Energy Efficiency and Differentiated QoS in Next Generation PONs

by

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Abstract

Energy conservation in next generation Passive Optical Network system (NG-PON) has gained more and more attention. NG-PON system can not only deliver best-effort data traffic, but also real-time data traffic, e.g. voice and video, that have strict bandwidth, delay, and jitter requirements. To meet the energy and service requirements, a NG-PON system must have energy efficiency and differentiated QoS mechanism built in.

Few research efforts have been reported on maximizing energy efficiency while maintaining QoS in the fairly new PON system design. We have extended the Upstream Centric Scheme (UCS-based) scheduling scheme idea into a novel QoS-differentiated energy-efficient PON system consisting of two main modules: firstly, the proposed differentiated QoS analytical model is described in detail to reduce the packet delay in the upstream traffic scheduling. The simulations further demonstrate the QoS metrics of the system: packet delay, bandwidth utilization, dropped packet rate, and queue length.

Secondly, a novel analysis is proposed for downstream traffic scheduling with limited service discipline at Optical Line Terminal (OLT) side under the UCS-based Green Bandwidth Allocation (GBA) framework. We, first, derive the mean packet delay expression of this model. Then, the sleep time for each Optical Network Unit (ONU) is derived by setting identical upstream/downstream transmission cycle time. Based on the analytical model, an approach is developed to save the maximum energy in a dynamic PON system while without violating the delay requirement.

Moreover, simulation is conducted to verify the developed analytical model and the proposed approach. In the end, considering the differentiated QoS and downstream traffic scheduling, an algorithm of the energy efficient scheduling scheme is proposed as well under the UCS-based GBA.

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Chapter 1

Introduction

It is estimated that 2-10% of the CO2 produced by human activity comes from Information and Communications Technologies (ICT). Such emissions are expected to raise steadily in the next years, due to the increase of users and increased utilization. Today most of access network segment is based on energy-demanding technologies and wireless access. However, even with the introduction of optical fibre in the access, the energy consumption is forecast to grow with the average access bit rate increase. Furthermore, the energy per bit requested by Optical Network Units (ONUs) of Passive Optical Networks (PONs) is at the top among the communications network devices [1].

Typically, EPON has the Optical Line Terminal (OLT) located at the root and ONUs connected to the leaves of the tree topology. Fig. 1.1 shows the system architecture of EPON. In the downstream traffic transmission, packets sent by the OLT are broadcasted to all ONUs using the 1:N passive splitter and each ONU selects only the packets destined for it. In contrast to the downstream traffic, a medium access control (MAC) protocol is needed to arbitrate for ONUs having data to transmit to the OLT, since they share a single optical fiber trunk in the upstream traffic transmission. IEEE 802.3ah task force has developed the Multi-Point Control Protocol (MPCP) which is used to allocate the upstream bandwidth to each ONU via time division multiplexing (TDM).

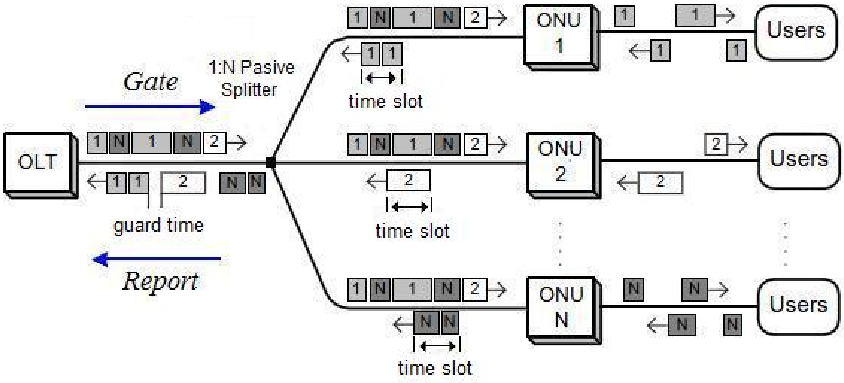

Figure 1.1: System architecture of EPON.

1.1 Problems and Motivations

However, to implement the sleep mode in ONUs, some issues must be solved. In current time division multiple access (TDMA)-Ethernet PON (EPON), ONUs synchronize their local clock to the OLT clock through their clock and data recovery (CDR) circuit that receives the continuous bit stream (data) from the OLT [2]. If an ONU stops receiving downstream transmission, clock synchronization at ONU is lost. Moreover, the absence of synchronization among different ONUs clocks might cause upstream data collisions at the OLT.

Green Ethernet Passive Optical Networks (EPONs) have been subject to extensive research efforts in the recently years. To achieve efficient energy conservation, each ONU should be put into sleep mode as long as each data packet in each cycle of bandwidth allocation doesn't violate any pre-defined QoS constraint. Current ONU architecture requires a overhead time when the ONU wakes up from the sleep mode. To meet the goal, most previous studies manipulate dynamic bandwidth allocation (DBA) schemes such that each

ONU can be put into sleep while the OLT is receiving data from the other ONUs [3] [4] [5] [6] [7], despite the long overhead time in total when ONUs wake up every time.

Upstream Centric Scheme (UCS) is a recently proposed approach for PONs to enable the maximum sleeping time and maximum energy conservation by overlapping the downlink and uplink transmissions at each ONU. Our previous study in [8] integrated a new UCS-based framework of Green EPON design, called Green Bandwidth Allocation (GBA). The GBA framework enables batch-mode transmissions in the network and computes the maximum sleep time for every ONU based on its QoS requirements.The advantage of such a UCS-based GBA framework is to ensure the maximum saved energy at the ONUs by reducing the total overhead time significantly. All the above studies are based on a common assumption that the OLT can buffer the downstream traffic until the sleeping ONU wakes up without violating the downlink traffic delay constraint. With UCS-based GBA framework, nonetheless, a new problem on downstream traffic scheduling emerges, which is essential in achieving efficient resource allocation without sacrificing quality of services (QoS).

Motivated by the above observations, this thesis studies the downstream traffic scheduling for green EPON design under the UCS-based GBA framework. The goal of design is to avoid as much idle listening at ONUs as possible while leaving the OLT to determine the timing of transmissions without collision. We will firstly analyze this scheduling mechanism in a round-robin manner for downstream transmissions at OLT, in which a mean packet delay expression is derived with the limited service discipline. An approach will be further developed to determine the maximum sleep time at each ONU without violating the delay constraint in both directions of upstream/downstream transmissions. Lastly we will present our simulation results that verify the proposed analytical model and the effectiveness of the proposed approach.

On the other hand, we can further improve the QoS metrics such as packet delay, dropped packet rate, and bandwidth utilization to support differentiated classes of service in the upstream traffic scheduling. Paper [9] explores packet delay for different classes of traffic, using a strict (exhaustive) priority queue scheduling for the upstream traffic. The result shows that the queuing delay for lower-priority classes increases when the network load decreases (a phenomenon we call light-load penalty). To address this problem, some optimization schemes are applied to eliminate the light-load penalty, but it causes the side effect, where packet delay increases even for the high-priority class packets.

In addition, when ONU wakes up from the sleep mode, the ONU i will send the *Report* message to request the times slot (transmission window). During the time lag between ONUs sending a *Report* and the arrival of its allocated times lot (i.e., between sending a *Report* and transmission of the reported data), more packets arrive to the queue. Newly arrived packets may have higher priority than some packets already stored in the queue during the sleep, and they will be transmitted in the transmission slot before the lower-priority packets. Since these new packets were not reported to the OLT, the given slot cannot accommodate all the stored packets. This causes some lower-priority packets to be left in the queue. The situation may repeat many times, causing some lower-priority packets to be delayed for multiple sleep cycles. Thus, this additional packet delay together with the delay caused by the sleep mode should be managed properly not to impair the system performance.

As the packet delay becomes very critical in the upstream traffic scheduling for energy conservation, the priority-queue scheduler model is proposed to improve the QoS performances for the upstream traffic scheduling under the UCS-based GBA. Simulation results show that this model has less packet delay in comparison with the strict-priority queue scheduling.

1.2 Thesis Contributions

Energy conservation in next generation PON system has gained more and more attention. Research on either EPON energy consumption or differentiated QoS network has been extensively reported in the past. However, few work has been reported to consider energy efficiency and differentiated QoS in the relatively new field of next generation PON system design. In this theis, we have extended the UCS-based scheduling scheme idea into a novel QoS-differentiated energy-efficient PON system consisting of two main modules as listed in the following.

In the upstream traffic scheduling, the proposed priority-queue model is developed along with the analysis. The contribution is to improve the QoS performance for the implementation of UCS-based GBA framework.

In the downstream traffic scheduling, the contributions are listed as follows: 1) It defines and addresses the issues of downstream traffic scheduling in EPONs in order to enable UCS-based GBA. 2) A downstream analytical model for mean packet delay is presented, which serves as the basis for maximum sleep time analysis and packet scheduling. It is noted that downstream traffic scheduling has never been taken as an issue in the legacy EPON research due to the broadcast in nature for the downstream transmissions from the OLT to all the ONUs.

At last, a novel energy efficient scheduling scheme is designed to implement the UCS-based GBA framework with QoS consideration. During sleep, the OLT determines whether a "wake-up" condition is met. The "wake-up" conditions include, but are not limited to: time-critical upstream traffic detected, new multicast group joined (such as IPTV channel change is detected), an alarm condition, and an upstream queue has exceeded certain threshold. Particularly because UCS-based GBA has a longer sleep time and MPCP enforces *gate_timeout* and *report_timeout* messages to keep ONU function properly, the timeout problem is addressed as well in the newly developed algorithm.

The thesis is organized as follows. Chapter 2 discusses the issue of supporting differentiated classes of service in EPON, and the priority-queue scheduler model is proposed with differentiated QoS consideration. In Chapter 3, the expressions of the sleep time analysis for downstream traffic scheduling is introduced based on the analytical model. An algorithm of energy efficient scheduling scheme under the UCS-based GBA framework are developed in Chapter 4. In Chapter 5, simulations and numerical analysis are presented to verify the proposed analytical model. Finally, Chapter 6 provides the conclusion and future work for further studies.

Chapter 2

Differentiated QoS Consideration in EPON System

EPON system is expected to deliver not only best-effort data traffic, but also multiple services, such as voice, HDTV, video conferencing and real-time transactions. To meet the service requirements of different users and be compliant with class of services (CoS) in IEEE 802.1D, an EPON system must consider differentiated QoS provisioning [10]. The IEEE 802.1D standard lists seven traffic classes: network control, voice, video, controlled load, excellent effort, best effort and background.

In this thesis, the traffic classes are grouped together into three classes that are used for delivering voice, video and data traffic, which also maps DiffServ's expedited forwarding (EF), assured forwarding (AF), and best effort (BE) classes into 802.1D classes. The high-priority class is expedited forwarding (EF), which is delay-sensitive and requires bandwidth guarantees. The medium-priority class is assured forwarding (AF), which is not delay-sensitive but requires bandwidth guarantees. Finally, the low-priority class is best effort (BE), which is neither delay-sensitive nor bandwidth guaranteed.

Performance of a packet based network including EPON can be evaluated by several parameters: bandwidth, latency, jitter, throughput, and packet-loss ratio. An EPON system is very complicated due to distributed nature, limited control-plane bandwidth, and notable switching overhead, so only the packets delay, bandwidth utilization, dropped packet rate, and average queue length will be highlighted.

2.1 Problem of Light-load Penalty

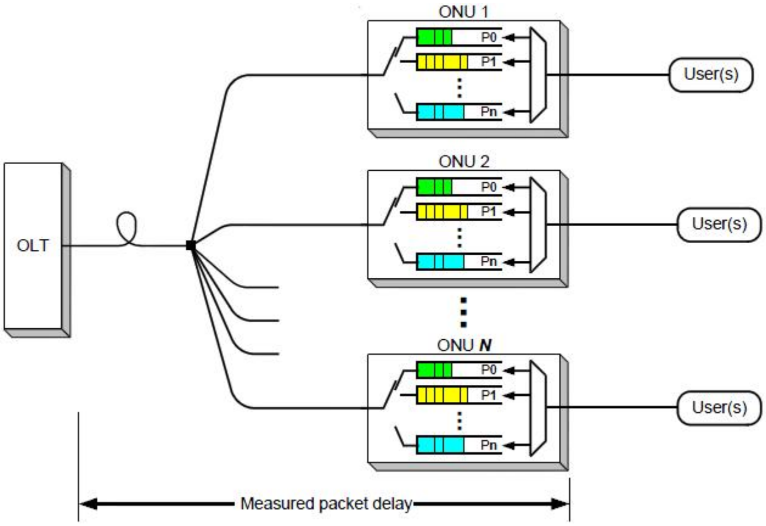

Figure 2.1: Strict-priority queuing built in ONUs.

A system architecture of integrating Priority Queuing in ONU has been presented in [9], and the combination of Multipoint Control Protocol (MPCP), Interleaved Polling with Adaptive Cycle Time (IPACT) and a strict-priority queuing has been investigated as well. When the time slot arrives, the ONU serves higher-priority packets to exhaustion before serving low-priority packets. Figure 2.1 shows this system architecture of an intral-ONU scheduling. The average packet delay of the classes in Figure 2.2 can meet the needs of the QoS requirement. However, the experiment for this scheduling also results in an unexpected network behavior. When the network load decreases, the queuing delay for lower-priority classes increases, which is the phenomenon called light-load penalty. The reason why this phenomenon is that some classes of traffic are treated unfairly when the network load is light.

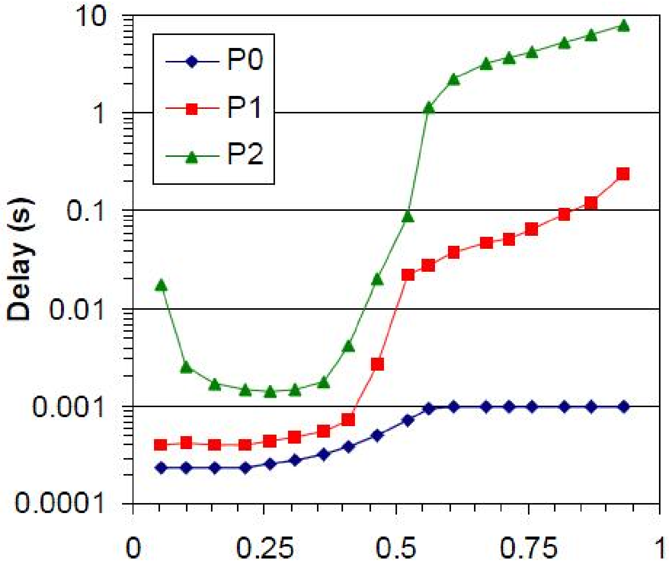

Figure 2.2: Light-load penalty.

The light-load penalty could have a detrimental impact on the operations of certain protocols. For example, TCP Vegas, a TCP congestion avoidance algorithm, emphasizes packet delay, rather than packet loss, as a signal to help determine the rate at which to send packets [11]. An unstable fluctuation that reduces the traffic load could increase the delay, which could be interpreted as increased congestion. The data source will reduce its load in turn and cause the delay increasing even more.

In order to eliminate the light-load penalty, an optimization scheme of a two-stage buffer in an ONU is implemented. The drawback of this scheme, however, is the increased packet delay for the highest priority class packets three times larger than the delay without the optimization scheme.

2.2 Proposed Priority-queue Scheduler Model

The key point for this proposed model to improve the packet delay is that we use a priority-queue scheduler instead of the strict priority scheduling algorithm introduced in the previous section. The drawback of the strict priority scheduling works in a preemptive way and is very unfair for the lowest priority traffic. The phenomenon of light-load penalty introduced above is directly related to the strict priority scheduling due to the preemption because it schedules packets from the queue only if all higher priority queues are empty. Another problem could lead to the high packets drop rate in order to handle the unexpected arrival packets of higher priority class immediately since it interrupts the ongoing processing of the lower priority packets in the priority queue. Thus, we recommend a priority-queue scheduling mechanism which processes the traffic load according to its priority level of different classes (Fig. 2.3).

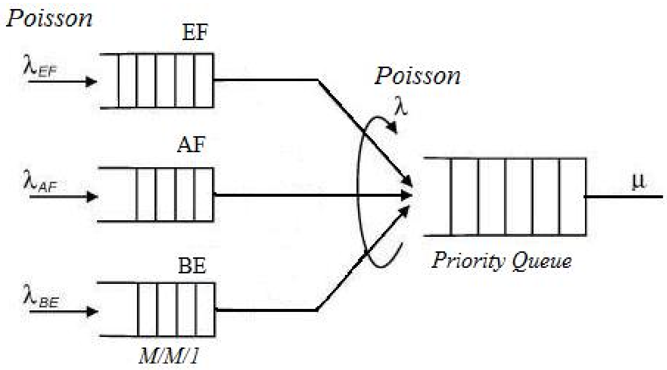

Figure 2.3: The priority-queue scheduler model.

If we assume all the class data are independent Poisson processes, combing those also results a Poisson process. Further, the nature of M/M/1 is a Markov chain and at the equilibrium the rate leaving the M/M/1 queue is the same as the rate entering the queue. Consequently, the packets arrival rate at the priority queue is the rate λ of the total traffic load, and the service rate is C (line rate of upstream). If we denote different classes of EF, AF, and BE as c, then $\lambda = \Sigma_c \lambda_c$, and λ_c is the class c traffic load.

The corresponding analysis of the average packet delay of different class in the priority queue with single sever can be found in [12], but the service time for each class packet needs to be accounted for the total packet delay of each class.

$$W_{\mathrm{c}} = \overline{X_{\mathrm{c}}} + W_{\mathrm{Q}}^{c}$$

where W_{Q}^{c} denotes the average wait in queue of a class c packet, c=EF, AF, and BE.

So, the total packet delay of the class EF, AF and BE from the ONU to the OLT in the upstream traffic scheduling is

$$W_{\mathrm{EF}} = \frac{\lambda_{\mathrm{EF}}\overline{X_{\mathrm{EF}}^2} + \lambda_{\mathrm{AF}}\overline{X_{\mathrm{AF}}^2} + \lambda_{\mathrm{BE}}\overline{X_{\mathrm{BE}}^2}}{2(1-\lambda_{\mathrm{EF}}\overline{X_{\mathrm{EF}}})} + \overline{X_{\mathrm{EF}}} \tag{2.1}$$

$$W_{\mathrm{AF}} = \frac{\lambda_{\mathrm{EF}}\overline{X_{\mathrm{EF}}^2} + \lambda_{\mathrm{AF}}\overline{X_{\mathrm{AF}}^2} + \lambda_{\mathrm{BE}}\overline{X_{\mathrm{BE}}^2}}{2(1-\lambda_{\mathrm{EF}}\overline{X_{\mathrm{EF}}} - \lambda_{\mathrm{AF}}\overline{X_{\mathrm{AF}}})(1-\lambda_{\mathrm{EF}}\overline{X_{\mathrm{EF}}})} + \overline{X_{\mathrm{AF}}} \tag{2.2}$$

$$W_{\mathrm{BE}} = \frac{\lambda_{\mathrm{EF}}\overline{X_{\mathrm{EF}}^2} + \lambda_{\mathrm{AF}}\overline{X_{\mathrm{AF}}^2} + \lambda_{\mathrm{BE}}\overline{X_{\mathrm{BE}}^2}}{2(1-\lambda_{\mathrm{EF}}\overline{X_{\mathrm{EF}}} - \lambda_{\mathrm{AF}}\overline{X_{\mathrm{AF}}} - \lambda_{\mathrm{BE}}\overline{X_{\mathrm{BE}}})(1-\lambda_{\mathrm{EF}}\overline{X_{\mathrm{EF}}} - \lambda_{\mathrm{AF}}\overline{X_{\mathrm{AF}}})(1-\lambda_{\mathrm{EF}}\overline{X_{\mathrm{EF}}})} + \overline{X_{\mathrm{BE}}} \tag{2.3}$$

Class EF has the highest priority, class AF has the second highest, and class BE has the lowest. Suppose that class EF packets are in service, and that service will never begin on a class AF or BE packet if a class EF packet is waiting. However, if a class AF or BE packet is being served and a class EF packet arrives, we assume that the service of the class AF or BE packet is continued until completion. That is, there is no preemption once service has begun.

$$\overline{X_{\mathrm{c}}} = 1/\mu_{\mathrm{c}} = Average\ service\ time\ of\ class\ c\ packet$$

$$\overline{X_{\mathrm{c}}^2} = Second\ moment\ of\ service\ time\ of\ class\ c\ packet$$

$$\rho_c = \lambda_c/\mu_c = System\ utilization\ factor\ for\ class\ c\ packet$$

We assume that the overlall system utilization is less than 1 under the steady-state condition, that is

$$\rho_{\mathrm{EF}} + \rho_{\mathrm{AF}} + \rho_{\mathrm{BE}} < 1$$

In the scenario of using a preemptive queue in the system, the service of a packet is bumped when a higher-priority packet arrives and continues from the break point only after all packets of higher priority have been served. Thus, for the class c packet in the preemptive queue, the packet delay is

$$W_{\mathrm{Q}}^{c} = W_{\mathrm{Q}}^{c}(nonpreemptive) + [Extra\ time]$$

where the extra time is due to the fact that the lower priority packet may be bumped. This results in an important conclusion that the preemptive queuing system incurs an increased packet delay for the lower priority packet.

In summary, at the ONU side, our proposed priority-queue scheduler model has the overall better QoS performance, compared with the strict-priority scheduling algorithm. The strict-priority scheduling algorithm serves the high priority class packets to exhaustion before processing a low-priority class packet, which is very unfair to BE data traffic. The corresponding consequence leads to the phenomenon of light-load penalty, and then the second stage buffer has to be implemented or applying other optimization schemes such as Constant-Bit-Rate Credit scheme in order to eliminate the phenomenon at the expense of extra delay even to the highest priority class packets. This can impair the system performance significantly, for example, if the highest priority class data is ”must get there” for network control.

The simulation for the proposed priority-queue scheduler model will be presented in Chapter 5.1.

Chapter 3

Sleep Time Analysis of Downstream Traffic Scheduling

3.1 Preliminaries

Most of the studies conducted within the research community build upon the idea of allowing PON network elements, specifically the ONUs, to switch to sleep mode for saving energy. The concept of such approach stems from the broadcast and TDMA nature of the PON. Downstream traffic is broadcast to all the ONUs, thus data are received by each ONU, but discarded if not destined to that ONU. Without right sleep mode MAC control, receivers at ONUs need to be awake all the time to avoid missing their downstream packets. This implies wasting significant energy at the ONU side to receive and process the broadcast data. Similarly, if ONU need not transmit, it remains silent while other ONUs are transmitting. Therefore, each ONU can conserve energy by switching to sleep mode when it need not send nor receive traffic with the proper scheduling.

3.1.1 Related Work

To implement the ONU sleep mode efficiently and practically is still an open problem. Energy can be conserved at the ONUs by switching to sleep mode when the ONUs are idle [13]. The paper provides feasible implementations of sleep mode in passive optical networks (PONs) and discusses many issues as well such as synchronization clock, overhead time, and QoS requirements incurred by delay sensitive applications when considering sleep mode for energy saving PONs. In the end, the authors leave the downstream traffic scheduling through buffering as the future work.

The approaches of ONUs' deep sleep mode and dozing mode are discussed in [6] to lower PON energy consumption. The former approach puts a ONU into lower power consumption states only for fairly long inactive period while the second approach keeps all the downstream functions operational but turns off the transmitter. Due to the new technology of fast clock recovery circuit [14], the energy can be saved within the millisecond-long transmission cycle with Just-In-Time sleep control. The sleep time in the sleep cycle at ONU i is at least the time when other ONUs are transmitting or receiving traffic. To maintain the synchronization and traffic detection functions, the fast sleep mode is implemented [6] for the ONU to be able to wake up when the allocated slot arrives.

A new Medium Access Control (MAC) in [7] is presented for each ONU to wake up within the designated slot periodically when the load is lower than a pre-determined threshold, where the system enters power saving mode. Thus, an ONU can turn off its transmitter and receiver to reduce power consumption. In power saving mode, EPON performs Fixed Bandwidth Allocation (FBA) instead of DBA used in the normal mode.

According to [4], there is a trade-off between sleep period and power savings. To avoid frequent mode switching and long sleep time causing more delay and latency, a energy-saving mechanism with sleep mode needs to be applied to the procedures of upstream and downstream traffic scheduling. The handshake flow can be implemented either by OLT-initiated or ONU initiated procedures. The paper also found that the frequent switching between sleep mode and active mode is detrimental to the energy conservation and around 25-30 ms seems the best tradeoff between sleep period and power savings.

Furthermore, two energy management mechanisms for EPONs have been proposed in [3], namely Upstream Centric Scheduling (UCS) and Downstream Centric Scheduling (DCS). UCS algorithm aggregates the downstream traffic in order to minimize the time allocated to ONUs for idle states while DCS algorithm stores downstream traffic in an FIFO buffer, and the ONU wakes up to receive downstream traffic whenever the OLT sends it. Clearly, UCS saves more energy, but DCS has a better QoS performance.

While these papers are making great efforts to save energy, the issue of overhead incurred by the sleep mode has been overlooked. For example, the aggressive and conservative total overhead can reach 2.125 ms and 5.125 ms high respectively. Therefore, UCS-based GBA framework that leverages the sleep mode of the ONU is proposed to achieve the maximum possible energy conservation. The feature of GBA is that the UCS-based GBA takes the QoS requirements of variety of services as constraints when determining the sleep time for each ONU. Due to its novel design in terms of batch-mode transmissions, more energy can be saved with the same amount of sleep time, but with significantly reduced overhead.

3.1.2 Overview of UCS-based GBA Framework

The GBA framework is a very promising software scheme and the solution to save energy in NG-PONs with low cost of the power consumption. Some techniques are summarized as the following:1) Hybrid cyclic/deep sleep at ONUs. 2) Batch-mode transmission at OLT and ONUs. 3) UCS-based bandwidth allocation. The proposed GBA computes a longer ONU sleep time in total because of a shorter overhead time, saving more energy. In order to conserve the energy efficiently, the function of all kinds of buffer and queues in OLT and ONUs needs to be enhanced especially. In the deep sleep mode, the ONU turns off its transmitter and receiver, while any incoming downstream or upstream traffic is buffered at queues to avoid being lost. The buffered downstream traffic destined for the ONU is only transmitted during the allocated upstream transmission window.

The fast sleep mode of the ONU maintains the ability to wake up from the sleep mode whenever new traffic arrives. During the transitional wake-up time, the OLT would buffer the downstream traffic until the ONU is fully awake. However, the fast sleep mode works well specifically for the sleep within the millisecond-long range with just-in-time control because of the faster on-off of the receiver/transmitter, but it doesn't consume the least energy.

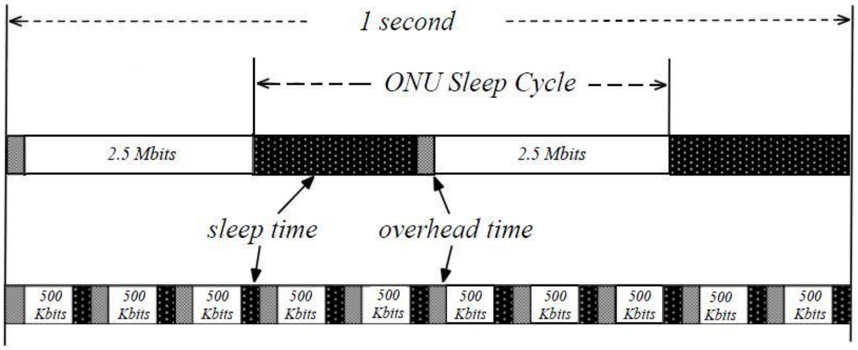

Figure 3.1: Overhead comparison between UCS-based GBA (upper part) and legacy energy saving schemes (lower part).

The UCS-based GBA framework improves the EPON efficiency, and the easy way to achieve the better performance is to reduce the total overhead time. In the proposed GBA, the ONU goes into sleep mode for a certain amount of time before waking up to send/receive a batch of buffered upstream/downstream traffic while the legacy energy saving schemes perform a frequent switching shown by Fig. 3.1. In [8], the total overhead is being reduced 80% significantly.

The GBA introduced the sleep cycle at ONU i, C_i, which consists of the sleep, overhead, one active upstream transmission and control message time. The ONU sleep time for the upstream traffic scheduling under the gated service discipline was formulated as well by only considering the upstream packet delay requirement introduced in [15]. The advantage of GBA is the likelihood that the ONU can have a deep sleep, during which the upstream and downstream traffic are buffered. This is very desirable for energy conservation.

The paper did not give the answer to the question how the downstream traffic should be scheduled at the OLT such that the downstream delay constraint is also considered. To satisfy delay constraints of both transmission directions, it is essential to make the scheduling of the two sides to be consistent with each other. In order to make the ONUs to sleep as long as possible, some downstream traffic has to be buffered in the queues at the OLT. Thus, at the OLT side, queues need to be equipped for all the related ONUs, and the broadcast nature has to be changed to the moderate buffering fundamentally in order to conserve energy for the system.

3.2 System Model

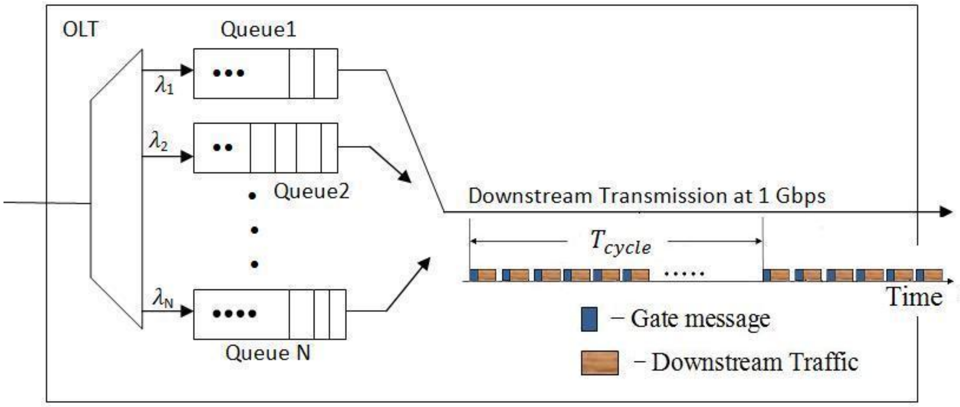

Figure 3.2: The OLT model for the downstream traffic scheduling.

Conceptually, this new OLT system for the downstream traffic scheduling shown by Fig. 3.2 can be viewed as multiaccess communication in queuing terms, in which each queue has buffered packets to be transmitted to the related ONU, and only one queue can transmit successfully on the channel at any one time. The mutiaccess channel is a common server. Because the downstream traffic is bursty in optical access network and Dynamic Bandwidth Allocation (DBA) is applied to upstream transmissions, a fixed channel assignment such as TDMA or FDMA is not efficient. To organize transmissions from several packet streams into a statistical multiplexing system, we propose a quasi-leaved polling model in which downstream traffic is scheduled in a round-robin manner to avoid packets' collisions under UCS-based GBA. The OLT is responsible for monitoring traffic load. Now the questions are: 1) When the OLT sends downstream traffic destined for ONUs. 2) How long a reserved transmission interval can last.

To answer the first question, we consider a precise synchronized scheduling, and each Multi-Point Control Protocol (MPCP) message in the MAC sublayer defines a field called timestamp to synchronize ONU's MPCP clock to the OLT's clock. Because the OLT has full knowledge to schedule upstream and downstream transmissions to all ONUs, a *Gate* MPCP control message sent from OLT is used to inform the ONU the slot size and the sleep time for power saving. The period of *Gate* message together with the guard interval serves as a fixed reservation interval used for scheduling future data, and the downstream transmission denotes the data interval. The OLT stores the downstream traffic in the queues destined to ONUs in sleep mode, and the OLT is scheduled to transmit the downstream traffic when the ONU is in the active mode. The T_{cycle} in the figure denotes a periodic transmission cycle time for downstream transmissions to all ONUs in a round-robin manner. The upstream transmissions from ONUs and downstream transmissions to ONUs have the identical transmission cycle time, so T_{cycle} stands for either the upstream or downstream transmission cycle time.

For the second question, we will analyze this system model in the following sections, and derive an expression of how long the data interval should be in the section of 3.2.3. Note that the size of the control message is 64 bytes by the MPCP standard [16].

Among the different access-control disciplines of sharing the channel, namely fixed, gated, limited, constant credit, linear credit and elastic, only the limited service discipline for the downstream traffic scheduling at OLT will be analyzed in this thesis since this discipline has better bandwidth utilization with fairness to ONUs. By convention, the OLT assigns a queue a slot of the size equal to what the packets have accumulated in that queue, but not greater than some redefined maximum $W^{\max}$ bytes. To prevent the channel being monopolized by a single queue with high data volume, a maximum transmission window size is needed to guarantee maximum interval between slots (cycle time).

3.2.1 Overlapping Downstream and Upstream Transmission Window at ONU i

There are three polling operations introduced in [17], namely separated poling, quasi-leaved polling and interleaved polling. Although interleaved polling with adaptive cycle time (IPACT) scheme [18] offers the most efficient usage of the wavelength resource among the three polling schemes, especially when the network is highly loaded, the quasi-leaved polling in a round-robin manner is utilized in this thesis to be consistent with the GBA framework in order to conserve energy.

In quasi-leaved polling, the *Gate* messages for each ONU are sent sequentially to the downlink at the beginning of each service cycle, i.e., a service cycle where each ONU is serviced one time. Once receiving and processing these polling message, each ONU is determined to transmit the traffic reported in the previous cycle and the *Report* message. Note that the current *Report* message contains the size of packets arrived at the ONU before the polling response message. The new *Report* message is piggybacked to the current uplink transmission. Moreover, this scheme permits the *Gate* messages pass through the downlink channel and uplink data burst to be concatenated with the *Report* message in the uplink channel at the same time, thereby reducing signaling overhead and shrinking the service cycle.

Utilizing the advantages of the UCS-based GBA, each queue at OLT stores buffered downstream traffic to wait for its reserved transmission slot, which is overlapped with the transmission slot of bandwidth allocation for the upstream traffic as shown by Fig. 3.3. When the slot arrives in a round-robin manner, the OLT transmits the data in queue i to the corresponding ONU i. OLT determines the sleep time for each ONU and buffers traffic accordingly. Note that T_{cycle} in the figure varies in reality, depending on the traffic load, number of ONUs (N), and maximum window size.

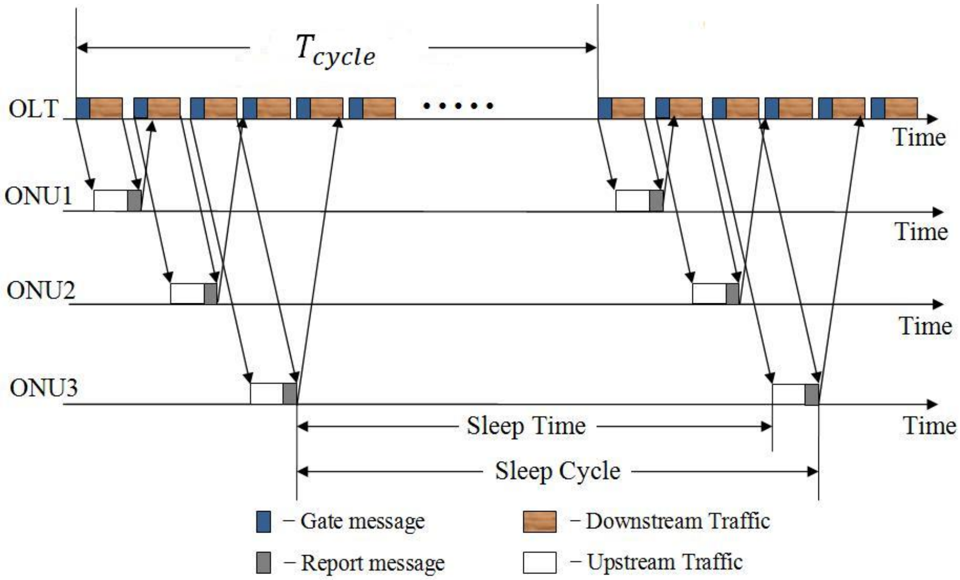

Figure 3.3: Overlapped upstream and downstream traffic scheduling.

In Fig. 3.3, the sleep cycle at ONU i for downstream transmissions consists of the sleep time, and active transmission time. However, there should be a overhead time when the ONU wakes up from the sleep. The overhead time accounts for the free running clock drifts, subsequent clock recovery time, and synchronization to the network after recovering the OLT clock [6]. Thus, the overhead time must be added into the sleep cycle for each ONU. The overlapping of downstream and upstream transmissions in a sleep cycle at ONU i is very critical since outside the active period of upstream/downstream transmissions the

ONU can turn off the transmitter and receiver for a sleep until its transmission slot in the next cycle arrives. It also indicates that an ONU can have a deep sleep and saves more energy.

From the above descriptions of the system model, the OLT performs the downstream traffic scheduling in a round-robin manner with the limited service discipline. The processing time of *Gate* message plus guard interval between transmission slots and transmission slot for each queue at OLT serve as a fixed reservation interval $\overline{V}$ and a data interval respectively. If the N queues at OLT are recognized as N multiple users of sharing the multiaccess channel, our system can be modeled as a multi-user M/G/1 reservation system described in [19]. Furthermore, the limited service discipline is utilized for the access control of the channel as well.

3.2.2 Downstream Traffic Scheduling System with Limited Service Discipline

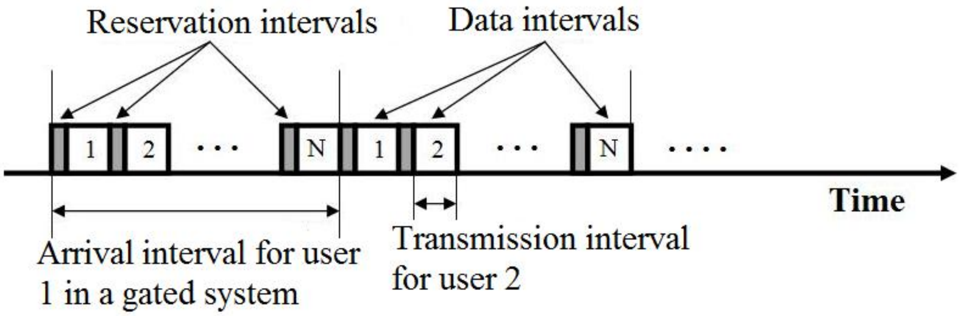

Figure 3.4: Downstream traffic scheduling with N queues at the OLT.

We assume that all N ONUs have the same Service Level Agreement (SLA) [16] under the steady-state condition of the traffic load, and the arrival processes of queues at the OLT are identical independent Poisson distributions. The service time and reservation time are independent with each other. We also assume that packets arriving before the reservation interval are transmitted in the downstream transmission. In a gated reservation system

[19], those packets that arrived prior to the beginning of the user's reservation interval are transmitted (Fig. 3.4). Therefore we begin with modeling the system as a gated N User reservation system. Note that the gated system in the queuing theory is different with the gated service of DBA in the EPON system.

According to a Poisson process, packets arriving to each queue at OLT have a rate of λ/N, so the utilization factor of the total ingress traffic load is $\rho = \lambda\overline{X}$. $\overline{X}$ denotes the mean service time of each packet and $\overline{X^2}$ is the second moment of service time. $\overline{V}$ and $\overline{V^2}$ denote the first two moments of the reservation interval. The corresponding packet delay analysis of the gated reservation system is shown as the following [19]:

$$R = \frac{\lambda\overline{X^2}}{2} + \frac{(1-\rho)\overline{V^2}}{2\overline{V}} \tag{3.1}$$

$$Q = \rho W \tag{3.2}$$

$$Y = \frac{(N+1)\overline{V}}{2} \tag{3.3}$$

$$\begin{aligned} W &= R + Q + Y \\ &= \frac{\lambda\overline{X^2}}{2(1-\rho)} + \frac{(N+2-\rho)\overline{V}}{2(1-\rho)} + \frac{\sigma_V^2}{2\overline{V}} \end{aligned} \tag{3.4}$$

where R: the residual delay, Q: the service delay, Y: the reservation delay, σ_V^2: the variance of each reservation time, and W: the expected packet delay in the queue.

Now, considering the limited service discipline for the downstream traffic scheduling at OLT, the maximum transmission window is $T^{\max}$, and the maximum number of packets transmitted in $T^{\max}$ is in the size of $W^{\max}$ bytes.

The limiting probability P is defined as the proportion in the long run that a reservation interval is followed by a data interval whose size is $W^{\max}$ bytes under the steady-state condition. The ν denotes the requested window size that is less than $W^{\max}$ bytes. The transmission period for ν bytes is T^{ν}. The relations are $T^{\max} = W^{\max}/C$ and $T^{\nu} = \nu/C$.

The ratio between data intervals and reservation intervals can be expressed as

$$\frac{\rho}{1-\rho} = \frac{PW^{\max}}{C\overline{V}}$$

Thus,

$$P = \frac{C\overline{V}\rho}{W^{\max}(1-\rho)} \tag{3.5}$$

Lemma 3.2.1. *The OLT can only transmit the maximum of $W^{\max}$ bytes for each queue per cycle, the additional mean reservation delay of a N user reservation scheduling system with limited service discipline is*

$$\Delta Y = \frac{\lambda W \overline{V}\,\overline{X} C P}{W^{\max}} \tag{3.6}$$

Proof. Let Ł be mean total queue size at OLT for the system, so each mean queue size is Ł$/N$. Since Ł $= \lambda W$ (Little's Law) and the OLT can only transmit the maximum of $L^{\max}$ packets (Limited Service), the number of groups $\frac{\lambda W}{N L^{\max}}$, leads to the additional cycles of reservations with the limiting probability P. Every cycle has $N\overline{V}$ reservations. Thus,

$$\Delta Y = \frac{\lambda W}{N L^{\max}} \times P \times N\overline{V} = \frac{\lambda W \overline{V}}{L^{\max}} \times P$$

Also note that

$$L^{\max} = W^{\max}/(\overline{X}C)$$

So, $\Delta Y = \frac{\lambda W \overline{V}\,\overline{X} C P}{W^{\max}}$, which ends the proof. □

In terms of the mean reservation delay of a N user reservation scheduling system with limited service discipline, we have

$$\begin{aligned} Y &= \frac{(N+1)\overline{V}}{2} + \Delta Y \\ &= \frac{(N+1)\overline{V}}{2} + \frac{\lambda W \overline{V}\,\overline{X} C P}{W^{\max}} \end{aligned} \tag{3.7}$$

From (3.1), (3.2), and (3.7),

$$W = \frac{\lambda\overline{X^2} + (N+2-\rho)\overline{V} + (1-\rho)\sigma_V^2/\overline{V}}{2(1-\rho-\lambda\overline{V}P\overline{X}C/W^{\max})} \tag{3.8}$$

and from (3.5) and (3.8),

$$W = \frac{\lambda\overline{X^2} + (N+2-\rho)\overline{V} + (1-\rho)\sigma_V^2/\overline{V}}{2(1-\rho-\frac{(C\overline{V})^2\lambda\overline{X}\rho}{(W^{\max})^2(1-\rho)})} \tag{3.9}$$

Thus, we have the following theorem.

Theorem 3.2.1. *Under the UCS-based GBA, the mean packet delay is determined by the expression (3.9) when the downstream taffic is scheduled in a round-robin manner with the limited service discipline.*

From this theorem, we note that if $W^{\max}$ is sufficiently large, then the expression (3.9) approaches the expression (3.4) of the gated service. This is reasonable because the limited service with the window size $W^{\max}$ being sufficiently large is equivalent to the gated service discipline in the EPON system.

The average size of queue i at OLT in terms of number of packets is given as the following by Little's Law.

$$Q_i = \lambda W/N \tag{3.10}$$

3.2.3 Sleep Time at ONU i for Downstream Traffic Scheduling

Let $E\{X_{\mathrm{i},\xi}\} = \overline{X_{\mathrm{i},\xi}}$, notations are shown in TABLE 3.1. $E\{X_{\mathrm{i},\xi}^2\} = \overline{X_{\mathrm{i},\xi}^2}$, $\rho_{\mathrm{i}} = \lambda_{\mathrm{i}}\overline{X_{\mathrm{i},\xi}}$, and $\lambda_{\mathrm{i}} = \lambda/N$. Under the steady-state condition at OLT, $\rho = \sum_{\mathrm{i}=1}^{\mathrm{N}} \rho_{\mathrm{i}} = \lambda\overline{X_{\mathrm{i},\xi}} < 1$

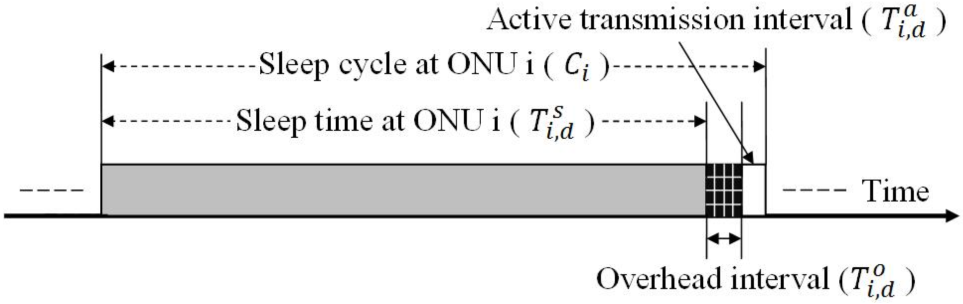

Figure 3.5: A sleep cycle at ONU i for the downstream traffic scheduling.

A diagram of the sleep cycle for the downstream traffic scheduling at ONU i is shown in Fig. 3.5.

$$C_{\mathrm{i}} = T^s_{\mathrm{i,d}} + T^o_{\mathrm{i,d}} + T^a_{\mathrm{i,d}} \tag{3.11}$$

Packet, ξ, will be subject to a total delay $D_{\mathrm{i},\xi}$,

$$D_{\mathrm{i},\xi}(\xi) = W_{\mathrm{i},\xi}(\xi) + T_{\mathrm{prop}} + X_{\mathrm{i},\xi}(\xi) \tag{3.12}$$

As $\xi \to \infty$, the expected total delay of a packet,

$$\overline{D_{\mathrm{i},\xi}} = W_{\mathrm{i},\xi} + T_{\mathrm{prop}} + \overline{X_{\mathrm{i},\xi}} \tag{3.13}$$

where T_{prop} is related to the ranging of round trip time (RTT) [2]. From this expression, the maximum allowable packet delay can be expressed as

$$W_{\mathrm{i},\xi} \leq \mathbb{D}_{\mathrm{i},\xi} - T_{\mathrm{prop}} - \overline{X_{\mathrm{i},\xi}} \tag{3.14}$$

So, $\mathbb{D}_{\mathrm{i},\xi} - T_{\mathrm{prop}} - \overline{X_{\mathrm{i},\xi}}$ is the upper bound of the expected packet delay $W_{\mathrm{i},\xi}$ from the OLT destined for ONU i in the system.

Using the delay expression (3.9) with the limited service discipline, the expected waiting time in the downstream traffic scheduling for a packet ξ destined for the ONU i is

$$W_{\mathrm{i},\xi} = \frac{\lambda\overline{X_{\mathrm{i},\xi}^2} + (N+2-\rho)\overline{V} + (1-\rho)\sigma_V^2/\overline{V}}{2(1-\rho-\frac{(C\overline{V}\rho)^2}{(W^{\max})^2(1-\rho)})} \tag{3.15}$$

An analysis of such a delay expression using the system parameters in TABLE 5.1 can be shown in the Fig. 3.6. The average packet delay rises up as the traffic load increases and when the number of ONUs increases. At the light traffic load, the delay doesn't have much difference. The figure also implies that with the same N and ρ (utilization factor) the average packet delay increases as the transmission window size $W^{\max}$ decreases (Fig. 3.7), which is expected due to the system behavior of the limited service discipline. How to decide the optimal maximum transmission window size for the limited service discipline can be further studied in the future.

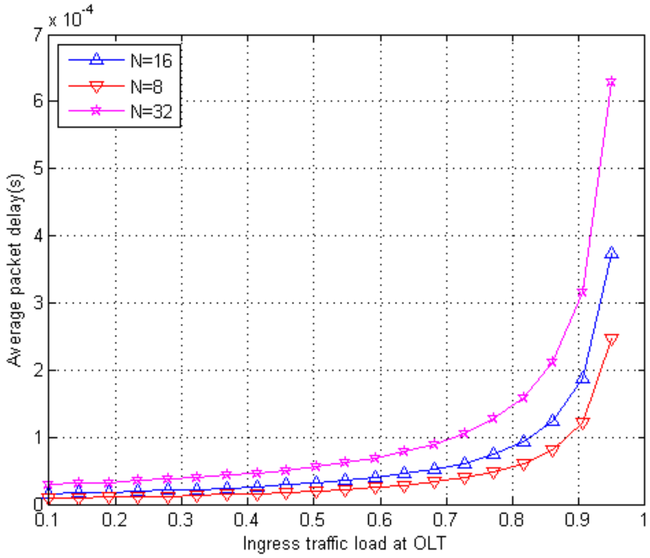

Figure 3.6: Average Packet Delay with the limited service discipline ($W^{\max}$=15,500 bytes).

By the expression (3.10) and expression (3.15), we have

$$T^{a}_{\mathrm{i,d}} = Q_{\mathrm{i}} \times \overline{X_{\mathrm{i},\xi}} = \frac{\lambda W_{\mathrm{i},\xi}\,\overline{X_{\mathrm{i},\xi}}}{N} \tag{3.16}$$

which provides an expression of active period of the reserved data interval for the downstream transmission to ONU i.

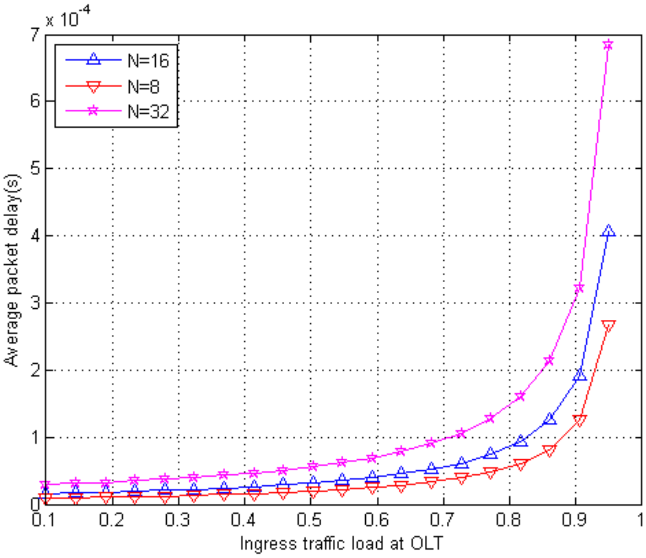

Figure 3.7: Average Packet Delay with the limited service discipline ($W^{\max}$=10,000 bytes).

From (3.11), (3.15), and (3.16),

$$\begin{aligned} T^{s}_{\mathrm{i,d}} &= C_{\mathrm{i}} - T^{o}_{\mathrm{i,d}} - T^{a}_{\mathrm{i,d}} = C_{\mathrm{i}} - T^{o}_{\mathrm{i,d}} \\ &- \frac{\rho}{N} \times \frac{\lambda\overline{X^{2}_{\mathrm{i},\xi}} + (N+2-\rho)\overline{V} + (1-\rho)\sigma_{V}^{2}/\overline{V}}{2\left(1-\rho-\frac{(C\overline{V}\rho)^{2}}{(W^{\max})^{2}(1-\rho)}\right)} \end{aligned} \tag{3.17}$$

This expression results in the next theorem.

Theorem 3.2.2. *Under the UCS-based GBA, the sleep time* $T^{s}_{\mathrm{i,d}}$*, in which ONU i can* *sleep in a sleep cycle during downstream transmissions, is determined by the expression of (3.17) when the downstream traffic is scheduled in a round-robin manner with the limited service discipline.*

In the round-robin scheduling system, the packet queuing delay can't exceed the upper bound during the upstream and downstream transmissions subject to the QoS constraints. Under the scenario of heavy traffic load, we have a longer active period of the downstream transmission, meaning less sleep time in a sleep cycle C_{i}. We also conclude that the minimum sleep time of this scenario for ONU i is

$$T_{\mathrm{i,d}}^{\mathrm{s,min}} = C_{\mathrm{i}} - T_{\mathrm{i,d}}^{o} - \frac{\rho}{N} \times (\mathbb{D}_{\mathrm{i},\xi} - T_{\mathrm{prop}} - \overline{X_{\mathrm{i},\xi}}) \tag{3.18}$$

Finally, the paper [15] develops an analytical model where each ONU is modeled as an M/G/1 system with vacations. The ONU can go into sleep mode for a certain amount of time before waking up to send or receive the buffered traffic. The model provides a closed-form expression for the maximum ONU sleep time based on the delay requirements of supported services, and the maximum sleep time for the upstream traffic scheduling at OUN i during a sleep cycle C_{i} is given by $T_{\mathrm{i,u}}^{\mathrm{s}}$. Using the derived sleep time, each ONU defines a queuing threshold that switches the ONU's mode to transmit or receive the buffered packets. Considering downstream and upstream transmissions present simultaneously at ONU i in a dynamic PON system, the maximum sleep time at ONU i, $T_{\mathrm{i}}^{\mathrm{s,max}}$, is the minimum of the values calculated from the upstream traffic scheduling and downstream traffic scheduling at ONU i under UCS-based GBA framework.

$$T_{\mathrm{i}}^{\mathrm{s,max}} = \min(T_{\mathrm{i,d}}^{\mathrm{s}}, T_{\mathrm{i,u}}^{\mathrm{s}}) \tag{3.19}$$

If we denote that the utilization factor of the total traffic load at OLT and at ONU is ρ_{down} and ρ_{up} respectively, and we assume the same overhead for upstream and downstream transmissions, generally speaking, we would expect that the maximum sleep time at ONU i is just the upstream-based sleep time developed in [15] when $\rho_{\mathrm{up}} > \rho_{\mathrm{down}}$. We would also expect that the maximum sleep time at ONU i is the downstream-based sleep time developed in this thesis in the situation vice versa, i.e. $\rho_{\mathrm{up}} < \rho_{\mathrm{down}}$ due to the longer active downstream transmission interval to ONU i.

The simulation for the sleep time analysis of downstream traffic scheduling will be presented in Chapter 5.2.

Table 3.1: Notations used in the analysis

NOTATIONS	DESCRIPTIONS
i	the queue index and the related ONU index
$\mathbb{D}_{\mathrm{i},\xi}$	maximum allowable packet delay at ONU i in the downstream transmission
$T^{s}_{\mathrm{i,d}}$	downstream sleep time at ONU i
$T^{a}_{\mathrm{i,d}}$	active period of the downstream transmission at ONU i
$T^{o}_{\mathrm{i,d}}$	overhead time at ONU i for downstream
$X_{\mathrm{i},\xi}$	service time of packet ξ to ONU i
$\overline{X_{\mathrm{i},\xi}}$	mean service time of packet ξ to ONU i
$\overline{X^{2}_{\mathrm{i},\xi}}$	the second moment of service time
$W_{\mathrm{i},\xi}$	the expected packet queuing delay destined to ONU i
$D_{\mathrm{i},\xi}$	total delay of a packet to ONU i
T_{prop}	Packet propagation time
ξ	a packet of the downstream transmission
λ_{i}	arrival packet rate to queue i at OLT
Q_{i}	the average queue size of queue i at OLT
C	the line rate for upstream/downstream e.g. 1Gbps
ρ_{i}	utilization factor of queue i at OLT
ρ	utilization factor of total traffic load at OLT

Chapter 4

Energy Efficient Scheduling Scheme

4.1 Sleep Time and Power Consumption

MPCP employs a gated transmission mechanism from multiple nodes to allow dynamic sharing of bandwidth while avoiding packet collisions. Although MPCP is not concerned with any particular inter-ONU scheduling algorithm, it has been designed in order to facilitate the implementation of various DBA algorithms. MPCP depends on two Ethernet control messages, *Gate* and *Report*, to provide the signalling infrastructure (control plane) for coordinating data transmission. Both *Gate* and *Report* messages are MAC control frames and are also used as a keep-alive mechanism. The goal is to inform the system that the OLT and the ONU are functioning properly.

If the DBA agent doesn't send a *Gate* message at OLT, the gate generation process will send an empty *Gate* message to the ONU autonomously and periodically. Currently, the expiration period of the *gate_periodic_timer* is set to 50 ms (timeout). The ONU becomes unregistered while waiting for the message to the timeout. The same process applies to the *Report* generation used as a keep-alive mechanism. The empty *Report* message is sent every 50 ms by the setting of the *report_periodic_timer* expiration period. If the time of waiting for the message reaches the timeout, the ONU becomes unregistered. As a result, a sleeping ONU must wake up every 50 ms to send the *Report* messages and receive the *Gate* messages to comply with MPCP protocol.

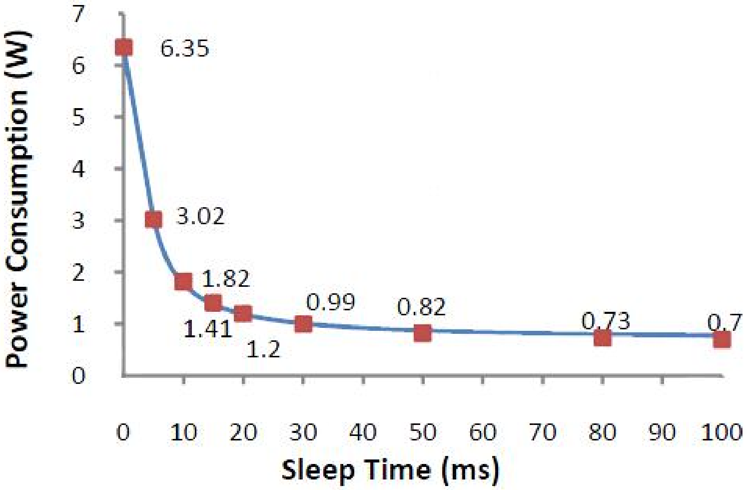

Figure 4.1: Power consumption of an sleeping ONU.

To address the power saving through sleep mode, the paper [4] implemented a handshake process between OLT and ONUs before ONUs go to sleep. Because the OLT knows the sleep mode of ONUs, it can buffer the downstream traffic until the sleeping ONU wakes up. Moreover, around 25-30 ms seems to be best tradeoff between sleep period and power savings shown by Fig. 4.1. Note that the power consumption of an ONU in active mode is 6.35 W, whereas the power consumption is 0.70 W in sleep mode. Thus, it takes around 20 ms for the ONU to reduce its power by 80%, which means that the energy saveing can never reach a higher percentage if the sleeping time of an ONU is less than 20 ms.

For the algorithm of energy efficient scheduling scheme, the expiration interval (timeout) of 50 ms will still be used to meet the requirement of keeping the ONU function properly and comply with MPCP as well. From the perspective of saving energy, this is good enough (Fig. 4.1) as long as high-priority class of EF packets don't arrive too often. If there are many EF packet arrivals, the energy can't be save efficiently due to frequent mode switching between the active and sleep modes.

4.2 Algorithm of Energy Efficient Scheduling Scheme

To avoid frequent mode switching and long sleep time causing more delay and latency, an sleep time based on the expression of the maximum sleep time (3.19) will be applied to the procedures of energy efficient scheduling scheme to maximize the energy saving. Besides, for delay-sensitive applications, an unique arrangement allows an ONU to quit sleep mode at once before the predefined sleep time is up when the expedited forwarding (EF) packets having strict service level agreement (SLA) arrive.

Under the UCS-based GBA framework, it is observed that the ONU can sleep up to 61.3 ms, 94.7 ms, and 111.3 ms for a delay requirement of 75 ms, 100 ms, and 150 ms respectively [8]. Thus, during the sleep time, the ONU should wake up every 50 ms just to send the empty *Report* messages and receive the empty *Gate* messages for ONU to function properly. In EPON system, UCS-based GBA should comply with MPCP while in GPON, GBA should comply with Physical Layer Operations and Maintenance (PLOAM). PLOAM defines a timeout interval of 100 ms [20], after which an ONU will fully be deactivated.

There is a major difference of the keep-alive mechanism when comparing the UCS-based GBA with Energy Management Mechanism (EMM) developed in [3], because EMM puts an ONU in a sleep mode only when an ONU i waits for its next upstream transmission period while other ONUs are busy. The sleep time of EMM is within the millisecond-long transmission cycle. Accordingly, the DBA agent can always issue a request to send a grant to a particular ONU before the timer expires, which means that the ONU is always kept registered and alive.

From this algorithm 4.1, the ONU i can wake up immediately during the sleep mode if high priority EF packets arrive, regardless of whether the predefined sleep time is over. Within the sleep period, all the coming AF and BE packets are stored in the buffer at OLT and ONU i. The step 21 in the algorithm is arranged to transmit all the classes of packets buffered at OLT and ONU i, when an ONU quits sleep and enters active mode. To maximize channel efficiency and energy saving, the overlapped the upstream and downstream transmissions under the UCS-based GBA framework are applied, and the details of this algorithm are shown as the following.

Algorithm 4.1 Energy efficient scheduling with differentiated QoS consideration

```
1:  while (1) do
2:    ONU i sends a request to go to sleep;
3:    OLT sends ONU i a Gate message to have it sleep and stop sending data to OUN i;
4:    T=50 ms; {Setting Gate_timeout and Report_timeout}
5:    ONU i goes to sleep;
6:    while (no EF packets arrive) and (Timer < $T_i^{s,max}$) do
7:      ONUi sleeps and buffering all the AF and BE packets in OLT and ONU for
        upsteam/downstream;
8:      if (EF packets arrive) then
9:        goto 18;
10:     else {Gate and Report messages are sent every 50 ms to keep ONU i alive.}
11:       ONU i wakes up at t =T;
12:       OLT sends ONU i an empty Gate message and ONU i sends an empty Reprot
          message to OLT;
13:       ONU i sends a request to continue sleep;
14:       T=T + 50 ms; {for the next timeout}
15:       OLT instructs ONUi to go back to sleep;
16:     end if
17:   end while
18:   Quitting sleep mode to be in active mode, recovery and synchronization;
19:   OLT sends ONU i a Gate message;
20:   OLT sends ONU i a Grant message that allocates the upstream bandwidths;
21:   All packets in buffer of OLT and ONU are transmitted to maximize channel efficien-
      cy; ONU i sends the Report message (piggybacked) using the reserved slot;
22:   OLT receives packets form ONU i, meanwhile OLT sends downstream traffic to ONU
      i; {Overlapped upstream and downstream transmissions.}
23: end while
```

Chapter 5

Simulation Results

5.1 Simulations of Proposed Priority-queue Scheduler Model

In this section the QoS metrics of the priority-queue scheduler model have been demonstrated in regard to the overall performance of the system: packet delay, bandwidth utilization (normalized throughput), dropped packet rate, and queue length. For the simulation, discrete-event simulator of Matlab has been used to analyze the proposed model. To be consistent with Expedited Forwarding (EF), Assured Forwarding (AF) and Best Effort (BE) classes, three priority classes are used as *P0*, *P1*, and *P2*. *P0* traffic has constant-bit-rate, and is generated 1000 times per second with the packet size of 70 bytes. Class *P1* and class *P2* traffic have variable-size ranging from 64 to 1518 Bytes, and the arrival packets occur according to a Poisson process. In the simulations, we assume that Class *P1* and class *P2* have the same arrival Poisson rate and all ONUs have the same Service Level Agreement (SLA) with the gated service discipline.

Fig. 5.1 shows that the normalized throughput reaches the peak of 1 around the ingress traffic load of 0.78. As the ingress traffic load decreases, the throughput falls down asymptotically to a certain value because of the constant load flow of EF data packets.

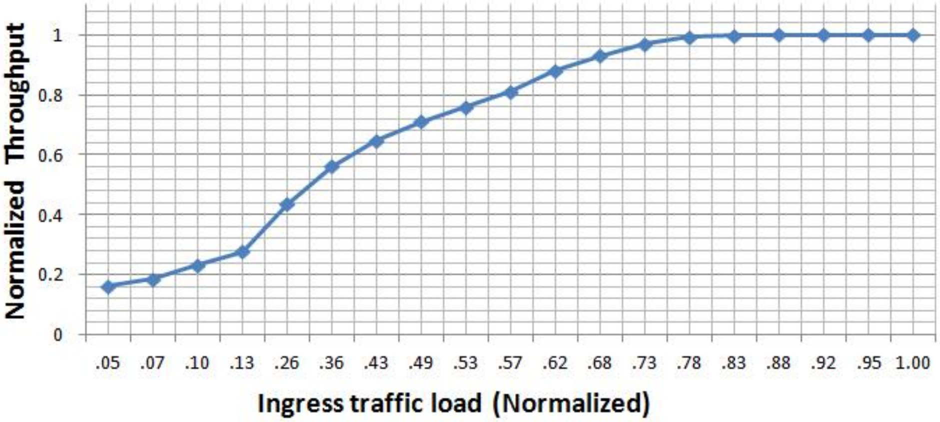

Figure 5.1: Throughput of the priority-queue system.

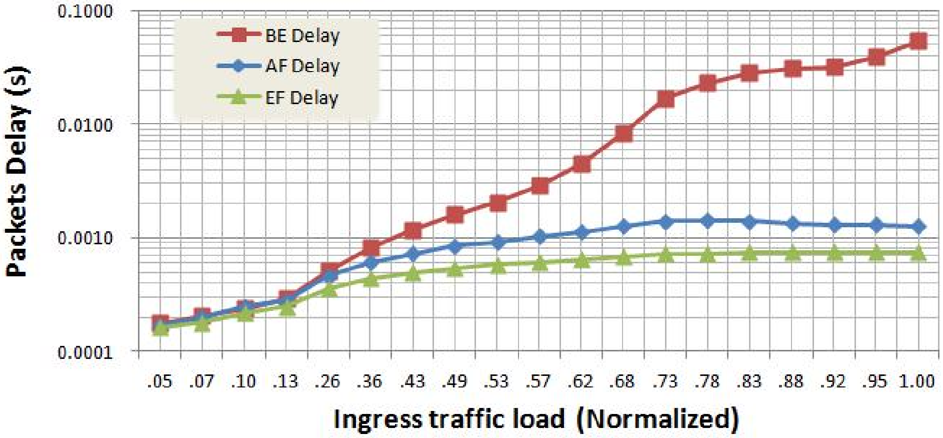

Figure 5.2: Packet delay of the priority classes.

In general, the EF packets has the least delay while the AF packets is the second one and BE has the largest delay in Fig. 5.2. When the traffic load is very light, the packet delays of different classes are all very tiny to 0.17 ms and almost the same for EF, AF and BE classes. As the traffic load increases, all delays rise up as expected, but the BE delay has a larger increment in comparison with EF and AF delays due to the lower priority among all the classes. A very interesting phenomenon is that after the traffic load at 0.78, the delays for the EF and AF packets become stable at the expense of the further delay of BE packets.

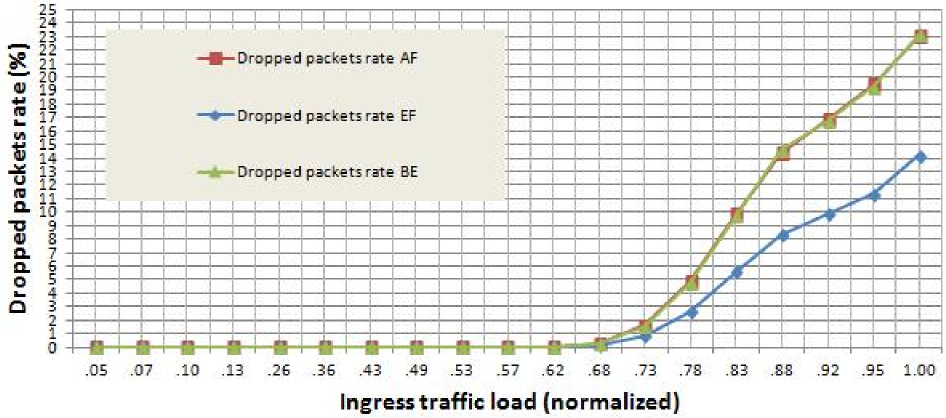

Figure 5.3: Dropped packet rate of the priority-queue system.

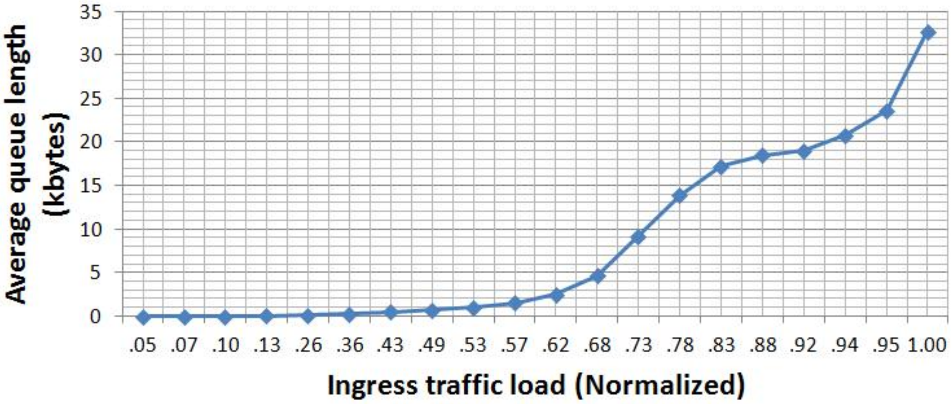

Figure 5.4: The priority-queue length of the buffer in the ONU.

The dropped packet rates for EF, AF and BE are zero until the ingress traffic load gets to 0.57. Then, the dropped packet rates increase as the load goes higher. From Fig. 5.3, the EF packet has the lowest dropped packet rate because it has a highest priority being processed in the priority buffer among the different classes of incoming packets. When the normalized throughput reaches the peak at ingress traffic load of 0.78, the dropped packet rates for all classes start rising up dramatically.

The average length of the priority queue is less than 1 kbytes before the ingress traffic load reaches 0.49. It continues going up to 15 kbytes approximately at the traffic load of 0.78, where the throughput reaches a peak. After the load of 0.78, the queue length gets high significantly to 32.6269 kbytes, at which the very heavy traffic load becomes 1 as shown in Fig. 5.4.

In summary, the numerical study and simulation results of the proposed priority-queue scheduler model demonstrate the differentiated QoS performances under the different ingress traffic load. Applying a nonpreemptive queue in the system not only avoids the light-load penalty, but also improves the latency of the system, comparing to the strict-priority scheduling even with an optimization scheme. The priority-queue scheduler model can be beneficial to the upstream traffic scheduling of UCS-based GBA framework, especially reducing the packet delay when there are different priority classes of packets present in the system.

5.2 Numerical Results of Sleep Time Analysis of Downstream Traffic scheduling

In this section, simulation results show how the effects of the limited service discipline and the number of ONUs in the system impact the sleep time of ONU i during the downstream traffic scheduling. Matlab has been used to simulate the proposed analytical model, and the number of ONUs is set as 8,16 and 32. The interarrival time of downstream packets destined for the ONUs is exponentially distributed. In addition, a gated UCS-based upstream bandwidth allocation scheme is employed. Each ONU has an equal share of the cycle time, T_{cycle}. The simulation results verify the proposed analytical model and the effectiveness of the proposed approach.

Table 5.1: System parameters

Parameters	Description and Values
N	Number of ONUs: 8,16 and 32
C	Line rate of downstream 1 Gbps [16]
G	Guard interval: 1 μs [16]
T_{cycle}	Cycle time (N=16): 2 ms [16] and 1.3 ms
$W^{\max}$	Maximum transmission window size: 15,500 bytes [16], 15,000 bytes, etc.
$\overline{V}$	Mean reservation interval: 1.512 μs
$\overline{X_{\text{i},\xi}}$	Mean service time: 5.08976 μs [1]
$\overline{X^2_{\text{i},\xi}}$	The second moment of service time: 51.1604 $(\mu s)^2$ [1]
$T^o_{\text{i,d}}$	Overhead for downstream at ONU i: 0.125 ms [8]

[1] : The values are calculated based upon the data in [15].

System parameters can be seen in TABLE 5.1. Variable bit rate (VBR) and best effort (BE) packets are generated using a Poisson distribution and have packet payload sizes that vary from 64 to 1518 bytes with the distribution based on [9] as followings: 64 bytes (47%), 300 bytes (5%), 594 bytes (15%), 1300 byte(5%), and 1518 bytes (28%). Packets arrive to each queue at the OLT with the rate λ/N of the Poisson process, and the total traffic load ρ (utilization factor) varies from 0.1 to 0.96.

Fig. 5.5, Fig. 5.6, and Fig. 5.7 compare the sleep time of the analytical mode with the simulation results. The close match between the simulations and analytical results validates the sleep time analysis of the downstream traffic scheduled in a round-robin manner with the limited service discipline described in Chapter 3.

In a system with 16 ONUs, the sleep time is stable at the light traffic load (Fig. 5.5). Until the utilization factor of the traffic load at OLT reaches 0.6 approximately, the sleep time starts decreasing. The figure shows that with the same N and the utilization factor ρ the sleep time is getting shorter as the maximum transmission window size $W^{\max}$ decreases, which leads to a shorter cycle time. This is also expected regarding the system behavior of the limited service discipline. Three maximum transmission window size have bee used such as 15,500 bytes, 15,000 bytes, and 14,500 bytes shown in the figure. Note that this figure also implies that there is a minimum sleep time at a certain window size subject to the upper bound of packets' delay when the traffic load is very heavy during the downstream traffic scheduling.

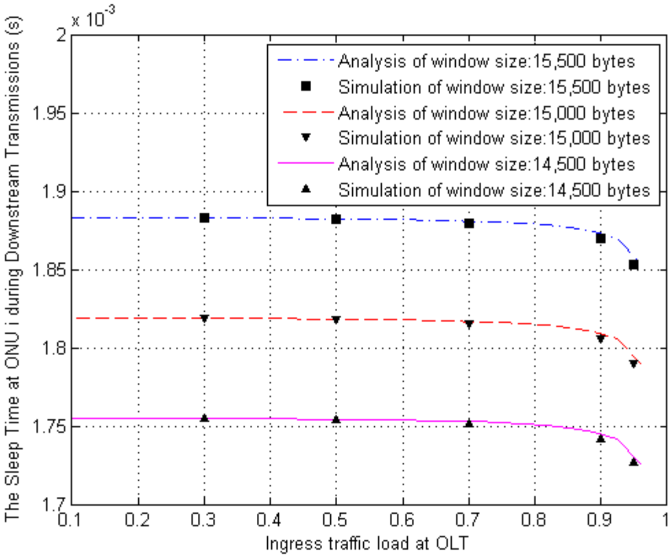

Figure 5.5: Sleep time for different transmission window size with 16 ONUs in the system.

When the number of ONUs in the system varies, the sleep time of ONU i during downstream transmissions gets longer as the the number of ONUs increases shown by Fig. 5.6. The maximum transmission window size used in this figure is 15,500 bytes.

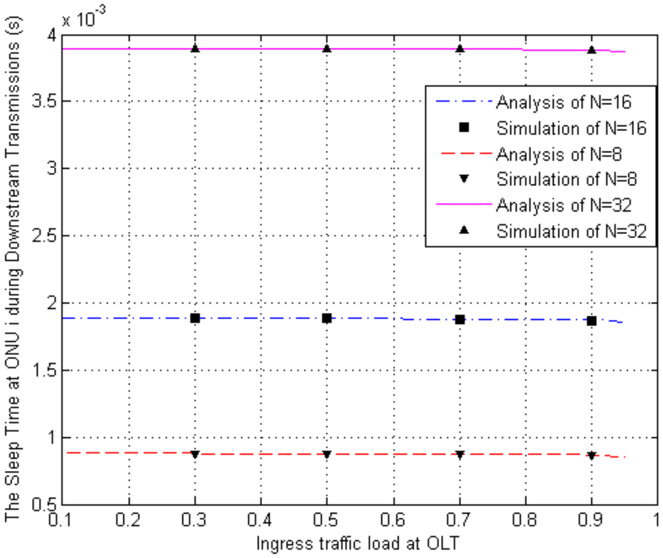

Figure 5.6: Sleep time at the different number of ONUs in the system ($W^{\max} = 15,500\,bytes$).

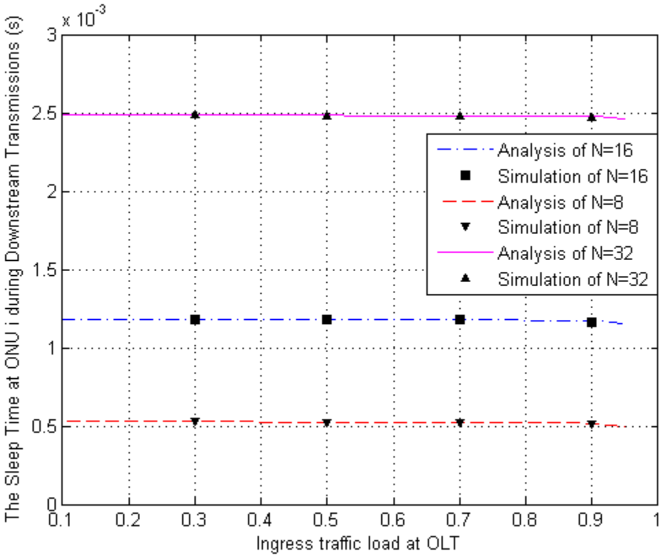

Figure 5.7: Sleep time at the different number of ONUs in the system ($W^{\max} = 10,000\,bytes$).

If the transmission window size, $W^{\max}$, decreases to 10,000 bytes, the sleep time all decreases accordingly as shown by Fig. 5.7 with different number of ONUs in the system, which is expected due to the shorter cycle time.

Chapter 6

Conclusion and Future Work

In essence, the analytical modeling of such a system is very complicated [16]. Firstly, we have surveyed the papers on energy efficiency EPON and differentiated QoS in EPON. We designed the priority-queue scheduler model to eliminate the phenomenon of light-load penalty because the preemptive queue is unfair to the low priority data traffic and could even have a detrimental impact on certain protocols such as TCP Vegas emphasizing on packet delay. The results of the simulation show that the proposed scheduler model outperforms the strict-priority scheduling. It also shows that the delay of different classes is reasonable and within the range of requirements of SLA. The proposed priority-queue scheduler model can be embedded in the upstream traffic scheduling to improve the performance of UCS-based GBA framework.

Then, we developed the downstream traffic scheduling analytical model with the limited service discipline based upon the UCS-based GBA framework, overlapping the downstream and upstream transmission window at the ONU. When the downlink and uplink transmissions overlap perfectly at the ONU (ρ_{down} is close to ρ_{up}), the more energy can be conserved, combing with the method developed in [15]. Simulation results show the system performance of the downstream traffic scheduling with the access-control of the limited service discipline. Further possible research can explore on how to maximize the sleep time of the ONU subject to QoS constraints when the traffic load between uplink and downlink is not balanced, where there is a huge difference among the utilization factors of the traffic load ρ_{up} and ρ_{down} at ONU and OLT respectively.

Finally, an algorithm of energy efficient scheduling scheme with differentiated QoS consideration is provided based on the principles of UCS-based GBA framework to reduce the frequent mode switching while keeping ONUs alive all the time. We also learned that the maximum energy saving is 80% and it can never reach 90% energy saving with frequent mode switching. Moreover, newly SLA-based energy-efficient scheduling scheme for EPON with sleep-mode ONU could be another research topic, in which OLT can adjust sleep time according to traffic while ONU can quit sleep mode for sending or receiving delay-sensitive packets with strict SLA.

In the future, a problem formulation will be built based upon the energy efficient algorithm to demonstrate how much extra energy can be saved under different uses and practical power consumption settings. Next, a simulation with system aware and network aware could be further developed and implemented to maintain the dynamic QoS since PONs need to have differentiated QoS provisioning embedded in order to support applications with diverse requirements for the next-generation access network.

We have done the preliminary research work in Long-Reach PONs (LRPONs). LRPON is one of the most promising NG-PON systems, and LRPONs is a strong candidate for next generation PONs [21]. It aims to combine the capacity of the optical access and the optical backhaul by offering some very attractive features, such as large split ratio and long feeder distance. It can extend the coverage span of PONs from the traditional 20 km range to 100 km and consolidates the multiple OLTs and central offices (COs), thus it is considered as a cost-effective solution for providing broadband access spanning large areas from operator perspective. However, few work has been reported to consider energy efficiency and differentiated QoS in the relatively new field of next generation LRPONs system design. The integration of differentiated QoS scheme and multi-thread polling scheme developed in LRPONs [22] as well as the implementation of the remaining energy efficient scheduling scheme are also the future work for us.

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