Integration of OMNeT++ Hybrid TDM/WDM-PON Models into INET Framework

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ABSTRACT

It is critical to take into account both the interactive nature of actual traffic resulting from TCP congestion control and the end-user service experiences at the application layer in assessing the performances of next-generation optical access architectures. In this paper we present the results of our efforts to integrate OMNeT++-based hybrid time division multiplexing (TDM)/wavelength division multiplexing (WDM)-passive optical network (PON) simulation models — the models up to the data link layer which were originally developed for the study of Stanford University aCCESS-Hybrid PON (SUCCESS-HPON) architecture — into the INET framework where we can provide an end-to-end simulation environment with end-user applications, including new application-layer traffic models for Internet web browsing (HTTP), file downloading (FTP), and HDTV-quality streaming video, as well as a complete TCP/IP protocol stack. Using developed models, we have carried out a comparison study with a dedicated, point-to-point access architecture and demonstrated the benefits of the shared access architecture, i.e., the hybrid TDM/WDM-PON.

Categories and Subject Descriptors

C.2.1 [**Network Architecture and Design**]: Network Communications and Network Topology—*passive optical networks*; C2.5 [**Local and Wide-Area Networks**]: Access schemes—*hybrid TDM/WDM*; I.6.5 [**Model Development**]: Modeling methodologies—*OMNeT++ and INET framework*

General Terms

Design, Experimentation, Performance

Keywords

Passive Optical Networks, Hybrid TDM/WDM, OMNeT++, INET Framework

1. INTRODUCTION

The Stanford University aCCESS-Hybrid Passive Optical Network (SUCCESS-HPON) architecture was proposed for next-generation optical access networks [1, 2]. Especially the hybrid time division multiplexing (TDM)/wavelength division multiplexing (WDM)-PON under the SUCCESS-HPON architecture can provide economical migration paths from the current-generation TDM-PONs to future WDM-based optical access networks by sharing high-performance but costly components and resources: First, the optical line terminal (OLT) uses tunable transmitters and receivers that are shared by all the optical network units (ONUs) served by the OLT to reduce the number of expensive dense WDM (DWDM) transceivers. Second, also for cost reduction and ease of maintenance, ONUs have no local DWDM light sources but use optical modulators to modulate optical continuous wave (CW) bursts provided by the OLT for upstream transmissions. Therefore, the tunable transmitters at the OLT are used for both upstream and downstream transmissions.

As we studied scheduling algorithms for the hybrid TDM/-WDM-PON under the SUCCESS-HPON architecture, we implemented simulation models based on OMNeT++ [3], which capture the detailed aspects of the physical and the data link layers including the tuning times of tunable transceivers at the OLT, the guard band between consecutive PON frames for absorbing the effects of non-zero tuning times and unstable local ONU clock frequencies, and the encapsulation of Ethernet frames at the PON sublayer [4]. Because the main focus of the study was on the lower layer issues up to the data link layer, the performance evaluation was carried out with a simple IP packet generator based on Poisson process. The interaction between the congestion control of TCP at the transport layer and the medium access control (MAC) protocol & the scheduling algorithm at the data link layer, however, couldn't be investigated. Therefore, we decided to integrate the OMNeT++-based lower-layer hybrid TDM/WDM-PON models into the INET framework where we can provide an end-to-end simulation environment with end-user applications as well as a complete TCP/IP protocol stack, the results of which are now available as "inet-hnrl"[1], a new fork of INET framework [5].

In this paper we discuss design issues related with the said integration and describe the current status of implemented hybrid TDM/WDM-PON models under the INET framework. The rest of the paper is organized as follows: Section 2 reviews the hybrid TDM/WDM-PON under the SUCCESS-HPON architecture. Section 3 discusses several

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[1]http://github.com/kyeongsoo/inet-hnrl.

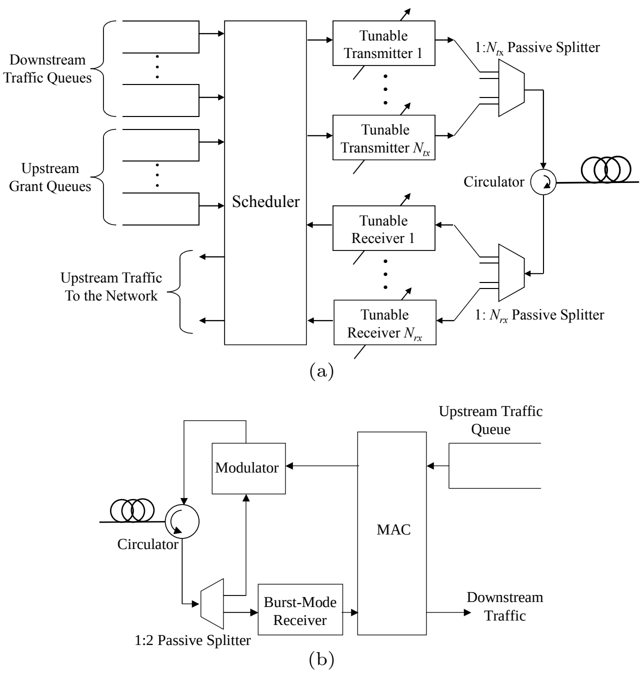


Figure 1: Block diagrams of (a) OLT and (b) ONU of hybrid TDM/WDM-PON under SUCCESS-HPON architecture.

design issues in integrating the existing OMNeT++-based simulation models into the INET framework and describes the current status of the implementation in the inet-hnrl fork of the INET framework. Section 4 presents and discusses the results of a comparison study with a dedicated, point-to-point access architecture based on the implemented simulation models. Section 5 summarizes our work in this paper.

2. HYBRID TDM/WDM-PON UNDER SUCCESS-HPON ARCHITECTURE

In this section we focus on the hybrid TDM/WDM-PON under the SUCCESS-HPON architecture and review its OLT and ONU structures, MAC protocol and frame formats, and sequential scheduling with schedule-time framing (S^3F) algorithm. For a general overview of the whole SUCCESS-HPON architecture and detailed discussions of scheduling algorithms, readers are referred to [1] and [4], respectively.

2.1 OLT and ONU Structures

Fig. 1 shows the block diagrams of OLT and ONU of the hybrid TDM/WDM-PON under the SUCCESS-HPON architecture. Note that the OLT and the ONUs are connected through a WDM multiplexer/demultiplexer, e.g., arrayed waveguide grating (AWG), at a remote node (RN) which is not shown in the figure. As shown in Fig. 1 (a), tunable transmitters and tunable receivers are used at the OLT, whose numbers are typically less than the number of ONUs: Because the average load of the network is usually lower than the peak load [6], we can expect statistical multiplexing gain by sharing tunable components, which also reduces the total system cost by minimizing the transceiver count for a given number of ONUs and user demand on bandwidth.

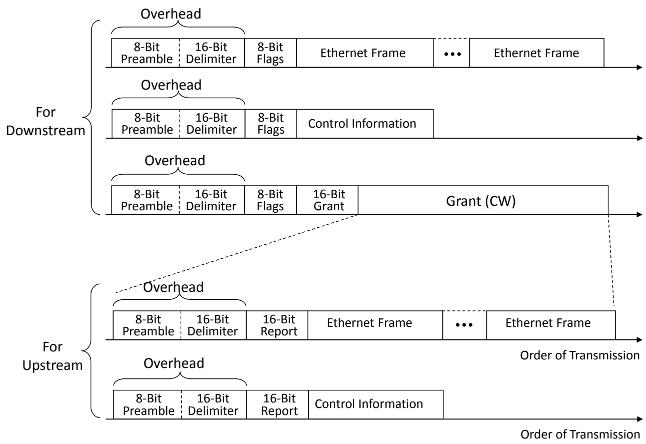


Figure 2: Hybrid TDM/WDM-PON frame formats.

Downstream optical signals from the tunable transmitters in DWDM channels are transmitted to the ONUs through a passive splitter and a circulator. Upstream optical signals from the ONUs pass the same circulator but are separated from the downstream signals. The scheduler controls the operation of both tunable transmitters and tunable receivers based on the scheduling algorithm that will be described in Section 2.3.

The tunable transmitters at the OLT are used for both downstream frames and CW optical bursts to be modulated by the ONUs for their upstream frames. This design could significantly lower the operation and maintenance costs by realizing colorless ONUs [7]. As a tradeoff, however, we need a rather complicated scheduling algorithm to provide efficient bidirectional communication at the MAC sublayer because this configuration allows only half-duplex communication at the physical layer between the OLT and each ONU.

As the ONU has no local light source and uses an optical modulator to modulate optical CW bursts received from the OLT for its upstream transmission, a semiconductor optical amplifier (SOA) can be used as a modulator for this purpose [8]. The ONU MAC protocol block not only controls the switching between upstream and downstream transmissions but also coordinates with the scheduler at the OLT through a polling mechanism.

2.2 MAC Protocol and Frame Formats

As in TDM-PONs, the hybrid TDM/WDM-PON OLT polls to check the amount of upstream traffic stored at the ONUs and sends grants – but in the form of optical CW bursts in this case – to allow the ONUs to transmit upstream traffic. For this reason, the MAC protocol uses several different frame formats shown in Fig. 2, where the report and grant fields are defined for the polling process.[2] The 8-bit flags are used for indicating the type and operation of a frame and the usage of the fields in the 8-bit flags is summarized in Table 1.

Each ONU reports the amount of traffic waiting in its up-

[2]Although the figure shows Ethernet frames carried in the payload part of PON frames, any other protocol frame or packet, e.g., IP packets, can be encapsulated and carried in a PON frame because it does not depend on any specific layer 2 or 3 protocols.

Table 1: 8-Bit Flags in Downstream PON Frame

Bit	Field	Values
0-3	Frame Type	0 - Normal Data 1 - GATE (Grant) 2 - REGISTER_REQ 3 - REGISTER 4 - REGISTER_ACK 5-15 - Unused
4	Force Report	0 - No action required 1 - ONU should report
5-7	Unused	-

stream traffic queue in octets through the report field in an upstream frame when the "Force Report" field of a received downstream frame is set, and the OLT uses the grant field to indicate the actual size of each grant (also in octets). Note that, as shown in Fig. 2, the length of the whole CW burst corresponds to that of all upstream Ethernet frames (i.e., the size of grant) plus the report field and the overhead.

We use two control parameters to govern the polling process consisting of reporting and granting operations as follows:

- *ONU_TIMEOUT*: The OLT maintains one timer per ONU and resets it whenever a grant frame is sent downstream to an ONU. It clears the timer when the corresponding upstream frame with a nonzero report field is received. If the timer expires after the *ONU_TIMEOUT* period, which means either there was no upstream traffic when the ONU received a grant frame or the report message was lost during the transmission to the OLT, the OLT sends a new grant to poll that ONU again and resets the timer. This parameter keeps the polling process going on even in the case of the loss of polling messages and bounds the maximum polling cycle. It also affects the average packet delay of upstream traffic when the system is under light load.
- *MAX_GRANT*: This parameter limits the maximum size of a grant (i.e., the payload part of the CW burst) for ONU upstream traffic.

We will discuss in detail the usage of 8-bit flags and their corresponding operations in Section 3.3 where we describe the ONU discovery procedure and control frames used for it.

2.3 Sequential Scheduling with Schedule-time Framing (S^3F)

The major design goal of the S^3F algorithm is to overcome the low transmission efficiency and the poor fairness guarantee between upstream and downstream traffic flows of the original sequential scheduling algorithm proposed in [9]. To achieve this goal, the original sequential scheduling mode is maintained but grants are used for downstream traffic as well, in addition to upstream traffic, together with schedule-time framing to reduce the overhead due to framing and guard bands. Also, virtual output queueing (VOQing) is used to separate and protect memory spaces among traffic flows.

Unlike the original sequential scheduling algorithm, the scheduling is done at the end of each frame transmission

```
begin
    if VOQ[i] is not empty then
        numBits ⟵ 0;
        pos ⟵ 0;
        ptr ⟵ &ethFrame(VOQ[i], pos);
        repeat
            dsTxCtr[i] ⟵ dsTxCtr[i] − length(*ptr);
            numBits ⟵ numBits + length(*ptr);
            pos ⟵ pos + 1;
            ptr ⟵ &ethFrame(VOQ[i], pos);
            if ptr is NULL then
                // no more frames to schedule
                exit the loop;
            end
        until dsTxCtr[i] < length(*ptr);
        schedule the transmission of a PON frame whose
        payload length is numBits;
        // using the original sequential scheduling
           algorithm in [10]
        store pos for the scheduled transmission later;
    end
end
```

Figure 3: Pseudocode for the scheduling of downstream data frame transmission for a given channel i in S^3F [4]. Note that *pos* denotes the relative position of an Ethernet frame from the head of the VOQ (*e.g.*, $pos = 0$ means it is the head-of-line (HOL) frame.).

(except in the case when a frame arrives at an empty VOQ, where the scheduling is done immediately after its arrival). It also uses grants for downstream traffic as well as upstream traffic to provide better fairness guarantee and schedule-time framing of downstream Ethernet frames in the VOQs to overcome the low transmission efficiency of the original scheduling algorithm. Due to the memory space protection among traffic flows through VOQing, the S^3F can provide better fairness guarantee than the original sequential scheduling algorithm.

For the purpose of granting downstream traffic, we maintain a downstream transmission counter per downstream VOQ. When granting upstream traffic based on a received request from an ONU, we also grant downstream traffic as well based on the VOQ status at the time of the arrival of the report message. Granting downstream traffic is done by setting the said grant counter to the minimum of the queue length of the VOQ and *MAX_GRANT*. When scheduling downstream transmission, the grant counter value controls the number of Ethernet frames to be scheduled and transmitted in one PON frame through the procedure shown in Fig. 3.

Note that the procedure in Fig. 3 allows at least one Ethernet frame transmission to be scheduled, irrespective of the value of the downstream transmission counter (i.e., $dsTxCtr[i]$). This allows the OLT to transmit downstream traffic for a particular ONU even when there is no granting for the ONU: In the case where there is no request for upstream traffic from that ONU and therefore no granting, it is still possible to transmit downstream frames, but one at a time.

3. INTEGRATION INTO INET FRAMEWORK

Here we discuss several important design issues that we faced and had to address during the integration of OMNeT++-based hybrid TDM/WDM-PON models into the INET framework and describe the current status of the implementation in the inet-hnrl.

3.1 Switching at OLT and ONUs

One of the major issues in the integration of the original, lower-layer-only hybrid TDM/WDM-PON models into the INET framework, which were developed and run in a rather isolated simulation environment with their own packet/frame sources and sinks at an OLT and ONUs, was interfacing with the upper layer (i.e., data link layer): First, we needed to decide how to map the addresses at the data link layer and those at the PON sublayer. Unlike Ethernet PON (EPON) where the tree topology brings a very unique challenge to Ethernet bridging, i.e., point-to-point connection for upstream communication from ONUs, but point-to-multipoint connection for downstream communication from an OLT, the hybrid TDM/WDM-PON provides point-to-point connections for downstream (through separate WDM channels) as well as upstream communication, so we can consider the whole PON as a transparent point-to-point network as shown in Fig. 4 (a).[3] Note that with the point-to-point model of underlying PON, there is no support of broadcasting/multicasting at the PON level, which should be handled at upper layers.

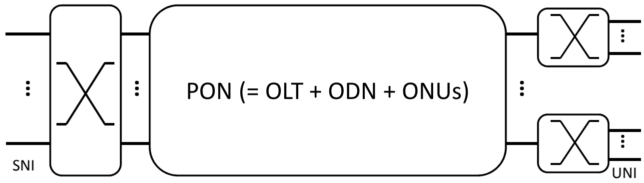
Second, we also needed to decide at which layer to implement the switching function: PON sublayer or data link layer? If we go with the former option, we could provide more efficient, PON-specific switching capability, but at the expense of the need to implement new switching modules. On the other hand, the second option allows us to use existing data link layer switching modules (i.e., Ethernet switches) in the INET framework probably at the expense of slight decrease in efficiency (e.g., due to bridge learning). For ease of implementation, we decided to use the existing Ethernet switching modules rather than developing our own, PON-specific ones. The resulting layered-view of switching at OLT and ONUs are shown in Fig. 4 (b).

3.2 Physical (Optical) Layer Modeling

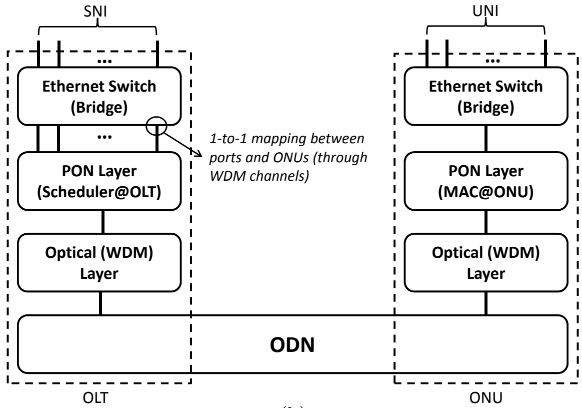
There are several important operations to model in detail in the physical (optical) layer of the hybrid TDM/WDM-PON: WDM multiplexing & demultiplexing, encapsulation & decapsulation to and from optical frames (corresponding to electrical to optical (E/O) and optical to electrical (O/E) conversion in a real system), tuning time of optical transceivers, and optical frame reception & transmission.

Currently the WDM multiplexing & demultiplexing at the OLT, together with frame transmission and tuning times of optical transceivers, are well implemented in detail, which, as described before, are critical to the study of scheduling algorithms. On the other hand, the WDM multiplexing & demultiplexing is not needed at the ONUs under the current SUCCESS-HPON architecture and therefore not implemented. This could be changed, however, when we move to a different, more advanced hybrid TDM/WDM-PON architectures in the future where, for instance, either a tunable transceiver or an array of transceivers are used at the ONUs as well.

[3]It is possible to emulate point-to-point downstream connections in EPON with the help of logical link ID (LLID), but we need to implement Ethernet bridging function specific to EPON in this case [10].



(a)



(b)

Figure 4: Switching at OLT and ONUs: (a) An overview and (b) a layered view, where SNI and UNI stand for service node interface and user network interface, respectively.

As for the reception and transmission of optical frames at the ONUs — which directly modulate incoming optical CW bursts — and the RN, we need to model them based on the "cut-through" switching mechanism instead of OMNeT++'s default "store-and-forward" one, as shown in Fig. 5.[4] Unlike the existing shared medium modules (e.g., Ethernet bus) which are based on infinite-rate channels and internally calculate the times of frame receptions and transmissions using location information of nodes, the use of "cut-through" reception mode at the RN and the ONUs enables the use of finite-rate channels in modeling feeder and distribution fibers, which makes the network configuration becomes more general and easier: For example, in the original hybrid TDM/WDM-PON, the configuration of distances between the OLT and the ONUs was done through a text string of those distances, which now can be done by directly configuring the channels (i.e., feeder and distribution fibers). Also, this change in the implementation of the ONU and the RN modules makes rather straightforward the ONU discovery procedure which will be described in Sec. 3.3.

3.3 ONU Discovery

As discussed in Sec. 3.2, the round-trip times (RTTs) between an OLT and ONUs were manually configured through a configuration file (e.g., omnetpp.ini) in the original hybrid TDM/WDM-PON models. As we integrated the models into the INET framework, however, we implemented a

[4]Note that the reception mode of a node can be changed by calling the *setDeliverOnReceptionStart()* member function of the corresponding gates in OMNeT++.

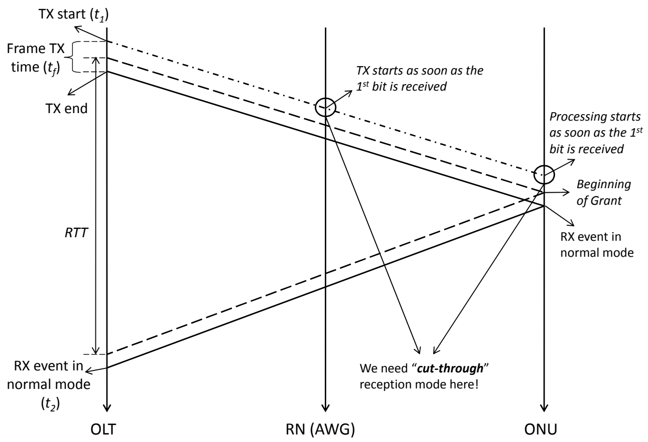


Figure 5: Optical layer modeling.

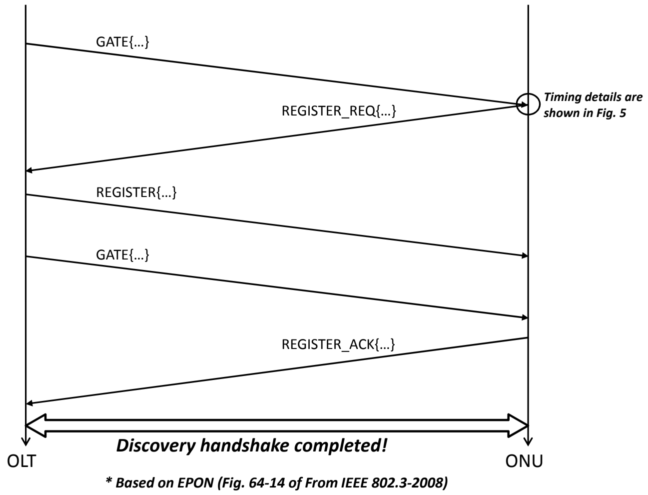


Figure 6: Handshake message exchange in ONU discovery.

ranging protocol as part of the ONU discovery procedure shown in Fig. 6, which eliminates the manual configuration and makes the models more self-configurable. Note that the handshake message exchange in the ONU discovery is based on the EPON standard (see 64.3.3 of Section 5 in [11]) and that for the implementation of this procedure, we introduced additional frame types and extended the usage of 8-bit flags as shown in Table 1.

During the discovery procedure, the RTT of a hybrid TDM/WDM-PON ONU is calculated by

$$RTT = t_2 - t_1 - t_f \qquad (1)$$

as shown in Fig. 5, where t_1, t_2, and t_f are the start time of a frame transmission at OLT, the reception time of a response from ONU, and the frame transmission time at OLT, respectively.

3.4 Implemented Modules

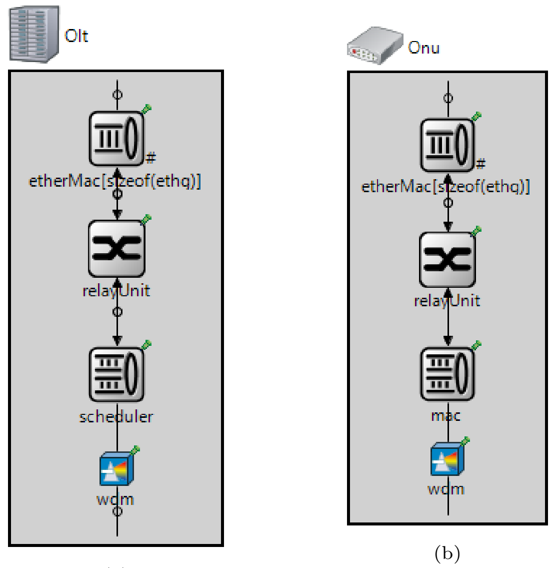
Table 2 summarizes the major modules introduced in the inet-hnrl for the hybrid TDM/WDM-PON and application-layer traffic generation and statistics gathering.

The modules for the hybrid TDM/WDM-PON are located under two new subdirectories, i.e., "linklayer/hybridpon" and "nodes/hybridpon" of "src" directory. The modules under "linklayer/hybridpon" implement functional blocks shown in Fig. 1. *IOltScheduler* is a module interface for all OLT scheduler modules and *OltSchedulerSSSF* is the implementation of the S^3F algorithm. Currently the *OltSchedulerSSSF* module implements a simple ranging protocol based on normal grant and data frames; full implementation of the ONU discovery procedure discussed in Sec. 3.3 will be done later. Fig. 7 shows *Olt* and *Onu* modules implementing the hybrid TDM/WDM-PON OLT and ONU based on the component modules at the link layer.

In addition to the hybrid TDM/WDM-PON modules, new application-layer traffic modules are also implemented: *HttpClientApp* under "applications/tcpapp" is a session-level traffic module based on the existing *TCPSessionApp* and provides session-level statistics, i.e., average session delay, average session throughput, and mean transfer rate[5]; it was mainly developed for modeling HTTP traffic, but can be

Table 2: Major modules introduced in the inet-hnrl.

Directory	Modules
linklayer/hybridpon	OltWdmLayer OnuWdmLayer IOltScheduler OltSchedulerSSSF OnuMacLayer
nodes/hybridpon	LambdaSplitter Olt Onu
applications/tcpapp	HttpClientApp
applications/udpapp	UDPVideoStreamCliWithTrace UDPVideoStreamSvrWithTrace



(a) (b)

Figure 7: Implemented modules for Hybrid TDM/WDM-PON: (a) Olt and (b) Onu.

[5]The mean transfer rate is defined as the mean of the ratio of the size and the delay of a session.

used for modeling FTP traffic as well.

UDPVideoStreamCliWithTrace and *UDPVideoStreamSvrWithTrace* under "applications/udpapp" are the extensions of the existing UDP video stream modules for traffic generation based on real video trace files and provide the decodable frame rate (DFR) [12] of a video stream as an indirect measure of video quality perceived by end-users. Frames are first encapsulated within a real-time transport protocol (RTP) packet and then a UDP packet before being carried in an IP packet. Considering that Ethernet frames are used in the data link layer, the total overhead in this case is 66 octets.[6] The starting frame is selected randomly from the trace at the beginning of simulation, and the whole trace is cycled throughout the simulation as suggested in [13].

4. A COMPARISON STUDY: DEDICATED VS. SHARED ACCESS

We carry out a comparison study with a dedicated, point-to-point access architecture based on the simulation models implemented in the inet-hnrl.

Fig. 8 shows simulation models for a dedicated and a shared (i.e., hybrid TDM/WDM-PON) access architectures where the backbone rate (R_B) and all other line rates — i.e., the feeder rate (R_F), the distribution rate (R_D), and the user network interface (UNI) rate (R_U) — are set to 1 Tb/s and 10 Gb/s respectively, the end-to-end round-trip time (RTT) to 10 ms, and the number of ONUs (N) to 16. For both the models, we use the Reno flavor of TCP [14] for TCP protocol and connect all nodes with Ethernet links using Drop-Tail queues with the capacity of 10,000 frames at network interface cards except the point-to-point protocol (PPP) [15] links between the OLT and the ONUs in the dedicated architecture.[7]

In the dedicated architecture model, the OLT and the ONUs are implemented using general Ethernet switches. In the hybrid TDM/WDM-PON model, the number of tunable receivers are set equal to the number of tunable transmitters throughout the simulations. Because we mainly focus on the downstream traffic in this comparison study, the impact of the number of tunable receivers would be minimal. We use the same parameters given in [4] for the simulation of the hybrid TDM/WDM-PON except the size of virtual output queues (VOQs) at the OLT that is set to 15,180,000 octets.[8]

Fig. 9 shows a model for an end-user node (e.g., PC) which is connected to the ONU through a UNI. Because a user can interact with at most one web page at any given time, we set the number of HTTP sessions (n_h) to one. The same is the case for a streaming video (i.e, $n_v = 1$). On the other hand, a user can run multiple FTP sessions in the background. Therefore we set n_f to 10, especially to get a higher combined rate for 10-Gb/s access out of well-established, lower-rate FTP parameters from 3GPP2 [16].

Fig. 10 shows behavioral models for HTTP and FTP traffic: As for HTTP traffic, we adapt the model proposed in

[6]That is, RTP(12) + UDP(8) + IP(20) + Ethernet(26).

[7]This is because the line rates of the links needed to be adjusted flexibly for the equivalent circuit rate (ECR)-based study of 10-Gb/s next-generation optical access architectures, whose results will be reported in separate publications.

[8]This corresponds to 10,000 times the maximum Ethernet frame size, matching the size of the frame queues in other network interface cards.

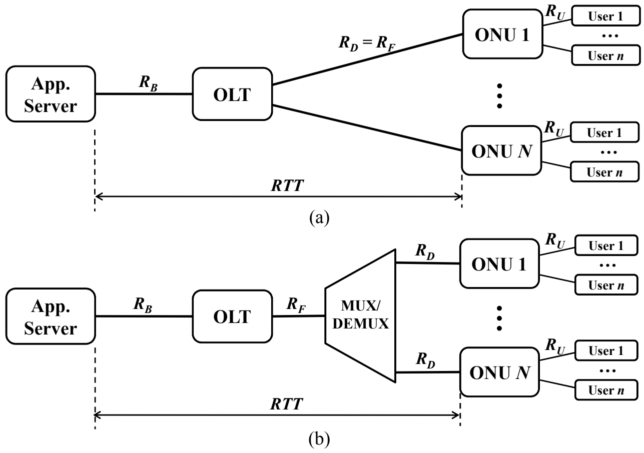


Figure 8: Simulation models for (a) dedicated and (b) shared (hybrid TDM/WDM-PON) access architectures where R_B, R_F, R_D, and R_U denote backbone, feeder, distribution, and UNI rates, respectively, and RTT end-to-end round-trip time.

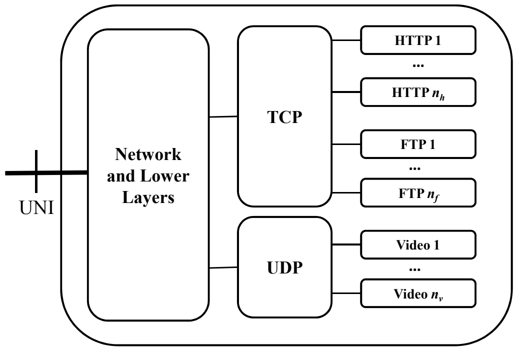


Figure 9: An end-user node (host) model.

[17] for traffic generation at the client side above the transport (i.e., TCP) layer and without caching and pipelining in a browser, while we use the FTP model from [16] without any modification. The parameter values are summarized in Table 3.[9] Both the traffic models are implemented by the *HttpClientApp* module.

In addition to HTTP and FTP traffic, we also use a high-rate, HD-TV-quality streaming video traffic in the simulation, which is considered one of killer applications for the next-generation optical access. Specifically, we use "Terminator 2" VBR-coded H.264/AVC clip from ASU video trace library [18] with the *UDPVideoStreamCliWithTrace* and *UDPVideoStreamSvrWithTrace* modules, whose properties and frame statistics are summarized in Table 4.

We repeat each simulation five times with different random number seeds. Each simulation runs for 3 hours in simulation time, and the data are gathered after the warmup

[9]Because the truncated lognormal distribution function is not implemented in OMNeT++ (as of version 4.1), we provided a modified version of OMNeT++ "distrib.h", "distrib.cc", and "nedfunctions.cc" under the "etc/omnetpp-extension" directory of inet-hnrl. Refer to "README" there for details.

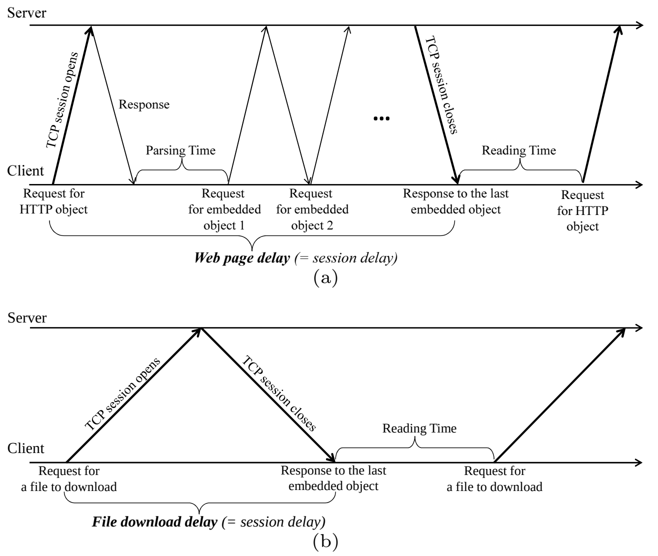


Figure 10: Traffic models for (a) HTTP and (b) FTP services.

Table 3: Parameters for HTTP and FTP traffic models

Parameters/Measurements	Best Fit (Parameters)
HTTP Model [17]	
HTML Object Size [Byte]: Mean=11872, SD=38036, Max=2M	Truncated Lognormal: μ=7.90272, σ=1.7643, Max=2M
Embedded Object Size [Byte]: Mean =12460, SD=116050, Max=6M	Truncated Lognormal: μ=7.51384, σ=2.17454, Max=6M
Number of Embedded Objects: Mean=5.07, Max=300	Gamma: κ=0.141385, θ=40.3257
Parsing Time [sec]: Mean=3.12, SD=14.21, Max=300	Truncated Lognormal: μ=-1.24892, σ=2.08427, Max=300
Reading Time [sec]: Mean=39.70, SD=324.92, Max=10K	Lognormal: μ=-0.495204, σ=2.7731
Request Size [Byte]: Mean=318.59, SD=179.46	Uniform: a=0, b=700
FTP Model [16]	
File Size [Byte]: Mean=2M, SD=0.722M, Max=5M	Truncated Lognormal: μ=14.45, σ=0.35, Max=5M
Reading Time [sec]: Mean=180	Exponential: λ=0.006
Request Size [Byte]: Mean=318.59, SD=179.46	Uniform: a=0, b=700

period of 20 minutes.[10]

[10]The warmup period should be long enough to reduce the transient effects from PON ranging procedure and start-up delays introduced by streaming video encoding/decoding processes as well as networking protocols like TCP. Here we indirectly determined the warmup period of 20 minutes by investigating the total number of scheduled events in the future-event list; we observed that after 20 minutes, the number of scheduled events throughout the system goes into a steady state for all the simulations considered.

Table 4: Overview of video traffic model

Property/Statistic	Value
Video Clip	"Terminator2 [18]"
Encoding	VBR-coded H.264/AVC
Encoder	H.264 FRExt
Duration	~10 min
Frame Size	HD 1280x720p
GoP Size	12
Number of B Frames	2
Quantizer	10
Mean Frame Bit Rate	28.6 Mb/s

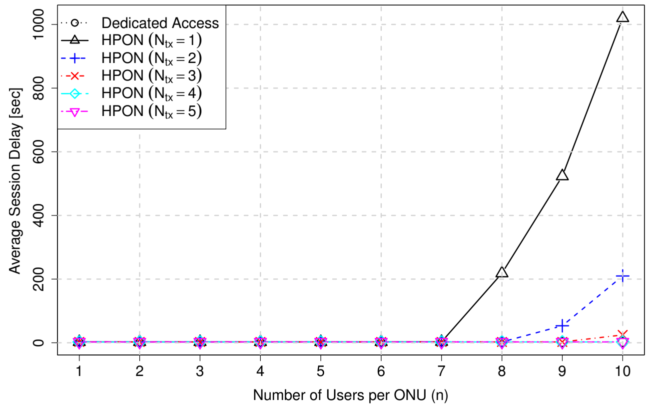


Figure 11: Average session delay of HTTP traffic.

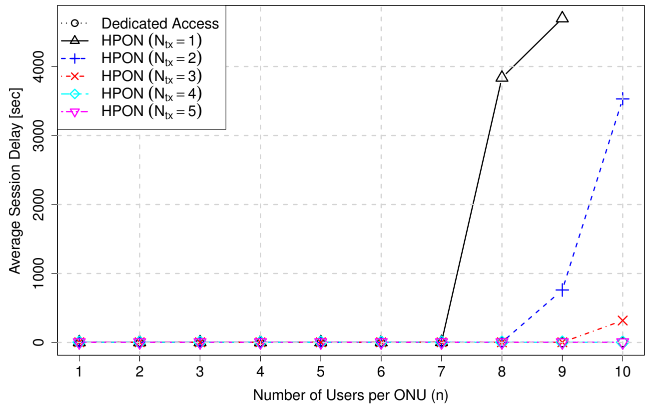


Figure 12: Average session delay of FTP traffic.

Figs. 11 and 12 show the average session delays of HTTP and FTP traffic, while Fig. 13 shows the DFR of UDP streaming video.

From the results, we found that adding more transceivers improves the overall performance of the hybrid TDM/WDM-PON. For example, with four or more transceivers (i.e., $N_{tx} \geq 4$), the performances of the hybrid TDM/WDM-PON are virtually equivalent to those of the dedicated access for all the range of input load considered. On the other hand, it is remarkable that the hybrid TDM/WDM-PON with just one transceiver can achieve nearly the same performance as

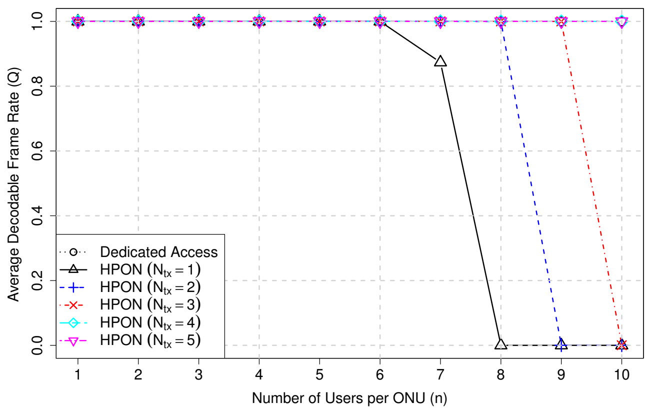


Figure 13: Decodable frame rate of UDP streaming video.

the dedicated access until n reaches 6 (especially for the DFR of streaming video); when $n = 6$, streaming video traffic alone pushes about 180-Mb/s stream into ONU and 2.88-Gb/s multiplexed stream into OLT (out of 16 ONUs).

5. SUMMARY

In this paper we have presented the results of the integration of OMNeT++-based simulation models of hybrid TDM/WDM-PON under the SUCCESS-HPON architecture into the INET framework. The major goal of this integration is to provide a complete end-to-end simulation environment for next-generation optical access network architectures, which can take into account both the interactive nature of actual traffic resulting from TCP congestion control and the end-user experiences of services at the application layer in assessing the performances. We discussed major design issues in this integration and summarized the newly introduced modules in the inet-hnrl fork of the INET framework. Through the comparison study with a dedicated access architecture, we could demonstrate the benefits of the shared access architecture, i.e., nearly equivalent performances achieved by the hybrid TDM/WDM-PON with a much less number of transceivers, in a realistic simulation setup with end-user applications as well as a complete TCP/IP protocol based on session- and stream-level performance measures.

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