader and one smart pointer of the corresponding SDU (an instance of Packet). At the recipient, it can then get XgponXgemHeader directly from XgponXgemFrame. Another observation is that some meta-data can be added into data structures for various purposes since they are exchanged between OLT and ONU as objects (instead of a byte array). For instance, all XGEM frames of one downstream frame need be checked by all ONUs and it is very expensive when the number of ONUs is large. We notice that due to the small size of the downstream frame and the bursty bandwidth allocation, the traffic in one downstream frame might belong to a few ONUs. Thus, a bitmap can be added to the downstream frame to indicate whether one ONU needs to check XGEM frames in this downstream frame. With this meta-data, the simulation can be speed up significantly when there are many ONUs in the simulated XG-PON network.

- Extensible DBA, Scheduling, and Queue Schemes:

  As discussed in subsection III-E, downstream scheduler at the OLT is responsible to allocate the downstream bandwidth to the downstream XGEM Ports. DBA at the OLT is responsible to allocate the upstream bandwidth to T-CONT, and upstream scheduler at ONU is responsible to allocate the transmission opportunity of one T-CONT to the upstream XGEM Ports. These algorithms and the queue used by each XGEM Port at the sender side are very important to the performance of the whole network and the QoS experienced by user traffic. In this XG-PON module, these classes will be designed carefully to support future extensions. New algorithms should be implemented easily through inheriting these classes and instantiating a few functions.

In summary, this XG-PON module can be used to carry out stand-alone packet-level simulations for studying XG-PON networks in operation. Table I summarizes how XG-PON functions are supported in this XG-PON module.

Function	Layer	Simulated?	Comments
Optical Distribution Network & Signal Propagation & Line Coding & Frame Detection	PMD	X	Use one simple channel to simulate ODN. We only simulate propagation delay and bandwidth of the channel. These information will be provided to other classes of this module.
Burst Profile	PMD	√	Instead of OMCI, they are configure through helper class.
FEC & Scrambling	PHY_ad	X	Just provide FEC overhead information to other classes.
XGTC Framing	Framing	√	*HEC* and CRC is not implemented for saving CPU.
PLOAM Engine	Framing	√	Just implement the logic and interface for exchanging messages.
DBA & QoS	Framing	√	Round-robin is implemented first.
DS Scheduling & QoS	N/A	√	In the first phase, Round-robin will be implemented.
US Scheduling & QoS	N/A	√	Round-robin will be used for XGEM Ports of one T-CONT.
XGEM Framing	Service_ad	√	*HEC* isn't implemented. *Fragmentation and reassembling* are implemented.
Encryption	Service_ad	X	Not implemented. Key management logic will be implemented.
(De)Multiplexing	Service_ad	√	Packet classification and flow management are implemented. Alloc-Id, XGEM Port-Id, and IP address are assigned carefully for speed.
Queue Mechanism	Service_ad	√	one FIFO queue per XGEM Port
OMCI & MIB	N/A	X	Configuration will be carried out through helper class.
Activation & Ranging	N/A	X	Not implemented. Per-ONU delay is configured through helper class.

TABLE I: Choices for Simulating XG-PON in NS-3

V. The XG-PON Module for NS-3

This section describes in detail the XG-PON module we have developed for NS-3. Our aim is to provide a standard compliant, configurable, and extensible module that can simulate XG-PON with reasonable speed and can support a wide range of research topics.

A. Overview of the XG-PON Module

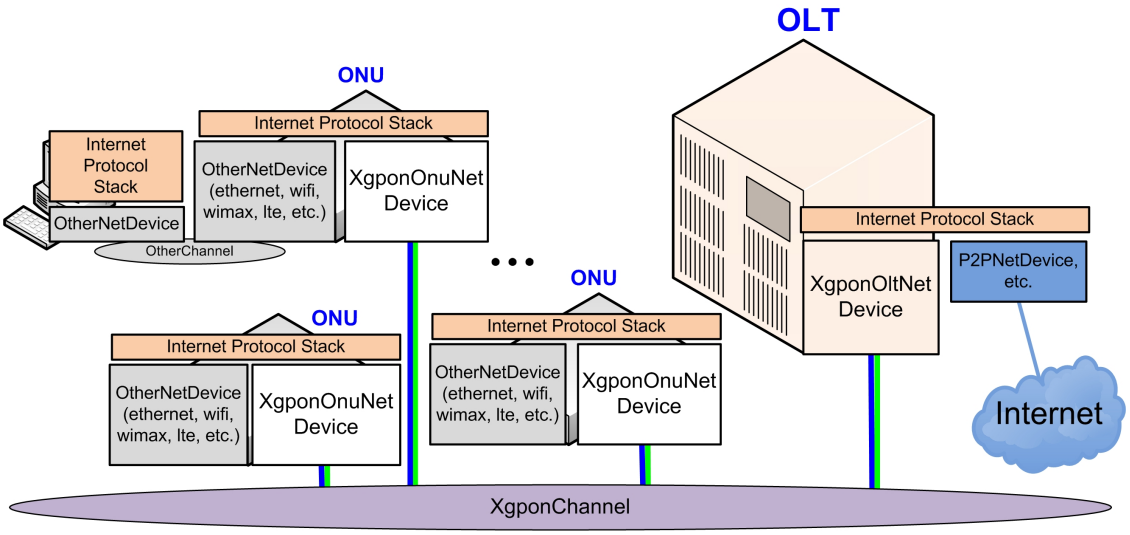


Fig. 8: The Reference XG-PON Simulation

Figure 8 illustrates a typical simulation that uses this module and NS-3 to study the performance issues arising with XG-PON. The OLT is simulated as a node that has one *XgponOltNetDevice* and another network device, such as PointToPointNetDevice, to connect to an external network. The ONU is simulated as a node with one *XgponOnuNetDevice* and other network devices (Ethernet, WiFi, WiMAX, LTE, etc.) for connecting user equipments to the ONU. Thanks to NS-3, network devices of a node can be configured and we can study different deployment scenarios of XG-PON easily. Although XG-PON is proposed to carry layer-2 frames of various network technologies (Ethernet, ATM, etc.), our XG-PON module interacts directly with the IP layer and IP packets are the SDUs. This is reasonable since we focus on FTTx networks connected to the Internet.

The OLT and ONUs are attached to *XgponChannel* that simulates the optical distribution network (ODN) of XG-PON. As illustrated in Figure 4, this ODN is a quite complex tree composed by optical fibers, splitters/jointers, and REs. To produce trustworthy simulation results, it is highly desirable to simulate all details. However, XG-PON is a high speed network with a very complex standard. In this module, many aspects have been simplified for reducing the development workload and speeding up the simulation speed.

Specifically, our XgponChannel just simulates d_{max}, i.e., the logic one-way delay of the channel that is determined by the maximal propagation delay of ODN and various processing delay. d_{max} can be configured through the

attribute system of NS-3. For a downstream frame from the OLT, XgponChannel will pass this frame to each ONU after waiting for d, i.e., the corresponding one-way propagation delay between the OLT and this ONU. Note that for avoiding unnecessary data copy, XgponChannel passes the smart-pointer of this frame to each ONU which will just copy and process the data for itself[5]. As for an upstream PHY burst, it will be postponed for the corresponding propagation delay, but XgponChannel will pass it to the OLT only. The equalization delay is considered by ONU when it schedules to produce the upstream burst based on BW_{map} from the OLT.

This means that although the difference of propagation delay among ONUs is simulated, the propagation of optical signals (fiber, splitter, etc.) is not simulated by the XgponChannel. This design is reasonable since the targeted research topics are related with MAC and upper layers. Through these simplifications, simulation speed can also be significantly improved. Otherwise, many events must be scheduled to pass a downstream XGTC frame to ONUs if fibers and splitters are considered. It is also very CPU-intensive to calculate the optical signal strength for each downstream frame when it arrives to each ONU.

In the following subsection, we will present how the XG-PON protocol stack is simulated. More specifically, we will identify its functional blocks, followed by the design and implementation details.

B. XG-PON Functional Blocks

Since we are interested in the performance of a running network, the functional blocks of XG-PON are identified below through explaining the data transmission paths in both downstream and upstream directions.

1) Downstream Traffic on OLT Side: As shown in Figure 9, when one SDU is received from the upper layer, it will first be mapped to the corresponding connection (XGEM Port) based on the destination IP address and put into the queue for transmitting in the future. Thus, there must be one algorithm for mapping the IP address to a XGEM Port-Id.

Since the OLT needs to broadcast the downstream XGTC frames every 125 μs, it will periodically ask the OLT's *Framing Engine* to generate a XGTC frame. This engine will first generate an XGTC header since the available space for data in the frame depends on the size of the XGTC header.

For the payload of a downstream XGTC frame, the Framing Engine resorts to the *XGEM Engine* to get an XGTC payload. This payload is comprised of concatenated XGEM frames that occupy all the available space. As for the SDUs to be encapsulated and transmitted, the XGEM Engine lets the *Downstream Scheduler* decide the connections to be served. This scheduler makes decisions based on *Downstream Connection Manager* which knows queue length, QoS parameters, and service history of each downstream connection. When carrying out encapsulation, fragmentation will be carried out by XGEM Engine if one SDU is too long for the current transmission opportunity. XGEM Engine is also responsible to encrypt these SDUs to avoid eavesdropping. The keys used for data encryption are negotiated through PLOAM messages and are maintained by *Ploam Engine*.

[5]In the future, this feature will be revised to support parallel simulation in which ONUs are simulated on different CPUs of a cluster.

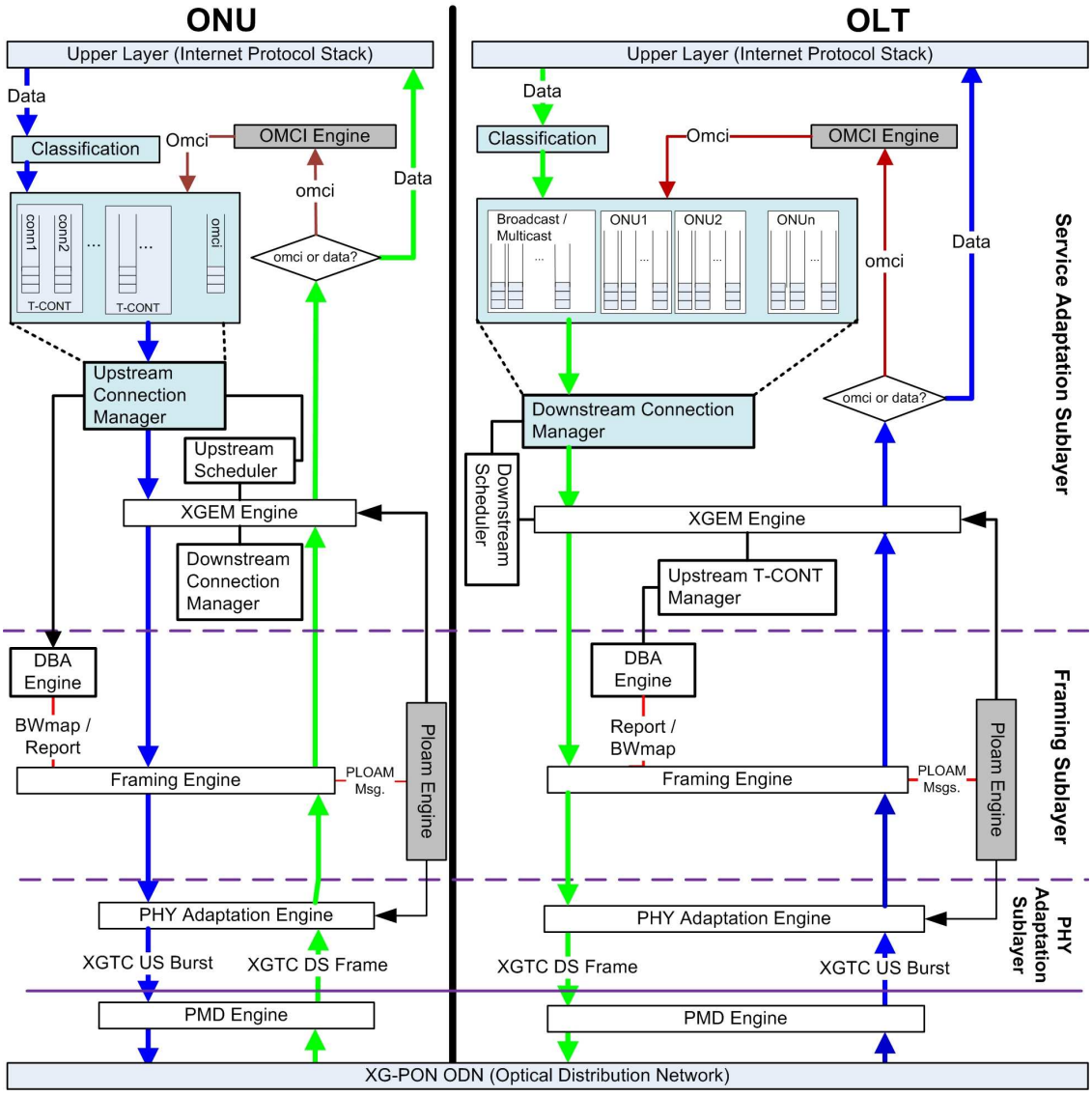


Fig. 9: Function Block Diagram of XG-PON

To construct the XGTC header of the frame, the *DBA Engine* is used to generate BW_{map} that tells ONUs how to share the upstream wavelength. DBA Engine makes decisions based on queue occupancy reports, QoS parameters, and service history of T-CONTs. As for the PLOAM messages in the header, they are generated by Ploam Engine.

The downstream frame is sent to the ODN after passing through *PHY Adaptation Engine* and *PMD Engine*.

2) Downstream Traffic on ONU Side: When a downstream PHY frame arrives to one ONU, it will pass through PMD Engine and PHY Adaptation Engine which will remove the physical-layer overhead. The Framing Engine is then responsible to parse the resulting downstream XGTC frame.

The PLOAM messages from the XGTC header will be given to the Ploam Engine, which will process the messages related with this ONU. The DBA Engine is responsible to process BW_{map} in the header, i.e., schedule

its upstream XGTC bursts if required by this BW_{map}.

As for the payload, the XGEM frames are passed to XGEM Engine. Based on the list of its connections maintained by Downstream Connection Manager, the XGEM frames for this ONU are first extracted. XGEM Engine then carries out decapsulation, decryption, and reassembly (if needed)[6]. The received SDUs are then sent to the upper layer.

3) Upstream Traffic on ONU Side: As illustrated in Figure 9, when a IP packet is received at the ONU, based on the source IP address, it is first mapped the corresponding upstream connection that are organized by *Upstream Connection Manager*. The packet is then put into the corresponding queue for transmitting in the future.

When it is the time to transmit one upstream XGTC burst (scheduled by the DBA Engine based on BW_{map} from the OLT), the Framing Engine is resorted to produce the XGTC burst. To do this, the Framing Engine asks the XGEM Engine to get an array of XGTC payloads. Each of these payloads is a concatenation of XGEM frames belonging to one T-CONT scheduled in the BW_{map}. To decide the SDUs to be encapsulated, the *Upstream Scheduler* is also needed since the upstream bandwidth is allocated to T-CONT and multiple upstream connections might belong to the same T-CONT. This scheduler makes decisions based on the amount of bandwidth allocated to one T-CONT, queue length, QoS parameters, and service history of this T-CONT's upstream connections.

If required by the OLT, Framing Engine at ONU will resort DBA Engine at ONU to generate queue occupancy report for the corresponding T-CONT. This report is deduced by Upstream Connection Manager based on the upstream connections of this T-CONT. For various purposes, PLOAM messages may be generated by Ploam Engine. When it is allowed by the OLT, one PLOAM message can be put into the header of this XGTC burst.

The upstream XGTC burst is then passed to PHY Adaptation Engine with the burst profile to be used. After going through PMD Engine, this burst is sent to the ODN.

4) Upstream Traffic on OLT Side: When the OLT receives one upstream XGTC burst, this burst first passes through PMD Engine and PHY Adaptation Engine. The Framing Engine at OLT is then responsible to parse the header and the payloads of this burst. The potential queue occupancy report will be sent to DBA Engine and the potential PLOAM message is sent to the Ploam Engine. As for the XGTC payloads, they are sent to XGEM Engine for decapsulation and reassembly (if needed). Hence, one *Upstream T-CONT Manager* is needed to hold the potential segments for reassembly.

As illustrated in Figure 9, both OLT and ONU should have one *OMCI Engine* for exchanging OMCI messages that are used for various purposes (ONU management, XGEM Port and T-CONT configuration, etc.).

[6]For each downstream connection, the Downstream Connection Manager at the ONU should hold the segments that have been received for carrying out reassembly when the remaining segments are received.

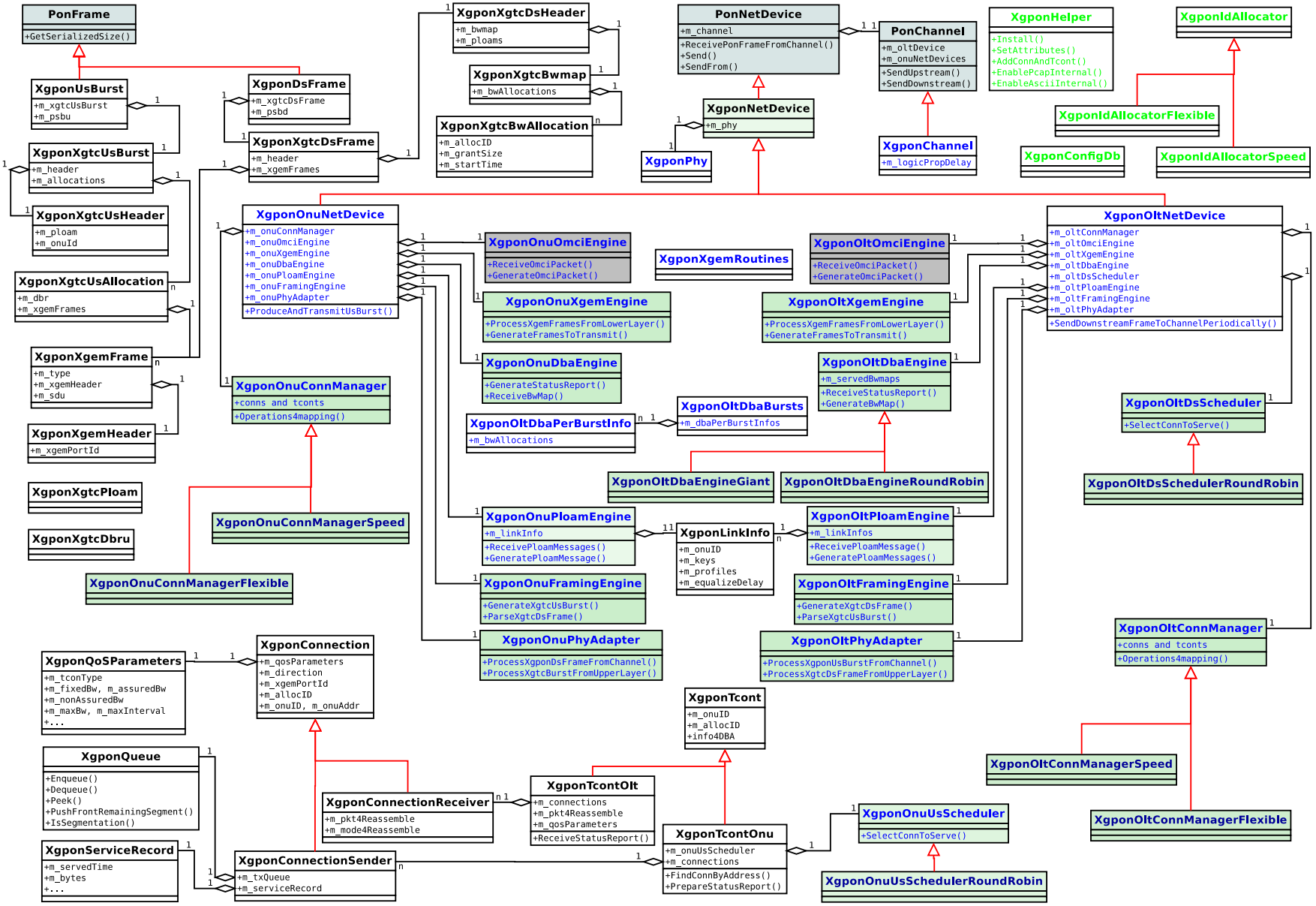


Fig. 10: Class Diagram of the XG-PON module for NS-3

C. The Design and Implementation Details

Figure 10 shows the main classes of this XG-PON module. Following this class diagram, the design and implementation details of this module are presented below.

1) Channel and Network Devices: PonChannel and PonNetDevice are the base classes for a general PON network. Through developing different subclasses, we can simulate other PON technology (10G-EPON [23], etc.) and compare with XG-PON. PonChannel is inherited from Channel of NS-3 and is used to simulate the optical distribution network (ODN). It has implemented the functions for managing network devices of the OLT and ONUs attached to this ODN. PonNetDevice is inherited from NetDevice of NS-3 and is responsible to communicate with upper layers and PonChannel.

XgponChannel is the subclass of PonChannel for XG-PON and its implementation has been discussed in V-A. As a subclass of PonNetDevice, *XgponNetDevice* is used to represent a network device attached to XgponChannel. It also implements the functions that are common for both OLT and ONU, such as the statistics for the network device. XgponOltNetDevice and XgponOnuNetDevice are its subclasses for the OLT and ONU, respectively. They mainly act as the container of various engines that implement the protocol stack of XG-PON.

2) Frame Structure: PonFrame represents the frame transmitted over the ODN of a PON and it just provides the interfaces for (de)serialization, etc. *XgponDsFrame* and *XgponUsBurst* are used to represent the downstream frame and the upstream burst of XG-PON, respectively. There are many other classes used to represent the related data structures, such as BW_{map}, PLOAM message, and the header of PHY adaptation sublayer (Figure 13).

XgponXgemFrame is used to represent XGEM frame. It includes the payload (one packet from the upper layer) and one header defined by XG-PON standard. *XgponXgemHeader* is used to represent this header of XGEM frame.

3) Connection Management: Since XG-PON traffic is carried by logic connections, many classes are designed and implemented for representing, organizing, and handling these connections.

XgponConnection is used to represent a connection (XGEM Port). It mainly contains the identifiers of this connection (XGEM Port-Id, ONU-ID, etc.). XgponConnectionReceiver and XgponConnectionSender are its subclasses that represents a connection at the receiver and sender side. XgponConnectionReceiver mainly holds the received segments for reassembling. XgponConnectionSender contains the service history (XgponServiceRecord), QoS parameters (XgponQosParameters), and the transmission queue for SDUs from upper layer (XgponQueue).

XgponTcont is the class for representing T-CONT. XgponTcontOnu, its subclass for the ONU, is designed to organize the upstream connections of the same T-CONT. As for XgponTcontOlt, the subclass of XgponTcont for the OLT, queue occupancy reports from ONU, QoS parameters and service history of this T-CONT are maintained for DBA algorithm. XgponTcontOlt is also responsible to hold the received segments for implementing reassembly.

XgponOnuConnManager contains a list of downstream connections (XgponConnectionReceiver) and a list of T-CONTs. Note that each T-CONT might have multiple upstream connections (XgponConnectionSender). It is also responsible to map SDU/XGEM frame to the corresponding connection. Thus, it implements both Downstream Connection Manager and Upstream Connection Manager for the ONU.

XgponOltConnManager is designed to fulfill the functions of Downstream Connection Manager and Upstream T-CONT Manager for the OLT. It contains a list of broadcast connections (XgponConnectionSender). It also contains all uni-cast downstream connections (XgponConnectionSender) and T-CONTs for upstream traffic (XgponTcontOlt).

For both XgponOnuConnManager and XgponOltConnManager, we have implemented several subclasses in which these data structures are organized in different ways for different purposes. XgponOnuConnManagerSpeed and XgponOltConnManagerSpeed impose some relationships among XGEM Port-Id, Alloc-Id, ONU-ID, and IP address of the computer connected to ONU. They can carry out mapping very quickly, but they also limit the number of XGEM Ports that one ONU could have. XgponOnuConnManagerFlexible and XgponOltConnManagerFlexible don't have such limitations,but they are much slower. Since millions of packets need to be processed per second, XgponOnuConnManagerSpeed and XgponOltConnManagerSpeed should be used for most cases.

4) PMD and PHY Adaptation: PMD Engine and PHY Adaptation Engine in Figure 9 are simplified significantly for simulating XG-PON with reasonable speed.

XgponPhy is used to implement PMD Engine and it mainly maintains the physical layer parameters that are common for the OLT and ONUs, such as the downstream data rate and the upstream data rate of XG-PON. The data rates can be configured through the attribute system of NS-3. The most important interface is to tell other classes about the size of one downstream/upstream frame.

XgponOltPhyAdapter and *XgponOnuPhyAdapter* are used to implement PHY Adaptation Engine for the OLT and ONU, respectively. Instead of simulating their functions (line coding, FEC, scrambling, etc.) step by step, they just passes frames/bursts between XgponChannel and Framing Engine after removed physical layer header. Hence, we implicitly assume that all frames/bursts can be received correctly. Since the network should be well planned and FEC has been adopted, the observed frame corruption rate will be very low and this assumption is reasonable. In the future, the corruption of frames will be simulated based on the distance between OLT and ONU or empirical measurements of XG-PON networks in real world.

5) Framing Engines: XgponOltFramingEngine implements Framing Engine on the OLT side. It is responsible to generate the downstream XGTC frames and parse the upstream XGTC bursts. *XgponOnuFramingEngine* implements Framing Engine on the ONU side. It is responsible to generate the upstream XGTC bursts and parse the downstream XGTC frames. Both of them follow the standard strictly.

6) XGEM Engine: XgponXgemRoutines implements some routines that are common for both the OLT and ONU, such as XGEM frame creation.

As for XGEM Engine functions, they are implemented by XgponOltXgemEngine and XgponOnuXgemEngine for the OLT and ONU. They carry out encapsulation, decapsulation, fragmentation, reassembly, etc. fragmentation and reassembly are implemented based on the Packet class of NS-3. The logic for data encryption/decryption is also implemented. But the cryptographic algorithm is not implemented and executed for saving CPU.

When they are called to produce the payload of a downstream frame or upstream burst, they will resort Downstream Scheduler or Upstream Scheduler for determining the traffic to be transmitted. When getting XGEM frames from Framing Engine, XgponOnuXgemEngine need extract and only process its own traffic.

7) Scheduling and DBA: To study different scheduling and DBA schemes, several abstract classes are used in this module for extensibility. The actual schedulers can then inherit these abstractions and implement their specific algorithms. The related classes in this module are introduced below.

XgponOltDsScheduler acts as the OLT Downstream Scheduler shown in Figure 9. When XgponOltXgemEngine generates the payload of a downstream XGTC frame, it will call one virtual function of XgponOltDsScheduler (*SelectConnToServe*) to decide the connection to be served. XgponOltSimpleDsScheduler is one subclass that follows the round robin scheme.

XgponOltDbaEngine is designed for the OLT DBA Engine shown in Figure 9. When XgponOltFramingEngine generates one downstream XGTC frame, it will resort XgponOltDbaEngine to generate a BW_{map}. XgponOltDbaEngine is also responsible to receive queue occupancy reports from ONUs. Currently, a simple DBA algorithm is implemented in XgponOltDbaEngineRoundRobin that serves a fixed amount of bytes for each T-CONT in a round robin manner. GiantMAC [22] has also been implemented in XgponOltDbaEngineGiant for supporting different kinds of T-CONTs with various QoS parameters.

XgponOnuDbaEngine acts as the ONU DBA Engine shown in Figure 9. It is responsible to process BW_{map}, generate queue occupancy report, and schedule to generate and transmit the upstream burst.

XgponOnuUsScheduler acts as the ONU upstream scheduler shown in Figure 9. When XgponOnuXgemEngine generates the payload of one upstream burst, XgponOnuUsScheduler is resorted to decide the connections to be served in the transmission opportunity assigned to one T-CONT. XgponOnuUsSchedulerRoundRobin is one subclass implemented to serve the connections of one T-CONT in a round robin manner. Note that XgponOnuUsScheduler is put within XgponTcontOnu so that T-CONTs of the same ONU may use different scheduling algorithms for their upstream traffic.

8) Miscellaneous: XgponOltPloamEngine and *XgponOnuPloamEngine* are designed for exchanging Ploam messages between the OLT and ONU. They also uses *XgponLinkInfo* to maintain per-ONU information, such as keys and burst profiles. As for *XgponOltOmciEngine* and *XgponOnuOmciEngine*, they are designed for implementing the OMCI channel. For these classes, we have just implemented their interactions with other classes of this module. We will simulate their messages and the related procedures in the future.

9) Helper: For facilitating researchers to configure one XG-PON network with hundreds of ONUs and thousands of connections, *XgponHelper* is also implemented in this module. Through XgponHelper, researchers can install XgponNetDevice on nodes and attach them to XgponChannel. They can also configure XGEM Ports and T-CONTs for carrying user traffic. Researchers can also use XgponHelper to enable Ascii and Pcap tracing.

XgponConfigDb is one database that holds the information used by XgponHelper. Before using XgponHelper, researchers should first configure subclasses and parameters used in the simulation. When adding XGEM Port/T-CONT/ONU into XG-PON, *XgponIdAllocator* is used to get the corresponding XGEM Port-Id/Alloc-Id/ONU-ID. *XgponIdAllocatorSpeed* is the subclass developed for imposing some relationship among XGEM Port-Id, Alloc-Id, ONU-ID, and IP address of the node connected to ONU with aim of speeding up XG-PON simulation. XgponConfigDb uses one flag to make sure that XgponOltConnManagerSpeed, XgponOnuConnManagerSpeed,

and XgponIdAllocatorSpeed are used together.

VI. Evaluation Results

Our XG-PON module is designed for simulating a 10Gbps optical network with hundreds of ONUs and the simulation performance is one of the most important metrics for researchers. Thus, in this section, we will evaluate its simulation speed and memory consumption under various scenarios with one off-the-shelf server. Extensive pressure tests are also carried out to demonstrate our XG-PON module can run for a very long time and work correctly under more random simulation settings.

A. Simulation Performance

To avoid interference from other processes, one dedicated computer is used to measure the performance of our XG-PON module. The server used by us is Dell PowerEdge R320 rack server. The processor is Intel(R) Xeon(R) CPU E5-1410 0 @ 2.80GHz and its cache size is 10MBytes. Note that although this processor has 4 cores, just one of them is used by our simulation. As for the main memory, the server is installed with 48GBytes in total.

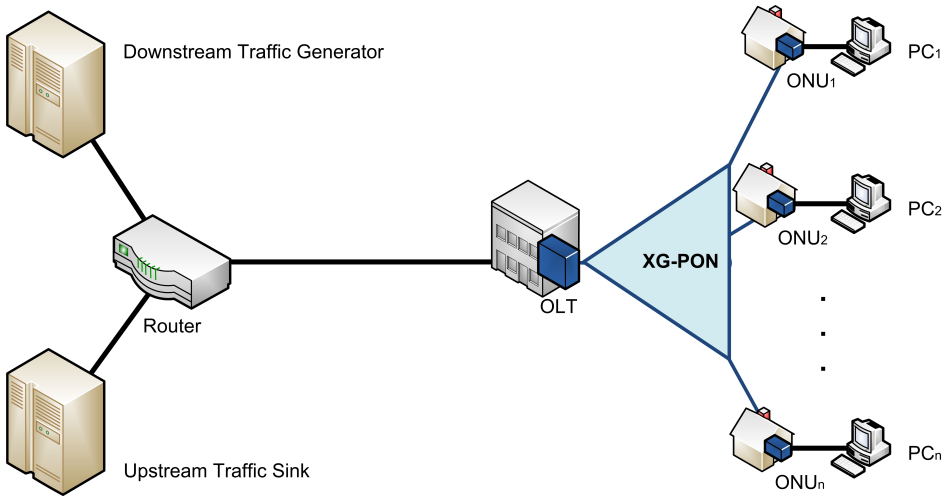


Fig. 11: Network Topology

The network topology used in our simulations is illustrated in Figure 11. We simulate one XG-PON network whose largest propagation delay is 0.4ms, i.e., the physical reach is around 60km. For the data rates of XG-PON, we follow XG-PON1, i.e., 10Gbps in downstream and 2.5Gbps in upstream. There are totally N ONUs in the XG-PON and one PC is connected to each ONU through a point-to-point link whose delay is 2ms. These PCs act as the customer of XG-PON and play the generators for the upstream traffic and the sinks for the downstream. The OLT is connected to Router and the point-to-point link between them is used to simulate the core network. More specifically, the delay of this link is set to 10ms. Downstream Traffic Generator and Upstream Traffic Sink are connected to Router through point-to-point links whose delay is 2ms. To generate network traffic in both directions,

each PC sends UDP packets to Upstream Traffic Sink and receives UDP packets from Downstream Traffic Generator. Due to the bandwidth asymmetry of XG-PON1, the generated data rate in the upstream direction is always one quarter of the data rate in the downstream direction. For all of the above point-to-point links, the bandwidth is set to 20Gbps so that XG-PON is the only bottleneck.

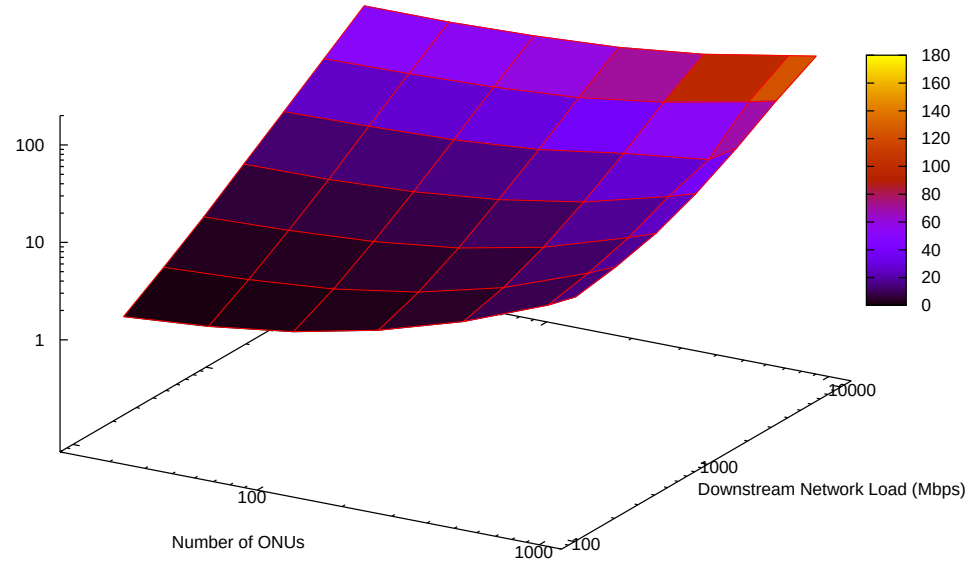
To study the simulation performance of our XG-PON module under various scenarios, the number of ONUs and the amount of network traffic are changed in our experiments. The evaluated values of N (the number of ONUs) are 25, 50, 100, 200, 400, 800, and 1000. As for the total amount of network load the downstream, the evaluated values are, 150Mbps, 300Mbps, 600Mbps, 1.2Gbps, 2.4Gbps, 4.8Gbps, and 9.6Gbps. Note that due to the overhead of XG-PON physical and XGTC layers, packets start to be dropped when the downstream network load is 9.6Gbps. Furthermore, for all experiments, the upstream network load is always one quarter of the downstream network load. Thus, when the downstream network load is 9.6Gbps, the upstream network load is 2.4Gbps and there are also packets dropped in the upstream direction.

To evaluate the speed of our XG-PON module, 400 seconds are simulated in each experiments, the total amount of time used to complete the simulation is recorded, and we then calculate and plot the amount of time consumed to simulated one second. Figure 12(a) shows the results under various scenarios. It indicates that the consumed time is increased linearly with the network load. It is reasonable since NS-3 is one packet-level network simulator and the number of events are increased linearly with the number of packets. Figure 12(a) also indicates that the consumed time increases with the number of ONUs much slower. Hence, our XG-PON module have successfully avoid to let each ONU process all packets in the downstream direction. Figure 12(a) also indicates that our XG-PON module takes around 160s to simulate one second even when there are 1000 ONUs and the downstream network load is 9.6Gbps with which XG-PON has been over-loaded.

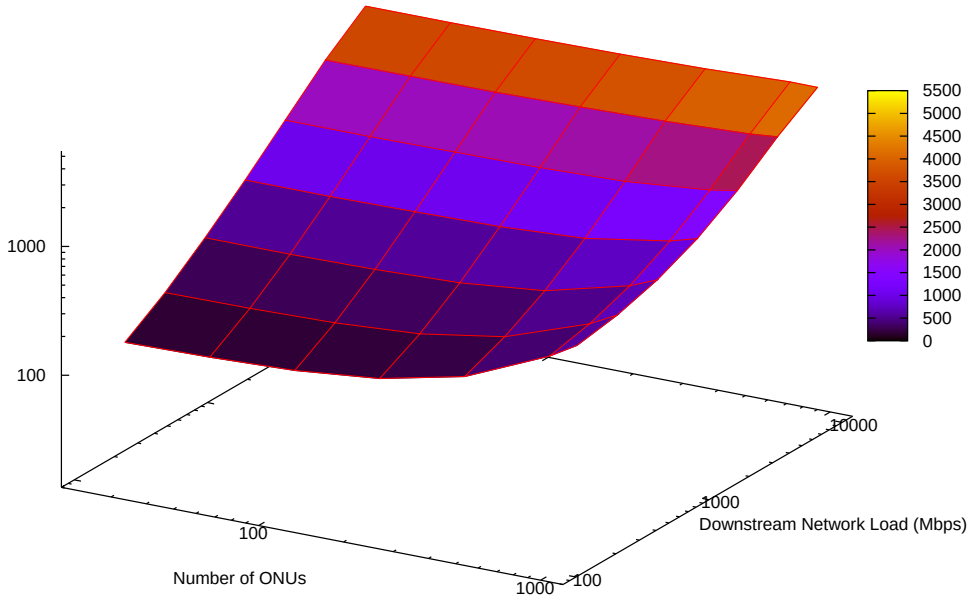
We have also used gdb to run the simulation of the most difficult scenario (ONUs: 1000; Network load: 9.6Gbps) in $debug$ mode. After the simulation enters into steady phase, we break it at random time, check the call stack, and continue the simulation. These steps are repeated for 126 times and the CPU is running our XG-PON code for only 4 times. Thus, our XG-PON module is not the bottleneck for simulation speed and other modules (routing, etc.) need be revised for improving the speed further.

Not only simulation speed, we have also evaluated the amount of memory consumed by XG-PON simulation. The same experiments are repeated to collect these results. For each experiments, after starting the simulation, we wait for a long time until the simulation enters into its steady phase and the amount of consumed memory does not increase anymore. These values for various scenarios are recorded and plotted in Figure 12(b). This plot indicates that the consumed memory increases linearly with the network load, and it increase much slower with the number of ONUs. When there are 1000 ONUs and the downstream network load is 9.6Gbps, the consumed memory is still less than 5GBytes.

In summary, with off-the-shelf servers, our XG-PON module can simulate a 1000 ONUs 10Gbps XG-PON network with reasonable speed and moderate memory consumption.



(a) The amount of time consumed to simulate one second



(b) The amount of memory consumed in steady phase

Fig. 12: Simulation Performance of XG-PON Module under Various Scenarios

B. Pressure Tests

To evaluate the robustness of our XG-PON module, we have carried out more experiments. In one group of experiments, we use the same configurations designed for performance evaluation and 4000 seconds are simulated in each experiment to demonstrate that our XG-PON module can simulate XG-PON for a long period (longer than one hour). Note that when there are 1000 ONUs and the downstream network load is 9.6Gbps, it takes more than one week to complete the simulation. All of these simulations have been carried out successfully, and there is no crash and memory leakage in the course. In another group of experiments, we randomly select the number of ONUs and the amount of network traffic, and 500 seconds are simulated in each experiment. For 49 random configurations evaluated by us, all simulations have been carried out successfully.

In summary, evaluation results in this section indicate that our XG-PON module is quite robust and can simulate XG-PON with reasonable speed and moderate memory consumption. It could be a good research platform for studying performance issues related with XG-PON.

VII. Summary and Future Work

In this report, we introduce an XG-PON module for the NS-3 network simulator. We describe the details of its design and implementation, and present some preliminary evaluation results. These results indicate that our XG-PON module is quite robust and can simulate XG-PON with reasonable speed and moderate memory consumption. As the first XG-PON module for NS-3, we believe that this work is a significant contribution to the scientific community as it allows us to simulate XG-PON and study the performance issues that arise with the deployment of XG-PON.

In the future, we will implement more scheduling and DBA algorithms that were proposed for G-PON or XG-PON. We will also keep improving its simulation speed and parallel/distributed simulation will be considered. Furthermore, we will study how to simulate Fiber to the Cell with this XG-PON module and the WiMAX/LTE modules distributed with NS-3. The potential performance issues mentioned in this report will also be investigated using this XG-PON module.

VIII. Acknowledgments

This work is supported in part by Science Foundation of Ireland through CTVR (http://www.ctvr.ie/).

APPENDIX A
INSTALLATION

This appendix briefly introduces how to install our XG-PON module with NS-3. Here, we assume that NS-3 had been installed on your computer and you are using the development code tree.

In this release of our XG-PON module, all files are put into one folder ”xgpon”. In ”xgpon”, there are several folders that are similar to other NS-3 modules, such as ”bindings” (for Ptyhon bindings), ”doc” (for documentations included this manual), ”examples” (for examples to demonstrate how to use this module), ”helper” (for classes provided to researcher with aim to facilitate its usage), ”model” (fore source code), and ”test” (for test cases).

In ”xgpon”, we have another folder ”changesOnOtherModules” that contains some bug fixes related with other modules. Currently, we just changed ”ipv4-l3-protocol.cc” of the internet module to avoid program crash when long simulations are carrying out.

To use this XG-PON module, you should first copy or link ”xgpon” under the folder ”ns-3-dev/src”. You should also copy the above ”ipv4-l3-protocol.cc” (within changesOnOtherModules) into ”ns-3-dev/src/internet/model”. Note that this file copy is necessary for NS-3.19 and the latest release of NS-3 may have already fixed this bug. You may compare the function ”ProcessFragment()” of the latest version with our copy to make sure that the bug has been fixed in the latest NS-3 release. After that, please configure and build NS-3 as normal. XG-PON module should be ready to be explored.

In addition, in ”xgpon”, there is one folder ”scripts4evaluation” that holds the scripts used by us to evaluate this module. Before running these evaluations, you need copy the corresponding script file into ”ns-3-dev”. To test GiantMAC through running ”pedro/pargiantscript.py”), you need set one new environment parameter (NS3) according to the path of NS-3 on your system. You should also create ”data/giant-data” folder in your NS-3 installation.

APPENDIX B
SOURCE FILES

This appendix briefly introduces all source files of this XG-PON module for NS-3.

1) pon-channel.h/.cc: source code for PonChannel. PonChannel has implemented how to send one upstream frame from one ONU to the OLT and how to broadcast one downstream frame from the OLT to all ONUs. It is one abstract class and its subclass should manage the OLT and all ONUs attached on the channel, especially the propagation delay between the OLT and each ONU. When subclass instantiates PonChannel, each ONU should have one unique index in the PonChannel and this index can be used to get its corresponding propagation delay.
2) pon-frame.h: source code for PonFrame. PonFrame is one abstract class with the interfaces for (de)serialization.
3) pon-net-device.h/.cc: source code for PonNetDevice. PonNetDevice is inherited from NetDevice of NS-3. It defines one abstract function ”ReceivePonFrameFromChannel” that should be implemented by its subclass for handling frames received from PonChannel. It also maintains the index of this device on the PonChannel. This index is useful to ONU only for getting its propagation delay.
   This group of files are used to model a general TDMA-based Passive Optical Network. EPON could also be implemented through instantiating these classes.

4) xgpon-burst-profile.h/.cc: source code for XgponBurstProfile. XgponBurstProfile implements the burst profile used by one ONU to produce one upstream burst. It specifies the physical layer overhead (the length of preamble and delimiter) and whether FEC is used for this burst. When the OLT assigns one upstream transmission opportunity to one ONU, it also notifies the ONU about the burst profile to be used. Thus, one ONU may use different burst profile for different bursts at different times. The OLT may make decision based on channel quality and the kind of payload, etc.
5) xgpon-key.h/.cc: source code for XgponKey. XgponKey is used to carry out encryption. It is just one stub class to be instantiated in the future if key management needs to be studied.
6) xgpon-link-info.h/.cc: source code for XgponLinkInfo. XgponLinkInfo is used to maintain the information of one ONU, such as the keys and burst profiles negotiated between the OLT and this ONU. It also includes the corresponding equalization delay of this ONU for avoiding collision in upstream direction. XgponLinkInfo also maintains one list of PLOAM messages to be sent to the OLT (at ONU side) or the corresponding ONU (at OLT side). It also includes many other state information to achieve various purposes through PLOAM messages, the header of downstream frame, the header of upstream burst, and the header of XGEM frame.
   This group of files are used to represent the information of one ONU, especially keys, burst profiles, PLOAM messages, and equalization delay. XgponLinkInfo will be managed by XgponOltPloamEngine and XgponOnuPloamEngine so that other engines of XgponNetDevice can get the corresponding information.

7) xgpon-xgtc-ploam.h/.cc: source code for XgponXgtcPloam.XgponXgtcPloam is used to represent one PLOAM message exchanged between OLT and ONU. Since PLOAM messages need to be allocated and released dynamically during simulation, the new and delete operators of XgponXgtcPloam are overridden and a pool is maintained for reducing the cost of the expensive ”malloc” operations.
8) xgpon-xgem-header.h/.cc: source code for XgponXgemHeader. XgponXgemHeader is the header of XGEM frame exchanged between OLT and ONU. It is one member variable of the following XgponXgemFrame.
9) xgpon-xgem-frame.h/.cc: source code for XgponXgemFrame. XgponXgemFrame is used to encapsulate SDU from upper layers. Except one XgponXgemHeader and the potential SDU, it also has one member variable used to specify the type of this XGEM frame (normal frame, idle frame, or short idle frame). Since huge amount of XGEM frames need to be allocated and released dynamically, its new and delete operators are also overridden and a pool is maintained for reducing the cost of the expensive ”malloc” operations.
10) xgpon-ds-frame.h/.cc: source code for XgponDsFrame. XgponDsFrame is one subclass of PonFrame for XG-PON. It is designed to represent one downstream frame broadcasted from OLT to ONUs. It mainly contains two member variables, one for physical layer header (XgponPsbd) and the other for XGTC layer downstream frame (XgponXgtcDsFrame). For saving CPU used to allocate and release this structure, its new and delete operators are also overridden and a pool is maintained for reducing the cost of the expensive ”malloc” operations.
11) xgpon-psbd.h/.cc: source code for XgponPsbd. XgponPsbd is the physical layer header of the downstream frame of XG-PON (XgponDsFrame).
12) xgpon-xgtc-ds-frame.h/.cc: source code for XgponXgtcDsFrame. XgponXgtcDsFrame is the downstream frame observed by XGTC layer. It mainly includes one XGTC layer header (XgponXgtcDsHeader) and a bunch of XGEM frames. To allow hundreds of ONUs to process one XgponXgtcDsFrame quickly, we separate the broadcasted XGEM frames that must be processed by all ONUs and the uni-casted ones. Considering that one XgponXgtcDsFrame may contain the traffic of just a few ONUs, most of ONUs need not parse these uni-casted XGEM frames for extracting their own traffic. Thus, a bitmap is also added into XgponXgtcDsFrame to indicate the ONUs whose traffic are within this frame.
13) xgpon-xgtc-ds-header.h/.cc: source code for XgponXgtcDsHeader. XgponXgtcDsHeader is the XGTC layer header of a downstream frame (XgponXgtcDsFrame). It contains a list of PLOAM messages (XgponXgtc-Ploam) to be sent to ONUs and the following XgponXgtcBwmap used to instruct ONUs how to share the upstream wavelength.
14) xgpon-xgtc-bwmap.h/.cc: source code for XgponXgtcBwmap. XgponXgtcBwmap is produced by the OLT and broadcasted to all ONUs in the header of the XGTC downstream frame (XgponXgtcDsHeader). It is used to instruct ONUs how to share the upstream wavelength in a TDMA-like manner. It includes a list of the following XgponXgtcBwAllocation. For saving CPU used to allocate and release this structure, its new and delete operators are also overridden and a pool is maintained for reducing the cost of the expensive ”malloc”

operations.

15) xgpon-xgtc-bw-allocation.h/.cc: source code for XgponXgtcBwAllocation. In XgponXgtcBwmap, there is one XgponXgtcBwAllocation for each T-CONT scheduled in the corresponding upstream frame. XgponXgtcBwAllocation is used to specify when one ONU should send the upstream traffic of this T-CONT, how many bytes it can send, and whether it can send one queue occupancy report. The XgponXgtcBwAllocation of the same ONU will form one upstream burst. For the first XgponXgtcBwAllocation of the same burst, it also specifies the burst profile used by the corresponding upstream burst and whether the ONU can send one PLOAM message to the OLT. For saving CPU used to allocate and release this structure, its new and delete operators are also overridden and a pool is maintained for reducing the cost of the expensive ”malloc” operations.

16) xgpon-us-burst.h/.cc: source code for XgponUsBurst. XgponUsBurst is one subclass of PonFrame for XG-PON. It is designed to represent one upstream burst that one ONU sends to the OLT in upstream direction. It mainly contains two member variables, one for physical layer header (XgponPsbu) and the other for XGTC layer upstream burst (XgponXgtcUsBurst). For saving CPU used to allocate and release this structure, its new and delete operators are also overridden and a pool is maintained for reducing the cost of the expensive ”malloc” operations.

17) xgpon-psbu.h/.cc: source code for XgponPsbu. XgponPsbu is the physical layer header of the upstream burst of XG-PON (XgponUsBurst). It contains the preamble and delimiter. Their length is determined by the burst profile used for this burst. And the burst profile is selected by the OLT and specified in the corresponding XgponXgtcBwmap.

18) xgpon-xgtc-us-burst.h/.cc: source code for XgponXgtcUsBurst. XgponXgtcUsBurst is the upstream burst observed by XGTC layer. It mainly includes one XGTC layer header (XgponXgtcUsHeader), a trailer, and a bunch of the following XgponXgtcUsAllocation (one for each T-CONT).

19) xgpon-xgtc-us-header.h/.cc: source code for XgponXgtcUsHeader. XgponXgtcUsHeader is the XGTC layer header of an upstream burst (XgponXgtcUsBurst). If scheduled by the OLT, one PLOAM message can also be sent to the OLT within this header.

20) xgpon-xgtc-us-allocation.h/.cc: source code for XgponXgtcUsAllocation. XgponXgtcUsAllocation is designed to represent the traffic of one T-CONT to be transmitted in the upstream burst. It mainly contains a bunch of XGEM frames. If scheduled by the OLT through XgponXgtcBwmap, one queue occupancy report (XgponXgtcDbru) is also transmitted in XgponXgtcUsAllocation. For saving CPU used to allocate and release this structure, its new and delete operators are also overridden and a pool is maintained for reducing the cost of the expensive ”malloc” operations.

21) xgpon-xgtc-dbru.h/.cc: source code for XgponXgtcDbru. XgponXgtcDbru is used to represent one queue occupancy report of one T-CONT.

This group of files are used to represent the information communicated between the OLT and ONU. For

all of these classes, they should support the (de)serialization. Since the current simulation is carried out in the same thread of the same computer and it could be quite complex, we have not fully implemented this feature. However, ”GetSerializedSize()” has been implemented for all so that we can compose the downstream frame and upstream burst with considering their length constraints. In many of these classes, some error detection/correction coding schemes are used to be robust to transmission error. In current phase, these algorithms are not implemented and we assume that these structures are correct. In the future, transmission errors might be simulated through discarding one whole frame/burst. Furthermore, in many of these classes, some meta-data member variables are added to facilitate (de)serialization and maintain some time-related information (creation time, receiving time, etc.). For instance, XgponXgtcBwmap maintains its creation time. The OLT uses this information, the logic one-way-delay of the channel, and the time that a upstream burst is received, to associate this upstream burst to its corresponding XgponXgtcBwmap. Figure 13 summarizes how these classes are used to represent the frame/burst transmitted in XG-PON.

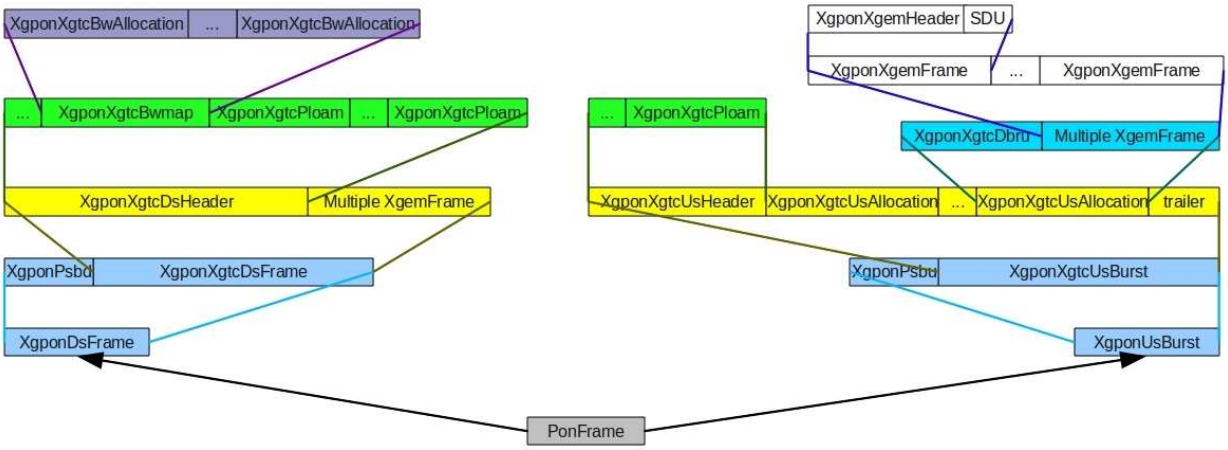


Fig. 13: Classes for frame/burst of XG-PON

22) xgpon-qos-parameters.h/.cc: source code for XgponQosParameters. XgponQosParameters is used to hold the Qos parameters of one XGEM Port or T-CONT (aggregated from its XGEM Ports) that XG-PON should satisfy. Its content follows XG-PON standard, such as fixed bandwidth, assured bandwidth, etc.
23) xgpon-connection.h/.cc: source code for XgponConnection. XgponConnection is used to represent one XGEM Port of XG-PON. It is one abstract class with basic information (the direction, Broadcast or Uni-cast, XGEM Port-Id, Alloc-Id for upstream XGEM Port, ONU-ID that this XGEM Port belongs to, and upper layer address of the computer whose traffic this XGEM Port will carry) and its QoS parameters should be satisfied by XG-PON. XgponConnectionReceiver is the subclass for the receiver and XgponConnectionSender is the subclass for the sender. Thus, for one upstream XGEM Port, there is one XgponConnectionSender at ONU and one corresponding XgponConnectionReceiver at OLT. For the downstream XGEM Port, there is

one XgponConnectionSender at OLT and one corresponding XgponConnectionReceiver at ONU. The QoS parameters at the sender and the receiver must be identical.

24) xgpon-connection-receiver.h/.cc: source code for XgponConnectionReceiver. As the subclass of XgponConnection for the receiver, XgponConnectionReceiver is quite simple. It mainly holds the segments that have been received to carry out reassemble in the future. Note that, for upstream traffic, reassemble is carried out by the OLT per T-CONT.

25) xgpon-connection-sender.h/.cc: source code for XgponConnectionSender. XgponConnectionSender is the XGEM Port instance at the sender. It has one queue (XgponQueue) to buffer the traffic to be transmitted on XG-PON and a list of service records (XgponServiceRecord) that could be used for scheduling purposes. It is also responsible to receive the SDU (put it into the queue), get the packet to be transmitted on XG-PON (fragmentation needs to be considered), maintain its serving history (a list of XgponServiceRecord), and return the occupancy of its queue.

26) xgpon-service-record.h/.cc: source code for XgponServiceRecord. XgponServiceRecord is used to store the event that one XGEM Port is served. It records the time that the traffic of this XGEM Port are transmitted and the amount of bytes transmitted through XG-PON. For saving CPU used to allocate and release this structure, its new and delete operators are also overridden and a pool is maintained for reducing the cost of the expensive ”malloc” operations.

27) xgpon-queue.h/.cc: source code for XgponQueue. XgponQueue is used for each XGEM Port at the sender. It is used to hold the traffic to be transmitted through XG-PON. Instead of Queue from NS-3, XgponQueue is added for three reasons. First, fragmentation need to be considered and it should hold the remaining part of one fragmented SDU and send the remaining part immediately once this XGEM Port is served again. Second, some variables in ns3::Queue are private and we cannot update them. Third, when SDU is encapsulated into XGEM frame, padding must be carried out for word-alignment. Thus, queue occupancy must be updated accordingly. Instead of calculating queue occupancy (visiting each packet in the queue) when needed, this value is maintained when packet is enqueued/dequeued, two calculations are necessary for each packet, and CPU can be saved. Note that XgponQueue is one abstract class and its subclass is responsible to manage packets in the queue and implement some queue discipline.

28) xgpon-fifo-queue.h/.cc: source code for XgponFifoQueue. XgponFifoQueue is one subclass of XgponQueue and it follows the principles of FIFO (First In, First Out).

29) xgpon-tcont.h/.cc: source code for XgponTcont. XgponTcont is used to represent one T-CONT (Note that one T-CONT might have multiple upstream XGEM Ports) of XG-PON. It is one abstract class with basic information (Alloc-Id, ONU-ID that this T-CONT belongs to). XgponTcontOlt is the subclass used by the OLT and XgponTcontOnu is the subclass used by ONU. In addition, XgponTcont also holds a list of XgponXgtcDbru (the history of queue occupancy reports) and a list of XgponXgtcBwAllocation (the serving history) related with this T-CONT. These information could be used by the OLT to deduce how many data

of this T-CONT is still waiting at ONU to be served.

30) xgpon-tcont-olt.h/.cc: source code for XgponTcontOlt. XgponTcontOlt is the T-CONT instance at the OLT. It has a list of XgponConnectionReceiver that are used to calculate its aggregated QoS parameters. It is responsible to carry out reassemble, receive queue occupancy report from ONU, maintain its serving history and queue occupancy reports, and calculate the amount of data at ONU that still needs to be served. When there is no queue occupancy reports from ONU, it is also responsible to tell the OLT whether to poll the ONU for the status of this T-CONT.
31) xgpon-tcont-onu.h/.cc: source code for XgponTcontOnu. XgponTcontOnu is the T-CONT instance at ONU. It has a list of XgponConnectionSender that belong to this T-CONT. It is responsible to maintain these connections, generate queue occupancy report, and maintain the serving history (a list of XgponXgtcBwAllocation from the OLT). Since the OLT just assigns the upstream bandwidth to T-CONTs, XgponTcontOnu has one upstream scheduler (XgponOnuUsScheduler) used to schedule traffic of the connections that belong to the same T-CONT. Through putting one upstream scheduler into XgponTcontOnu, we can use different upstream schedulers for different T-CONTs.
32) xgpon-onu-us-scheduler.h/.cc: source code for XgponOnuUsScheduler. XgponOnuUsScheduler is used to schedule traffic of the connections that belong to the same T-CONT. When one upstream burst need to be produced, XgponOnuUsScheduler is used by ONU to determine the traffic to be put into this burst. The main interface is ”SelectConnToServe”, a virtual function that its subclass must be implement to determine the connection to be served and the amount of data to be transmitted.
33) xgpon-onu-us-scheduler-round-robin.h/.cc: source code for XgponOnuUsSchedulerRoundRobin. XgponOnuUsSchedulerRoundRobin is one subclass of XgponOnuUsScheduler that schedules the upstream connections of the same T-CONT in round-robin manner with considering their queue occupancy.

    This group of files are used to represent XGEM Port and T-CONT in XG-PON. At the sender, there is one queue for each XGEM Port. Fragmentation and reassemble are considered in these classes. Qos parameters and serving history are also maintained in these classes.

34) xgpon-channel.h/.cc: source code for XgponChannel. XgponChannel is a subclass of PonChannel for XG-PON. It maintains the logic one-way-delay for the whole XG-PON network, which should be set based on the largest propagation delay among all ONUs and various processing delays. In XG-PON, all nodes (OLT and ONUs) have a consistent view of this value. Correspondingly, each ONU has one equalization delay that is related with the logic one-way-delay and its own propagation delay (between this ONU and the OLT).
35) xgpon-phy.h/.cc: source code of XgponPhy. XgponPhy contains the physical layer parameters of one XG-PON network and provides several common routines. These parameters can be configured through NS-3 attribute system. Through changing these parameters, we could simulate GPON approximately.
36) xgpon-net-device.h/.cc: source code for XgponNetDevice. XgponNetDevice is a subclass of PonNetDevice that

implements the common functions for both OLT and ONU. It implements ”Send” and ”SendFrom” inherited from NetDevice for accepting packets from upper layers. However, these functions just trace these events and the main jobs are done by ”DoSend” and ”DoSendFrom” that will be instantiated by XgponOnuNetDevice and XgponOltNetDevice. XgponNetDevice also provides functions to other components for sending SDU to upper layers and supporting Pcap and Ascii tracing. It also maintains a per-device statistics, such as the amount of data received from upper layer, dropped due to buffer overflow, etc. It also has one instance of XgponPhy so that the engines of XgponOltNetDevice/XgponOnuNetDevice can get to know physical layer parameters used in simulation.

37) xgpon-olt-net-device.h/.cc: source code for XgponOltNetDevice. XgponOltNetDevice is a subclass of XgponNetDevice for the OLT. It has a bunch of engines that implement various functions of the XGTC layer for the OLT. These engines will be introduced below. XgponOltNetDevice has implemented ”ReceivePonFrameFromChannel” for processing the upstream bursts from ONUs with its engines. It also has implemented ”DoSend” and ”DoSendFrom” to put the packets from the upper layers to their corresponding queues. When this class is initiated at the beginning of the simulation, ”SendDownstreamFrameToChannelPeriodically” is called to periodically (125 micro-second) generate a downstream frame with its engines and pass the frame to XgponChannel for broadcasting to all ONUs.

38) xgpon-onu-net-device.h/.cc: source code for XgponOnuNetDevice. XgponOnuNetDevice is a subclass of XgponNetDevice for ONU. It has a bunch of engines that implement various functions of the XGTC layer for ONU. XgponOnuNetDevice has implemented ”ReceivePonFrameFromChannel” for processing the downstream frames from the OLT with its engines. It also has implemented ”DoSend” and ”DoSendFrom” to put the packets from the upper layers to their corresponding queues. XgponOnuNetDevice also provides ”ProduceAndTransmitUsBurst” in which one upstream burst is produced with its engines and pass to XgponChannel for sending to the OLT. This function is used when ONU processes XgponXgtcBwmap and schedules to produce the burst assigned by the OLT.

This group of files are used to implement XG-PON through instantiating PonNetDevice and PonChannel. Within XgponOltNetDevice, their engines need to call each other’s functions quite frequently. Although we can decouple these engines through adding functions into XgponOltNetDevice (these functions will simply delegate the tasks to the corresponding engines), these engines are tightly coupled and too many functions need to be added. Thus, we let each engine have one reference of XgponOltNetDevice and the engine can access other engines through XgponOltNetDevice. For XgponOnuNetDevice, the situation is similar and we handle in the same way.

39) xgpon-olt-engine.h/.cc: source code for XgponOltEngine. XgponOltEngine is the base class of the following engines used by XgponOltNetDevice. Through inheriting from XgponOltEngine, each engine will have one reference of XgponOltNetDevice, which can be used to access other related engines.

40) xgpon-onu-engine.h/.cc: source code for XgponOnuEngine. XgponOnuEngine is the base class of the following engines used by XgponOnuNetDevice. Through inheriting from XgponOnuEngine, each engine will have one reference of XgponOnuNetDevice, which can be used to access other related engines.

41) xgpon-olt-conn-per-onu.h/.cc: source code for XgponOltConnPerOnu. At the OLT, XgponOltConnPerOnu is used to hold the downstream XGEM Ports and the T-CONTs that belong to one ONU.

42) xgpon-olt-conn-manager.h/.cc: source code for XgponOltConnManager. XgponOltConnManager is designed to maintain all XGEM Ports and T-CONTs at the OLT. For each XGEM Port or T-CONT, it could be put into several data structures for different purposes. In fact, There is only one instance of XGEM Port or T-CONT. We just put one smart pointer that points to this XGEM Port or T-CONT to these data structures. Thus, the memory overhead won't be increased significantly. There is one vector of XgponOltConnPerOnu and the index of one ONU's XgponOltConnPerOnu equals to its ONU-ID. The broadcast downstream XGEM Ports are organized separately. The main function of XgponOltConnManager is to find the corresponding XGEM Port when receiving one packet from the upper layer and to find the corresponding T-CONT when one upstream burst is received from XgponChannel. For processing the upstream burst quickly, all T-CONTs (XgponTcontOlt) are organized into one vector and the index of one XgponTcontOlt equals to its Alloc-Id. For the downstream XGEM Ports (XgponConnectionSender), they are organized differently in the following two subclasses of XgponOltConnManager.

43) xgpon-olt-conn-manager-speed.h/.cc: source code for XgponOltConnManagerSpeed. XgponOltConnManagerSpeed is one subclass of XgponOltConnManager designed to quickly map the packet from upper layer to its corresponding XGEM Port (XgponConnectionSender). All downstream XGEM Ports (XgponConnectionSender) are organized into one vector and the index of one XgponConnectionSender is its XGEM Port-Id. There is one pre-defined relationship between the XGEM Port-Id, the upper layer address of the computer that this XGEM Port is configured for, and the ONU-ID of the ONU that this computer is attached to. When the OLT gets one packet from the upper layer, based on the destination address in packet header, the corresponding XGEM Port-Id can be calculated directly and the corresponding XgponConnectionSender can be found very quickly ($O(1)$). There are several shortcomings in this solution. First, XGEM Port-Id is 16-bit and the vector may waste a lot of memory when there are a few XGEM Ports in the system. Considering that there are only one OLT, the memory overhead should be acceptable. Second, due to the relationship among XGEM Port-Id, Address, and ONU-ID, there will be some constraints on the number of XGEM Ports per ONU. In the current implementation, the maximal XGEM Ports of one ONU is 64. It should be enough unless we simulate some special cases.

44) xgpon-olt-conn-manager-flexible.h/.cc: source code for XgponOltConnManagerFlexible. XgponOltConnManagerFlexible is one subclass of XgponOltConnManager designed for flexibility, i.e., one ONU could have a large number of XGEM Ports. In this class, all downstream XGEM ports (XgponConnectionSender) are organized into one map and the key is the upper layer address of the computer that this XGEM Port is

configured for. Thus, it takes $O(log(n))$ to map one packet from upper layer to the corresponding XgponConnectionSender.

45) xgpon-onu-conn-manager.h/.cc: source code for XgponOnuConnManager. XgponOnuConnManager is designed to maintain the XGEM Ports and T-CONTs that belongs to one ONU. It also maintains XgponConnectionReceiver for the broadcast downstream XGEM Port for receiving the broadcasted traffic. For each XGEM Port or T-CONT, it could be put into several data structures for different purposes. In fact, There is only one instance of XGEM Port or T-CONT. We just put one smart pointer that points to this XGEM Port or T-CONT to these data structures. Thus, the memory overhead won't be increased significantly. The main functions of XgponOnuConnManager are to find the corresponding downstream XGEM Port (XgponConnectionReceiver) when receiving one XGEM frame from XgponChannel and to find the corresponding upstream XGEM Port (XgponConnectionSender) when receiving one packet from upper layer. Its T-CONTs (XgponTcontOnu) should also be maintained for T-CONT related operations. The following two subclasses of XgponOnuConnManager are designed for speed and flexibility, respectively.
46) xgpon-onu-conn-manager-speed.h/.cc: source code for XgponOnuConnManagerSpeed. For each ONU, it needs to check millions of XGEM frames per second to filter out the traffic for itself. Considering that there could be hundreds of ONUs in XG-PON, the operation of mapping XGEM frame to the corresponding XgponConnectionReceiver must be carried out very quickly. One naive solution is to add one vector for each ONU and let the index of XgponConnectionReceiver equal to its XGEM Port-Id. However, the vectors in all ONUs may consume too much memory. Thus, we use one pre-defined relationship between the XGEM Port-Id, the upper layer address of the computer that this XGEM Port is configured for, and the ONU-ID of the ONU that this computer is attached to. Based on XGEM Port-Id and ONU-ID, we can judge whether this XGEM Port belongs to this ONU. When it does belong to this ONU, we can produce a small number based on XGEM Port-Id and ONU-ID, and this number is used as the index of the corresponding XgponConnectionReceiver in a much smaller vector. The upstream XGEM Ports (XgponConnectionSender) and T-CONTs (XgponTcontOnu) are treated similarly. When receiving one packet from upper layer, we calculate the index of the corresponding XGEM Port (XgponConnectionSender) based on the source address in packet header. Similarly, due to the relationship among XGEM Port-Id, Address, and ONU-ID, there are some constraints on the number of XGEM Ports and T-CONTs configured for one ONU.
47) xgpon-onu-conn-manager-flexible.h/.cc: source code for XgponOnuConnManagerFlexible. XgponOnuConnManagerFlexible is one subclass of XgponOnuConnManager designed for flexibility, i.e., one ONU could have a large number of XGEM Ports and T-CONTs. In this class, all downstream/upstream XGEM Ports and T-CONTs are organized into one vector or one map. Thus, it takes $O(log(n))$ or $O(n)$ when searching the corresponding data structures (XgponConnectionSender, XgponConnectionReceiver, XgponTcontOnu, etc.). This group of files are used to manage XGEM Port and T-CONT at OLT and ONU. They are designed carefully so that the corresponding XGEM Port can be found quickly when one SDU is received from upper

layer or one XGEM frame is received from XgponChannel. In XG-PON standard, the SDU could be IP packets or layer-2 frames of various network technologies (Ethernet, ATM, etc.). In current implementation, we assume that the SDU is IP packet and the IP address of the computer attached to ONU is used for mapping. Furthermore, we can only configure one XGEM Port for each computer since only IP address is considered. Thus, to simulating multiple XGEM Ports per ONU, we need connect multiple nodes to this ONU. For XgponOltConnManagerSpeed and XgponOnuConnManagerSpeed, there are some pre-defined relationship among XGEM Port-Id, IP address, and ONU-ID. The same relationship should also be applied when allocating XGEM Port-Id and Alloc-ID to one ONU. This correlation is ensured through XgponHelper that will be introduced below.

48) xgpon-olt-dba-per-burst-info.h/.cc: source code for XgponOltDbaPerBurstInfo. In XG-PON, multiple T-CONTs of the same ONU may be served in the same XgponXgtcBwmap and their corresponding XgponXgtcBwAllocation should be put together to save the overhead of the upstream burst (Inter-burst gap, physical layer header, etc.). XgponOltDbaPerBurstInfo is designed here to maintain these XgponXgtcBwAllocation that belong to the same upstream burst.
49) xgpon-olt-dba-bursts.h/.cc: source code for XgponOltDbaBursts. In one upstream frame, multiple ONUs may be served and one XgponXgtcBwmap needs to specify multiple bursts. Thus, XgponOltDbaBursts is designed to maintain a list of bursts (XgponOltDbaPerBurstInfo) to be specified in one XgponXgtcBwmap. Note that when producing XgponXgtcBwmap from XgponOltDbaBursts, the burst that is changed lastly must be the last burst in XgponXgtcBwmap. Otherwise, if the size of the last changed burst is increased a lot, some short bursts at the end of the list may be totally out of the boundary the corresponding upstream frame and the OLT cannot process these bursts correctly.
50) xgpon-olt-dba-engine.h/.cc: source code for XgponOltDbaEngine. XgponOltDbaEngine is one engine of XgponOltNetDevice. It is responsible to process queue occupancy report from ONU, i.e., pass the report to the corresponding XgponTcontOlt. It also maintains a list of XgponXgtcBwmap that have been transmitted, but the corresponding upstream bursts have not been received. When receiving one upstream burst, the burst's receiving time, these XgponXgtcBwmap and their creation time, and the logic one-way-delay of XgponChannel will be used to find the XgponXgtcBwmap in which the burst was scheduled. The OLT can then get to know the burst profile used by this burst and process this burst further. The last and the most important task of XgponOltDbaEngine is to produce XgponXgtcBwmap for each downstream frame. XgponXgtcBwmap notifies ONUs about how to share the upstream wavelength. When producing XgponXgtcBwmap, XgponOltDbaBursts and XgponOltDbaPrBurstInfo are utilized. As for T-CONTs to be served and the amount of allocated bandwidth, we let the subclass of XgponOltDbaEngine make these decisions based on the DBA algorithm implemented by the subclass.
51) xgpon-olt-dba-engine-giant.h/.cc: source code for XgponOltDbaEngineGiant. XgponOltDbaEngineGiant is one

subclass of XgponOltDbaEngine and implements GiantMAC [22] proposed for GPON. It supports different types of T-CONTs specified in GPON (Fixed, Assured, Non-Assured, and Best-effort) and the correponding parameters can be configured through our helper class.

52) xgpon-olt-dba-parameters-giant.h/.cc: source code for the QoS parameters used by T-CONTs supported by GiantMAC [22].

53) xgpon-olt-dba-engine-round-robin.h/.cc: source code for XgponOltDbaEngineRoundRobin. XgponOltDbaEngineRoundRobin is one subclass of XgponOltDbaEngine. It treats all T-CONTs equally and allocates upstream bandwidth in a round-robin manner with considering queue occupancy reports from ONUs.

54) xgpon-onu-dba-engine.h/.cc: source code for XgponOnuDbaEngine. XgponOnuDbaEngine is one engine of XgponOnuNetDevice. It implements DBA related functions at ONU side. More specifically, it produces queue occupancy report of one T-CONT when asked by the OLT. It also processes XgponXgtcBwmap in each downstream frame. In case that one or more T-CONTs of this ONU appear in XgponXgtcBwmap, it will schedule one event to produce and transmit the upstream burst at the corresponding time.

This group of files are used to implement DBA related functions at OLT and ONU. Considering that DBA is a hot research topic, more subclasses of XgponOltDbaEngine will be developed to implement various DBA algorithms proposed for GPON or XG-PON.

55) xgpon-olt-ds-scheduler.h/.cc: source code for XgponOltDsScheduler. When producing the payload of each downstream frame, the OLT needs to determine the downstream XGEM Ports to be served. Thus, XgponOltDsScheduler is designed as one engine of XgponOltNetDevice. The main interface is ”SelectConnToServe”, a virtual function that its subclass must implement to determine the XGEM Port to be served and the amount of data to be transmitted in the downstream frame.

56) xgpon-olt-ds-scheduler-round-robin.h/.cc: source code for XgponOltDsSchedulerRoundRobin. XgponOltDsSchedulerRoundRobin is one subclass of XgponOltDsScheduler that schedules all downstream XGEM Ports in round-robin manner with considering their queue occupancy.

This group of files are used to schedule the downstream traffic. In the future, more subclasses of XgponOltDsScheduler will be developed to support different QoS parameters of the downstream XGEM Ports.

57) xgpon-xgem-routines.h/.cc: source code for XgponXgemRoutines. XgponXgemRoutines provides several routines used to generate one XgponXgemFrame. It is used by both XgponOltXgemEngine and XgponOnuXgemEngine.

58) xgpon-olt-xgem-engine.h/.cc: source code for XgponOltXgemEngine. XgponOltXgemEngine is one engine of XgponOltNetDevice. It is responsible to produce the payload of a downstream frame, a bunch of XGEM frames. It calls XgponOltDsScheduler to determines the traffic to be transmitted in this downstream frame. Fragmentation may be carried out in the course. XgponOltXgemEngine is also responsible to process XGEM

frames from ONU (Reassemble is carried out if needed). XgponOltXgemEngine is resorted once for the payload of each T-CONT (XgponXgtcUsAllocation).

59) xgpon-onu-xgem-engine.h/.cc: source code for XgponOnuXgemEngine. XgponOnuXgemEngine is one engine of XgponOnuNetDevice. It is responsible to produce the payload of one upstream burst. It is also resorted by XgponOnuFramingEngine once for each T-CONT within this burst and it resorts to XgponOnuUsScheduler of the T-CONT (XgponOnuTcont) for deciding the traffic to be transmitted. Fragmentation may be carried out in the course. XgponOltXgemEngine is also responsible to process the XGEM frames from the OLT. For each downstream frame, it will filter out XGEM frames for this ONU and carry out further processing (reassemble, etc.).

60) xgpon-olt-framing-engine.h/.cc: source code for XgponOltFramingEngine. XgponOltFramingEngine is one engine of XgponOltNetDevice and it is the core of the XGTC layer. Its main functions are to produce XgponXgtcDsFrame to be transmitted in downstream direction and to process XgponXgtcUsBurst received from ONU. When producing XgponXgtcDsFrame, it resorts other engines to compose different parts of XgponXgtcDsFrame. For instance, XgponOltDbaEngine is used to produce XgponXgtcBwmap and XgponOltXgemEngine is called to generate the payload, a bunch of XGEM frames. Similarly, other engines are resorted to process different parts of one XgponXgtcUsBurst received from ONU.

61) xgpon-onu-framing-engine.h/.cc: source code for XgponOnuFramingEngine. XgponOnuFramingEngine is one engine of XgponOnuNetDevice. It also plays the core role at ONU side. When producing XgponXgtcUsBurst, XgponOnuDbaEngine is used to produce queue occupancy report and XgponOnuXgemEngine is called to generate the payload, a bunch of XGEM frames. When processing XgponXgtcDsFrame, XgponOnuDbaEngine is used to process XgponXgtcBwmap and XgponOnuXgemEngine is called to filter out and process XGEM frames for this ONU.

62) xgpon-olt-phy-adapter.h/.cc: source code for XgponOltPhyAdapter. XgponOltPhyAdapter is one engine of XgponOltNetDevice. It is responsible to implement the physic adaptation sub-layer of XG-PON standard at OLT side. Currently, it is a stub class. In the future, transmission error may be simulated in this class.

63) xgpon-onu-phy-adapter.h/.cc: source code for XgponOnuPhyAdapter. XgponOnuPhyAdapter is one engine of XgponOnuNetDevice. It is responsible to implement the physic adaptation sub-layer of XG-PON standard at ONU side. Currently, it is a stub class. In the future, transmission error may be simulated in this class.
This group of files are used to implement the three sub-layers of XGTC layer. The framing sublayer plays the core role and the information flow among these sublayers is illustrated in Figure 14.

64) xgpon-olt-ploam-engine.h/.cc: source code for XgponOltPloamEngine. XgponOltPloamEngine is one engine of XgponOltNetDevice. It has a vector of XgponLinkInfo and the index of one XgponLinkInfo equals to the corresponding ONU-ID.

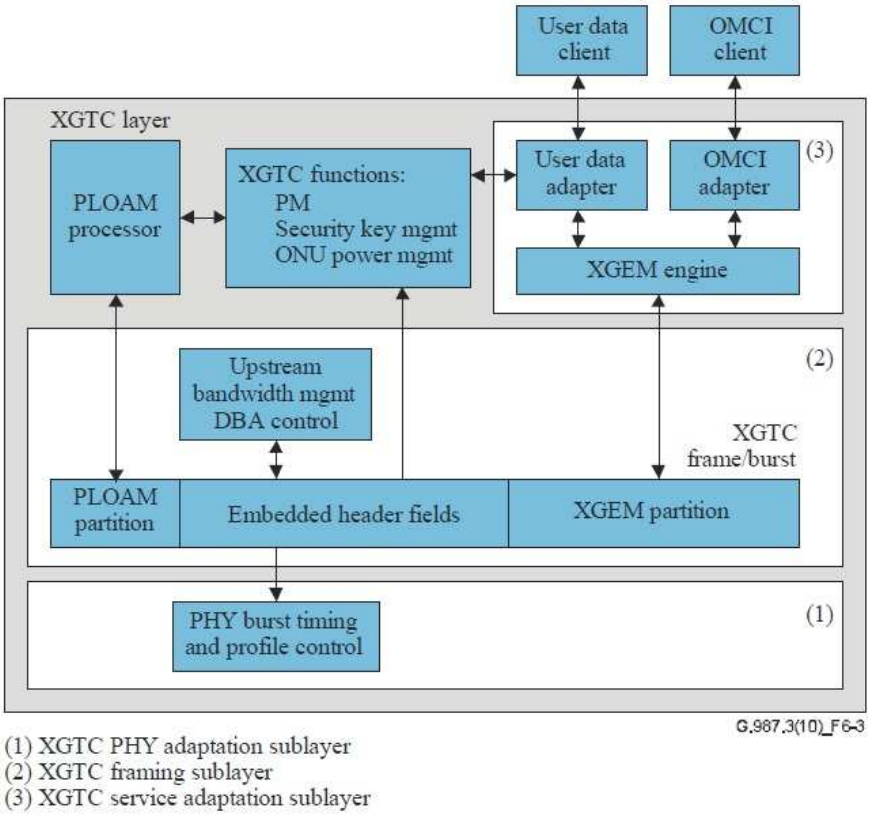


Fig. 14: XG-PON Information Flow

65) xgpon-onu-ploam-engine.h/.cc: source code for XgponOnuPloamEngine. XgponOnuPloamEngine is one engine of XgponOnuNetDevice. It has one XgponLinkInfo for itself.

Since our simulation module is designed to study performance issues of one running XG-PON, PLOAM messages and the corresponding procedures (activation, ranging, etc.) are not simulated. The two classes are used mainly for holding per-ONU information organized within XgponLinkInfo. In the future, these classes may be enriched to simulate some PLOAM messages needed by the research.

66) xgpon-olt-omci-engine.h/.cc: source code for XgponOltOmciEngine. XgponOltOmciEngine is one engine of XgponOltNetDevice.

67) xgpon-onu-omci-engine.h/.cc: source code for XgponOnuOmciEngine. XgponOnuOmciEngine is one engine of XgponOltNetDevice.

Both the two classes are stub classes. OMCI for XG-PON is very complex and it takes too much time to implement. For functions accomplished through OMCI channel (XGEM Port and T-CONT configuration, etc.), we implement through XgponHelper.

68) xgpon-id-allocator.h/.cc: source code for XgponIdAllocator. When adding XGEM Port/T-CONT/ONU into XG-PON, XgponIdAllocator is used to get one available XGEM Port-Id/Alloc-Id/ONU-ID. There are two subclasses designed for allocating these IDs in different ways for different purposes.

69) xgpon-id-allocator-speed.h/.cc: source code for XgponIdAllocatorSpeed. As introduced above, to speed up XG-PON simulation, we can impose some relationship among XGEM Port-Id, Alloc-Id, ONU-ID, and IP address of the node connected to ONU. XgponIdAllocatorSpeed is the subclass designed to impose this relationship.

70) xgpon-id-allocator-flexible.h/.cc: source code for XgponIdAllocatorFlexible. XgponIdAllocatorFlexible is the subclass of XgponIdAllocator. It does not impose any relationship on XGEM Port-Id, Alloc-Id, ONU-ID, and IP address of the node connected to ONU.

71) xgpon-config-db.h/.cc: source code for XgponConfigDb. XgponConfigDb is one database that holds the information used by XgponHelper to configure XG-PON. For instance, it can be used by the researcher to change the subclasses of XgponOltDbaEngine and XgponOltDsScheduler used in the simulation. It also uses one flag to make sure that XgponOltConnManagerSpeed, XgponOnuConnManagerSpeed, and XgponIdAllocatorSpeed are used together.

72) xgpon-helper.h/.cc: source code for XgponHelper. XgponHelper provides the main interfaces needed by researchers for simulating XG-PON. ”Install()” is provided to install XgponOltNetDevice on the OLT and install XgponOnuNetDevice on all ONUs. In this function, XgponOltNetDevice, XgponOnuNetDevice, and their engines are created and configured. Thus, before calling ”Install()”, XgponConfigDb should be used to specify the subclasses used in the simulation and the corresponding object factories must be initialized. The attributes of some classes (XgponPhy, XgponChannel, etc.) can also be changed before calling ”Install()”. Through XgponHelper, researcher can also enable Ascii or Pcap tracing. In XgponHelper, functions are also provided to create XGEM Port and T-CONT for the network. Before calling these functions, XgponHelper can be used to change QoS parameters and queue used by XGEM Port.

This group of files provide the interfaces used by researchers for simulating XG-PON. Firstly, the researcher need specify the parameters through XgponConfigDb and XgponHelper. Secondly, the nodes for the OLT and ONUs must be prepared and ”Install()” of XgponHelper is called to install XponOltNetDevice and XgponOnuNetDevice on these nodes. Thirdly, after getting the corresponding IP address of the computers connected to ONUs, XGEM Port and T-CONT can be configured through XgponHelper. Before creating XGEM Port or T-CONT, their QoS parameters and queue can also be changed through XgponHelper.

APPENDIX C
XG-PON SIMULATION EXAMPLE

This appendix presents one example for XG-PON simulation with aim to demonstrate the usage of XgponHelper. In this example, dumb-bell topology is adopted and bi-directional UDP traffics are generated between computers in core network (Left Servers and Left Clients) and computers that access the Internet through XG-PON. The code related with XG-PON simulation has been explained by comments started with "////". The most important steps are to install XgponNetDevice on the OLT and ONUs, configure IP addresses for these nodes, and add XGEM Port (and the T-CONT related with upstream XGEM Port) for carrying traffics of ONUs.

```
/*************************************************************
* This script will create UDP client and server at both sides  to generate two-way traffics.
*
*                                                                          P2P
*                                                          ------- ONU1 ---------- UDP sink/sender 1
*                      P2P              P2P (CN)           /
*   Left Servers ---------------- Gateway ---------------- OLT------
*                                  |                       \              P2P
*                        P2P       |                        ------- ONUn ---------- UDP sink/sender n
*   Left Clients ------------------
*************************************************************/

#include <iostream>
#include <fstream>

#include "ns3/core-module.h"
#include "ns3/network-module.h"
#include "ns3/internet-module.h"
#include "ns3/object-factory.h"
#include "ns3/applications-module.h"
#include "ns3/point-to-point-module.h"
#include "ns3/stats-module.h"

////this header file must be included for simulating XG-PON.
#include "ns3/xgpon-module.h"

using namespace ns3;

////Some constants used in the simulation: 100 seconds to be simulated; 2 ONUs;
////10Mbps per ONU for downstream and 2.5Mbps for upstream.
#define APP_START_TIME     0
#define APP_STOP_TIME     100
#define SIM_STOP_TIME     (APP_STOP_TIME + 1)
#define ONU_NUM            2
#define UDP_PKT_SIZE       1500
#define DS_PKT_INTERVAL    0.001
#define US_PKT_INTERVAL    0.004

////for supporting NS-3 Log
NS_LOG_COMPONENT_DEFINE ("XgponSimulationSpeedFanUdp");
```

```
////trace sink used to print per-device statistics periodically (per second).
void DeviceStatisticsTrace (const XgponNetDeviceStatistics& stat)
{
  static uint64_t time2print = 1000000000;    //1,000,000,000 nanoseconds per second.
  if(stat.m_currentTime > time2print)
  {
    std::cout << (stat.m_currentTime / 1000000000L) << "seconds_have_been_simulated.";
    std::cout << "DS-BYTES:" << stat.m_passToXgponBytes;
    std::cout << ";US-BYTES:" << stat.m_rxFromXgponBytes;
    std::cout << ";FROM-CN-DS-BYTES:" << stat.m_rxFromUpperLayerBytes;
    std::cout << ";DROPPED-DS-BYTES:" << stat.m_overallQueueDropBytes;
    std::cout << std::endl;
    time2print += 1000000000;
  }
}

int main (int argc, char *argv[])
{
  ////default values for command-line options
  bool p_verbose = false;
  uint16_t p_nOnus = ONU_NUM;
  uint16_t p_appStartTime = APP_START_TIME;
  uint16_t p_appStopTime = APP_STOP_TIME;
  uint16_t p_simStopTime = SIM_STOP_TIME;
  uint16_t p_pktSize = UDP_PKT_SIZE;
  double p_dsPktInterval = DS_PKT_INTERVAL;
  double p_usPktInterval = US_PKT_INTERVAL;

  ////get command-line options
  CommandLine cmd;
  cmd.AddValue ("verbose", "Tell_application_to_log_if_true", p_verbose);
  cmd.AddValue ("onus", "the_number_of_onus", p_nOnus);
  cmd.AddValue ("astarttime", "the_start_time_of_applications", p_appStartTime);
  cmd.AddValue ("astoptime", "the_stop_time_of_applications", p_appStopTime);
  cmd.AddValue ("sstoptime", "the_stop_time_of_whole_simulation", p_simStopTime);
  cmd.AddValue ("dspktinterval", "the_packet_interval_of_downstream_udp_client(second)", p_dsPktInterval);
  cmd.AddValue ("uspktinterval", "the_packet_interval_of_upstream_udp_client(second)", p_usPktInterval);
  cmd.AddValue ("pktsize", "the_UDP_packet_size(byte)", p_pktSize);
  cmd.Parse (argc,argv);

  if(p_verbose)
  {
    LogComponentEnable ("UdpClient", LOG_LEVEL_INFO);
    LogComponentEnable ("UdpServer", LOG_LEVEL_INFO);
    LogComponentEnable ("XgponChannel", LOG_LEVEL_FUNCTION);
  }
  Packet::EnablePrinting ();

  ///////Create all nodes and organize them into the corresponding containers for installing network devices.
  ////the ONUs, OLT nodes, and container for all xgpon nodes
  NodeContainer oltNode, onuNodes, xgponNodes;
  oltNode.Create (1);
```

```
onuNodes.Create (p_nOnus);
xgponNodes.Add(oltNode.Get(0));
for(int i=0; i<p_nOnus; i++) { xgponNodes.Add (onuNodes.Get(i)); }

//the gateway node, OLT node, and container for the link to simulate Internet's core network
NodeContainer gatewayNode, cnNodes;
gatewayNode.Create (1);
cnNodes.Add(oltNode.Get(0));
cnNodes.Add(gatewayNode.Get(0));

//the end hosts at both sides of the networks
NodeContainer leftServerNode, leftClientNode, rightNodes;
NodeContainer leftServerLinkNodes, leftClientLinkNodes;
NodeContainer rightLinkNodes[p_nOnus];
leftServerNode.Create (1);
leftClientNode.Create (1);
leftServerLinkNodes.Add(leftServerNode.Get(0));
leftServerLinkNodes.Add(gatewayNode.Get(0));
leftClientLinkNodes.Add(leftClientNode.Get(0));
leftClientLinkNodes.Add(gatewayNode.Get(0));

rightNodes.Create (p_nOnus);
for(int i=0; i<p_nOnus; i++)
{
  rightLinkNodes[i].Add(rightNodes.Get(i));
  rightLinkNodes[i].Add(onuNodes.Get(i));
}

///////Create all links used to connect the above nodes
////Xgpon network configuration through XgponHelper
XgponHelper xgponHelper;
XgponConfigDb& xgponConfigDb = xgponHelper.GetConfigDb ( );

xgponConfigDb.SetOltNetmaskLen (16);
xgponConfigDb.SetOnuNetmaskLen (24);
xgponConfigDb.SetIpAddressFirstByteForXgpon (10);
xgponConfigDb.SetIpAddressFirstByteForOnus (172);

////other configuration related information
Config::SetDefault("ns3::XgponOltDbaEngineRoundRobin::MaxServiceSize", UintegerValue(1000));  //1000 words
Config::SetDefault("ns3::XgponOltDsSchedulerRoundRobin::MaxServiceSize", UintegerValue(10000));  //10K bytes
Config::SetDefault("ns3::XgponOnuUsSchedulerRoundRobin::MaxServiceSize", UintegerValue(4000));  //4K bytes

////Set TypeId String for object factories through XgponConfigDb before the following call.
////initialize object factories
xgponHelper.InitializeObjectFactories ( );

////configuration through object factory
xgponHelper.SetQueueAttribute ("MaxBytes", UintegerValue(50000));  //queue size is 50KBytes

////install xgpon network devices
NetDeviceContainer xgponDevices = xgponHelper.Install (xgponNodes);
```

```
//Internet core network through PointToPointHelper
PointToPointHelper p2pHelper;
p2pHelper.SetDeviceAttribute ("DataRate", StringValue ("20000Mbps"));
p2pHelper.SetChannelAttribute ("Delay", StringValue ("10ms"));
p2pHelper.SetQueue ("ns3::DropTailQueue", "MaxPackets", UintegerValue (2000));
NetDeviceContainer cnDevices = p2pHelper.Install (cnNodes);

//links for connecting end hosts to routers/onus through PointToPointHelper
p2pHelper.SetDeviceAttribute ("DataRate", StringValue ("20000Mbps"));
p2pHelper.SetChannelAttribute ("Delay", StringValue ("2ms"));
p2pHelper.SetQueue ("ns3::DropTailQueue", "MaxPackets", UintegerValue (2000));
NetDeviceContainer leftServerLinkDevices, leftClientLinkDevices;
leftServerLinkDevices = p2pHelper.Install (leftServerLinkNodes);
leftClientLinkDevices = p2pHelper.Install (leftClientLinkNodes);

p2pHelper.SetDeviceAttribute ("DataRate", StringValue ("20000Mbps"));
p2pHelper.SetChannelAttribute ("Delay", StringValue ("2ms"));
p2pHelper.SetQueue ("ns3::DropTailQueue", "MaxPackets", UintegerValue (100));
NetDeviceContainer rightLinkDevices[p_nOnus];
for(int i=0; i<p_nOnus; i++)
{
  rightLinkDevices[i] = p2pHelper.Install (rightLinkNodes[i]);
}

///////install internet protocol stack
InternetStackHelper stack;
stack.Install (xgponNodes);
stack.Install (leftServerNode);
stack.Install (leftClientNode);
stack.Install (rightNodes);
stack.Install (gatewayNode);

///////Assign IP addresses to all interfaces of all nodes
Ipv4AddressHelper addressHelper;

//Assign IP addresses to core network nodes (point-to-point link)
std::string cnIpbase = xgponHelper.GetIpAddressBase (150, 0, 24);
std::string cnNetmask = xgponHelper.GetIpAddressNetmask (24);
addressHelper.SetBase (cnIpbase.c_str(), cnNetmask.c_str());
Ipv4InterfaceContainer cnInterfaces = addressHelper.Assign (cnDevices);
if(p_verbose)
{
  Ipv4Address tmpAddr = cnInterfaces.GetAddress(0);
  std::cout << "OLT_Internet_Interface'sIP_Address:";
  tmpAddr.Print(std::cout);
  std::cout << std::endl;
  tmpAddr = cnInterfaces.GetAddress(1);
  std::cout << "Internet_Gateway's_IP_Address:";
  tmpAddr.Print(std::cout);
  std::cout << std::endl;
}
```

```
//Assign IP addresses to end hosts at the left side (point-to-point link)
Ipv4InterfaceContainer leftServerLinkInterfaces, leftClientLinkInterfaces;
std::string leftServerIpbase = xgponHelper.GetIpAddressBase (160, 1, 24);
std::string leftServerNetmask = xgponHelper.GetIpAddressNetmask (24);
addressHelper.SetBase (leftServerIpbase.c_str(), leftServerNetmask.c_str());
leftServerLinkInterfaces = addressHelper.Assign (leftServerLinkDevices);
std::string leftClientIpbase = xgponHelper.GetIpAddressBase (160, 2, 24);
std::string leftClientNetmask = xgponHelper.GetIpAddressNetmask (24);
addressHelper.SetBase (leftClientIpbase.c_str(), leftClientNetmask.c_str());
leftClientLinkInterfaces = addressHelper.Assign (leftClientLinkDevices);

////Assign IP addresses to OLT and ONU (for xgpon network devices)
Ptr<XgponOltNetDevice> tmpDevice = DynamicCast<XgponOltNetDevice, NetDevice> (xgponDevices.Get(0));
std::string xgponIpbase = xgponHelper.GetXgponIpAddressBase ( );
std::string xgponNetmask = xgponHelper.GetOltAddressNetmask();
addressHelper.SetBase (xgponIpbase.c_str(), xgponNetmask.c_str());
Ipv4InterfaceContainer xgponInterfaces = addressHelper.Assign (xgponDevices);
for(int i=0; i<(p_nOnus+1);i++)
{
  Ipv4Address addr = xgponInterfaces.GetAddress(i);
  Ptr<XgponNetDevice> tmpDevice = DynamicCast<XgponNetDevice, NetDevice> (xgponDevices.Get(i));
  tmpDevice->SetAddress (addr);
  if(p_verbose)
  {
    if(i==0) std::cout << "OLT_IP_Address:";
    else std::cout << "ONU" << (i-1) <<"IP_Address:";
    addr.Print(std::cout);
    std::cout << std::endl;
  }
}

//Assign IP addresses to end hosts at the right side (point-to-point link)
Ipv4InterfaceContainer rightLinkInterfaces[p_nOnus];
for(int i=0; i<p_nOnus; i++)
{
  Ptr<XgponOnuNetDevice> tmpDevice = DynamicCast<XgponOnuNetDevice, NetDevice> (xgponDevices.Get(i+1));
  std::string onuIpbase = xgponHelper.GetOnuIpAddressBase (tmpDevice);
  std::string onuNetmask = xgponHelper.GetOnuAddressNetmask();
  addressHelper.SetBase (onuIpbase.c_str(), onuNetmask.c_str());
  rightLinkInterfaces[i] = addressHelper.Assign (rightLinkDevices[i]);
  if(p_verbose)
  {
    Ipv4Address addr = rightLinkInterfaces[i].GetAddress(0);
    std::cout << "Right_Node " << i <<"IP_Address:";
    addr.Print(std::cout);
    std::cout << std::endl;
    addr = rightLinkInterfaces[i].GetAddress(1);
    std::cout << "IP_Address_at_the_Corresponding_ONU:";
    addr.Print(std::cout);
    std::cout << std::endl;
  }
}
```

```
////Add OMCI Channels
//set attributes (QoS parameters, etc.) for connections to be added as OMCI channel
//we need get the address before setting OMCI channel.
//for(int i=0; i<p_nOnus; i++)
//{
//  Ptr<XgponOltNetDevice> oltDevice = DynamicCast<XgponOltNetDevice, NetDevice> (xgponDevices.Get(0));
//  Ptr<XgponOnuNetDevice> onuDevice = DynamicCast<XgponOnuNetDevice, NetDevice> (xgponDevices.Get(i+1));
//  xgponHelper.AddOmciConnectionsForOnu (onuDevice, oltDevice);
//}

////add xgem ports for end hosts connected to ONUs
for(int i=0; i<p_nOnus; i++)
{
  Address addr = rightLinkInterfaces[i].GetAddress(0);
  Ptr<XgponOltNetDevice> oltDevice = DynamicCast<XgponOltNetDevice, NetDevice> (xgponDevices.Get(0));
  Ptr<XgponOnuNetDevice> onuDevice = DynamicCast<XgponOnuNetDevice, NetDevice> (xgponDevices.Get(i+1));
  uint16_t allocId = xgponHelper.AddOneTcontForOnu (onuDevice, oltDevice);
  uint16_t upPortId = xgponHelper.AddOneUpstreamConnectionForOnu (onuDevice, oltDevice, allocId, addr);
  uint16_t downPortId = xgponHelper.AddOneDownstreamConnectionForOnu (onuDevice, oltDevice, addr);
  if(p_verbose)
  {
    std::cout << "ONU-ID="<<onuDevice->GetOnuId() << ";ALLOC-ID=" << allocId
              << ";UP-PORT-ID=" << upPortId << ";DOWN-PORT-ID=" << downPortId << std::endl;
  }
}

////////Populate routing tables for all nodes
Ipv4GlobalRoutingHelper::PopulateRoutingTables ();

/////////generating traffics
//Containers (downstream)
ApplicationContainer leftServers, rightServers;
uint16_t leftServerPort=9000;
uint16_t rightServerPort=9001;

//Set UdpServer on left nodes
UdpServerHelper leftServerHelper (leftServerPort);
leftServers = leftServerHelper.Install (leftServerNode);
leftServers.Start (Seconds (0));
leftServers.Stop (Seconds (p_appStopTime));

//Set UdpServer on right nodes
UdpServerHelper rightServerHelper (rightServerPort);
rightServers = rightServerHelper.Install (rightNodes);
rightServers.Start (Seconds (0));
rightServers.Stop (Seconds (p_appStopTime));

//SetUdpClient on left nodes (generate downstream traffic); connect to right servers
for(int i=0; i<p_nOnus; i++)
{
  UdpClientHelper udpClientHelper (rightLinkInterfaces[i].GetAddress(0), rightServerPort);
  udpClientHelper.SetAttribute ("MaxPackets", UintegerValue (2000000000));
  udpClientHelper.SetAttribute ("Interval", TimeValue (Seconds (p_dsPktInterval)));
```

```
    udpClientHelper.SetAttribute ("PacketSize", UintegerValue (p_pktSize));
    ApplicationContainer clientApp = udpClientHelper.Install (leftClientNode.Get (0));
    clientApp.Start (Seconds (p_appStartTime + i * 0.001));
    clientApp.Stop (Seconds (p_appStopTime));
  }

  //SetUdpClient on right nodes (generate upstream traffic); connect to left servers
  for(int i=0; i<p_nOnus; i++)
  {
    UdpClientHelper udpClientHelper (leftServerLinkInterfaces.GetAddress(0), leftServerPort);
    udpClientHelper.SetAttribute ("MaxPackets", UintegerValue (2000000000));
    udpClientHelper.SetAttribute ("Interval", TimeValue (Seconds (p_usPktInterval)));
    udpClientHelper.SetAttribute ("PacketSize", UintegerValue (p_pktSize));
    ApplicationContainer clientApp = udpClientHelper.Install (rightNodes.Get (i));
    clientApp.Start (Seconds (p_appStartTime + i * 0.001));
    clientApp.Stop (Seconds (p_appStopTime));
  }

  ////ascii and pcap feature
  if(p_verbose)
  {
    xgponHelper.EnableAsciiAll("xgpon-simulation-speed-fan-udp-ascii");
    xgponHelper.EnablePcapAll("xgpon-simulation-speed-fan-udp-pcap");
  }

  ////print per-net-device statistics at the OLT
  Ptr<XgponOltNetDevice> oltDevice = DynamicCast<XgponOltNetDevice, NetDevice> (xgponDevices.Get(0));
  oltDevice->TraceConnectWithoutContext ("DeviceStatistics", MakeCallback(&DeviceStatisticsTrace));

  std::cout<<std::endl;
  Simulator::Stop(Seconds(p_simStopTime));
  Simulator::Run ();
  Simulator::Destroy ();
  std::cout<<std::endl;
  return 0;
}
```

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