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Master's Thesis

에너지 효율적 TDM-PON을 위한 지연 인지 양방향 동기 전송방식

Delay Aware Synchronous Bidirectional Transmission Scheme for Energy-efficient TDM-PON

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A thesis submitted to the faculty of KAIST in partial fulfillment of the requirements for the degree of in the Department of Electrical Engineering . The study was conducted in accordance with Code of Research Ethics[1].

2013. 6. 28.

Approved by

Professor Choi, Jun Kyun

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ABSTRACT

Due to the rapid spread of the Internet, energy saving becomes important issues of ICT area. Particularly, a significant part, around 70%, of overall internet energy consumption is consumed by access networks. However, some studies show that TDM-PON (Time Division Multiplexing - Passive Optical Network) are low utilized in most of the day, which is major part of access networks. Most energy saving solutions in TDM-PON consider downlink traffic only. In that case when uplink traffic comes to ONU, ONU's sleep is interrupted. It imposes extra energy consumption due to frequent sleep mode transition. Also, as downlink and uplink are managed independently, there would be additional control message overhead than the cases where both uplink and downlink are managed together. To solve this problem, some researches propose synchronized uplink and downlink transmission. But these solutions do not take into account traffic delay requirement. In this study, it has been found that there are still room to save energy in those solutions. In this paper, Delay Aware Synchronous Bidirectional Transmission (DASBT) Scheme for Energy-Efficient TDM-PON is proposed. In detail, novel sleep interval decision algorithm is proposed that considers the uplink and downlink traffic conditions, and delay requirements. In addition, the uplink and downlink traffic is transmitted at the same time to reduce energy consumption. Simulation results show that proposed scheme minimizes energy consumption up to 15% in comparison with previous schemes.

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Chapter 1. Introduction

1.1 Motivation

Many studies show that the energy consumption in ICT (Information and Communication Technology) area is high and increasing fastly due to fast deployment of internet service all around the world [1]. To minimize energy consumption in network service, network equipments on both core and access network have been focused in industries and academia.

Particularly, a significant part, around 70%, of overall internet energy consumption is consumed by access networks [2]. However, some studies show that TDM-PON (Time Division Multiplexing - Passive Optical Network) are low utilized in most of the day, which is major part of access networks. In home areas, utilization is 50% in 8 hours and 10% in another 18 hours. In business areas, 40% in 12 hours and 2% in 12 hours [3]. Therefore TDM-PON has lots of room to save energy.

Most energy saving solutions in TDM-PON consider downlink traffic only [4–6]. In that case when uplink traffic comes to ONU, ONU's sleep is interrupted. It imposes extra energy consumption due to frequent sleep mode transition.

1.2 Problem Statements

As downlink and uplink are managed independently, there would be additional control message overhead than the cases where both uplink and downlink are managed together. To solve this problem, some researches propose synchronized uplink and downlink transmission [7, 8]. But these solutions do not take into account traffic delay requirement. In this study, it has been found that there are still room to save energy in those solutions.

1.3 Contributions

In this dissertation, Delay Aware Synchronous Bidirectional Transmission (DASBT) Scheme for Energy-Efficient TDM-PON is proposed. This proposed scheme contains:

- Novel sleep interval decision algorithm considering uplink and downlink traffic status and delay requirement.
- Synchronized uplink and downlink transmission for energy efficiency.

Simulation results show that proposed scheme minimizes energy consumption up to 15% in comparison with previous schemes.

Chapter 2. Backgrounds and Related Works

This chapter provides, first, backgrounds of Passive Optical Network (PON) that contains general architecture of Passive Optical Network (PON) and sleep mode of Optical Network Unit (ONU). Then, previous schemes and their drawbacks are presented.

2.1 General PON Architecture

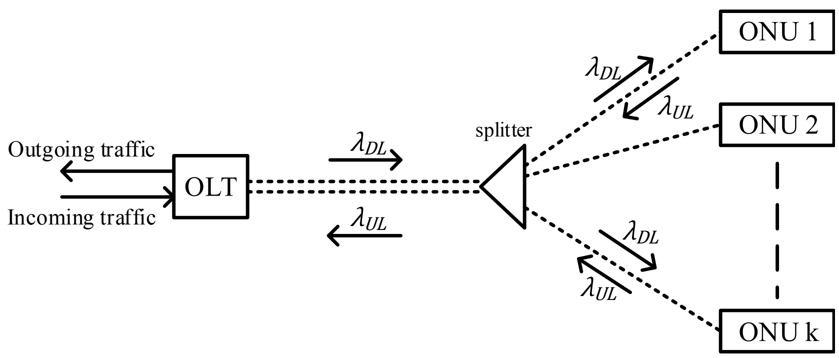
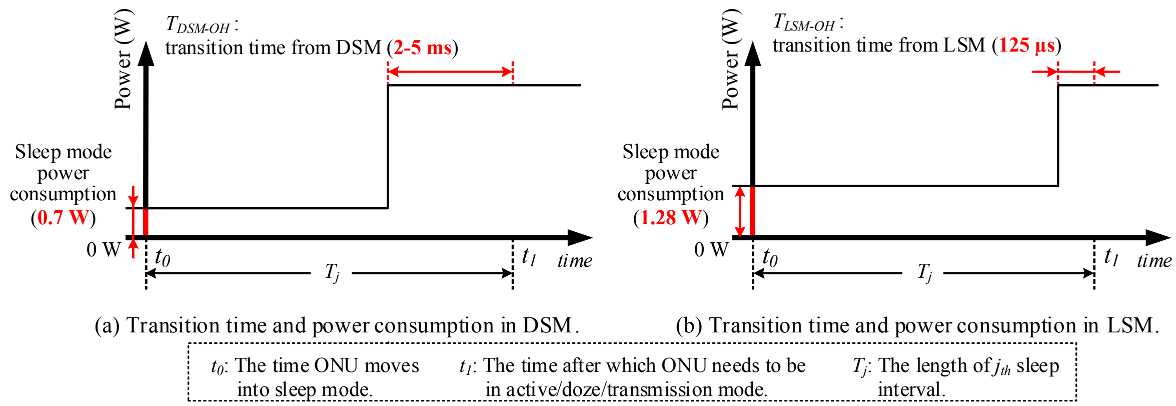


Figure 2.1: General PON Architecture

As shown in Figure 2.1., general PON architecture are composed of one Optical Line Terminal (OLT), one passive splitter, and multiple Optical Network Units (ONU)s [9]. Usually the splitting ratio is *1:n*, where n can be 16, 32, 64 or 128 ONUs. In this architecture, one wavelength is employed for downlink transmission and another one for uplink uplink transmission. In downlink transmission, broadcast and select mechanism is used. Downlink frames, which OLT receive from core network, are transmitted to optical fiber with Logical Link Identifier (LLID) which are uniquely allocated for each ONU. Then, those frames are broadcasted to ONUs by passive splitter and each ONU receive frames with their own LLID. In uplink transmission, the uplink wavelength is shared among all the ONUs that are connected with the OLT. Uplink frames, which ONU receive from user side network, are transmitted to OLT using pre-allocated slots only. Those slots are usually allocated by OLT using various Dynamic Bandwidth Allocation (DBA) schemes. By using DBA mechanism, uplink traffic demand can be adopted dynamically, and it improves uplink bandwidth utilization in a TDM-PON. To get uplink transmission opportunity, an ONU sends bandwidth request to the OLT in each polling cycle. OLT collects and analyze all the request from ONUs, and finally allocate slots to each ONUs. Sleep mode operations of ONU are usually done in centralized manner. OLT transmits control messages with a number of sleep related parameters to each ONU, and ONU sleep and wakes up based on those paramters.

2.2 Criteria for ONU Sleep Mode Selection



(a) Transition time and power consumption in DSM.

(b) Transition time and power consumption in LSM.

Figure 2.2: Transition time and power consumption in DSM and LSM

There are two sleep mode of ONU; Deep Sleep Mode (DSM) and Light Sleep Mode (LSM) [10, 11]. DSM is a state that all components are off which are used for transmittting and receiving frames in ONU. As shown in Figure 2.2., ONU consumes $0.7W$ and it's transition time is $5ms$ that is needed to recover clock and synchronize with OLT in DSM. LSM is the state ONU keeps the clock. In LSM, ONU consumes $1.28W$, that is slightly higher than energy consumption in DSM. That amount of energy is needed to keep the clock, and ONU needs $125\mu s$ to synchronize with OLT.

Within given sleep interval, ONU can sleep with one sleep mode;DSM or LSM. Let T_j is the given sleep time, and T_{DSM-OH} and T_{LSM-OH} are the transition times from DSM and LSM to active mode. If DSM is selected, ONU sleeps during $T_j - T_{DSM-OH}$ and wakes up within T_{DSM-OH} to synchronize with OLT. Otherwise, ONU sleeps during $T_j - T_{LSM-OH}$ and wakes up within T_{LSM-OH}. Therefore energy consumption in DSM, $E_{T_j}^{DSM}$, and energy consumption in LSM, $E_{T_j}^{LSM}$, are calculated as the

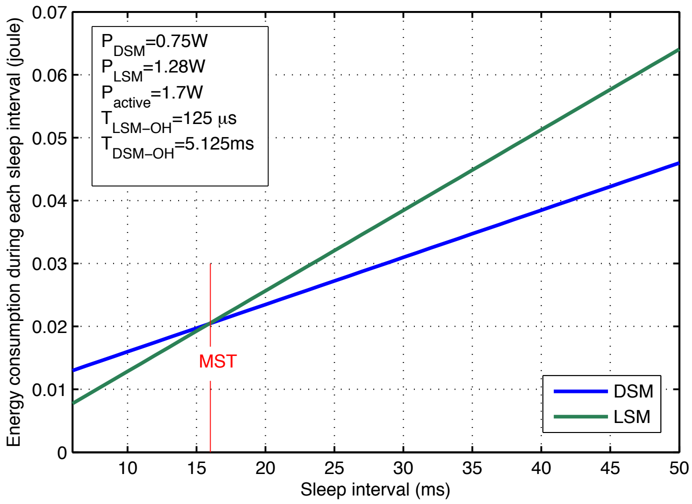


Figure 2.3: Energy consumptions in Deep Sleep Mode (DSM) and Light Sleep Mode (LSM) with sleep interval and Mode Selection Threshold

followings [6]:

$$E_{T_j}^{DSM} = P_{DSM}(T_j - T_{DSM-OH}) + P_{active}T_{DSM-OH} \tag{2.1}$$

$$E_{T_j}^{LSM} = P_{LSM}(T_j - T_{LSM-OH}) + P_{active}T_{LSM-OH} \tag{2.2}$$

$$T_{MST} = T, \quad if \quad \frac{E_T^{LSM}}{E_T^{DSM}} = 1 \tag{2.3}$$

In Figure 2.3., E_T^{DSM} and E_T^{LSM} are plotted. The crossing point is defined as Mode Selection Threshold (MST), T_{MST}, and calculated with Equation 2.3. In the case that the given sleep interval is less than T_{MST}, it is more energy efficient for ONU to sleep in LSM rather than sleep in DSM.

2.3 Independently Managed Uplink and Downlink Transmission

In previous sections, general PON architecture and sleep modes are described. In the following sections, previous schemes and their drawbacks are covered in detail.

Before ONU enters into sleep modes, both transmitter and receiver of ONU should not be used for a while. Therefore, ONU wakes up more longer in the case that both uplink and downlink are managed independently [5]. For example, uplink transmission starts before downlink reception and

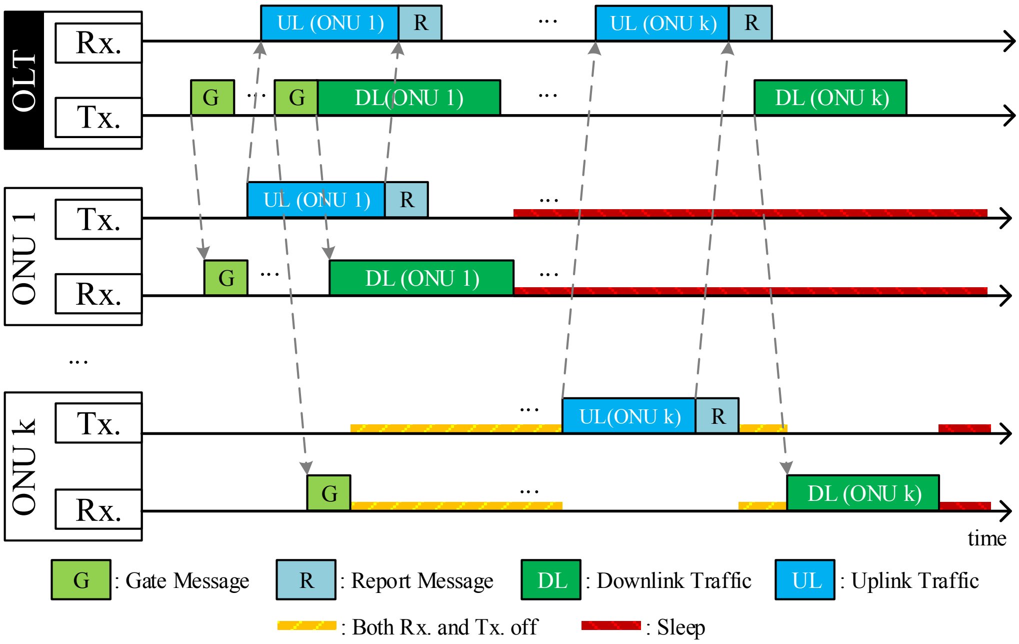


Figure 2.4: An example of independently managed uplink and downlink transmission

downlink reception ends after uplink transmission ends in ONU_1 and ONU_k in Figure 2.4. In those cases, the more uplink transmission duration and downlink reception duration are overlapped, the longer sleep inverval ONU can obtain. For that reason, total sleep time can be maximized in synchronous transmission.

2.4 Adaptive Delay Aware Downlink Scheduling

As mentioned in introduction, TDM-PON is low utilized in most of the day. ONU sleeps and wakes up and check frames to receive or transmit eventhough there are no frame. Therefore, as shwon in Figure 2.5., in low utilization and no frame to receive or transmit, sleep interval decide algorithms are proposed to increast sleep interval as twice. Additionally, in the consideration of downlink traffic rate and delay requirement, the algorithm is proposed to adjust upper and lower bound of sleep interval dynamically [6].

However, this scheme does not consider uplink traffic and some problem occurs described in Figure 2.6.. There are no traffic in the first sleep interval T_1, so, the next sleep interval T_2 becomes twice of this. In the same way, the third sleep interval T_3 becomes twice of T_2. In T_3, uplink traffic arrrives to ONU, and ONU's sleep is interrupted and wakes up to transmit this traffic.

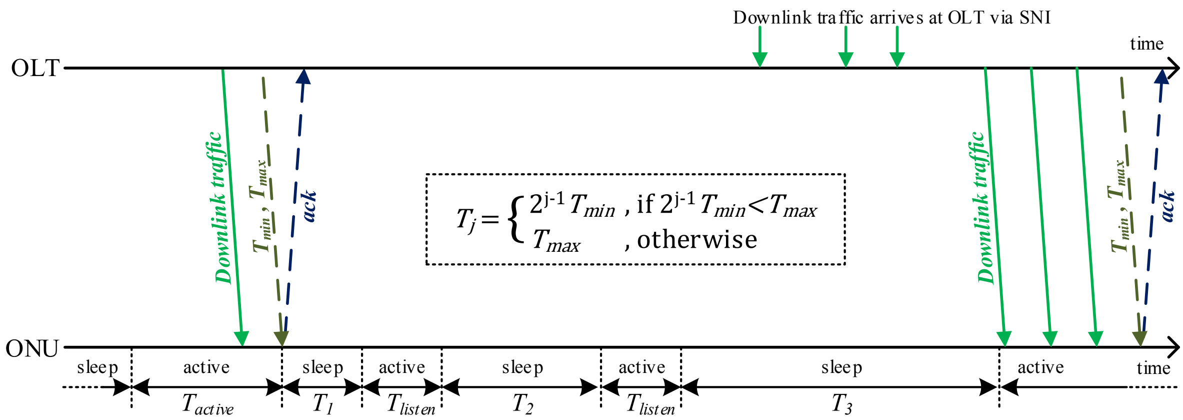


Figure 2.5: An example of sleep increment in Adaptive Delay Aware Downlink Scheduling

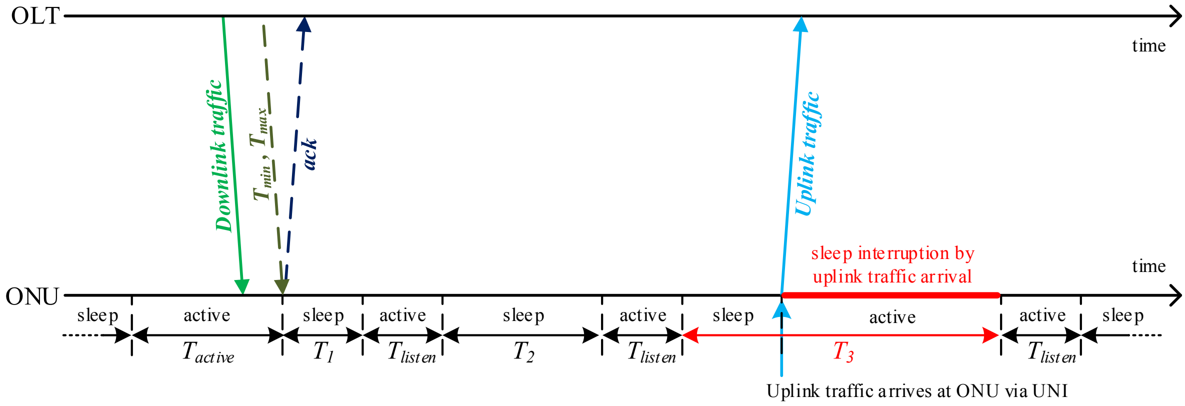
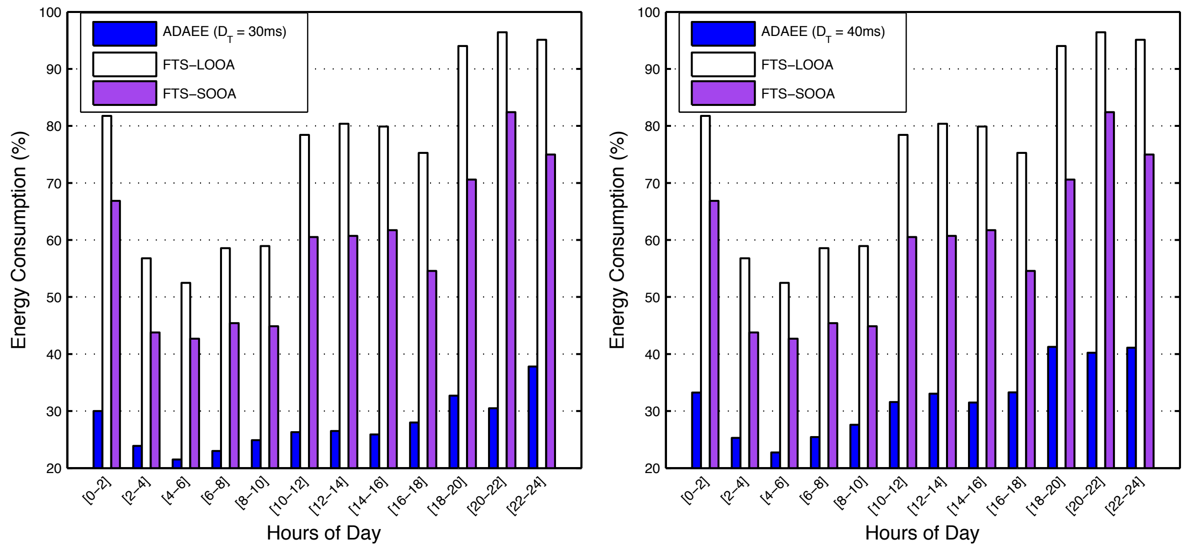


Figure 2.6: An example of sleep interruption in Adaptive Delay Aware Downlink Scheduling



(a) Delay requirement = 30ms

(b) Delay requirement = 40ms

Figure 2.7: An example of energy consumption using Adaptive Delay Aware Downlink Scheduling

Extra energy expenditure due to this phenomenon is shown in Figure 2.7. around 19 and 20 o'clock. Instinctly, the more larger delay requirement, the more longer sleep and the more energy saving. However, In 40ms delay requirment case, ONU consumes more energy than in 30ms case within 90 and 20 o'clock. In high traffic rate, sleep interruption occurs frequently and additional mode changes induce extra energy consumption.

2.5 Synchronized Uplink and Downlink Transmission

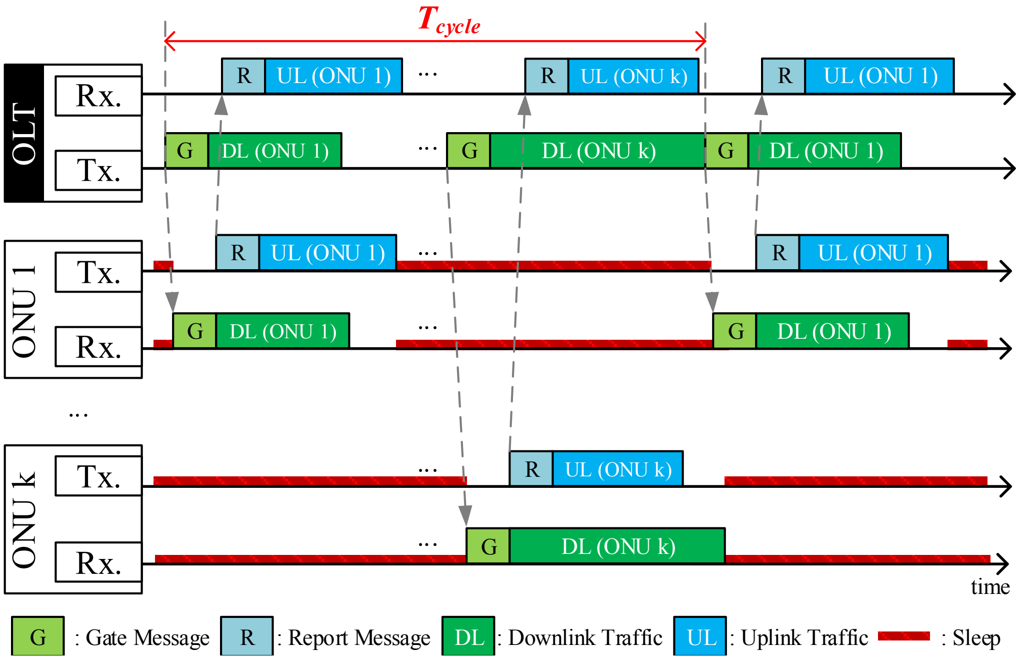


Figure 2.8: An example of synchronized uplink and downlink transmission

To solve this, synchronized uplink and downlink transmission schemes are proposed [7,8]. However, those schemes do not consider low traffic rate. In those schemes, one transmission cycle is defined as the time needed for completion of all ONU's transmission. In low traffic, one cycle time becomes short to wake up frequently and cannot preserve long time for DSM.

Chapter 3. Proposed Delay Aware Synchronous Bidirectional Transmission (DASBT) Scheme for Energy-efficient TDM-PON

In this chapter, Delay Aware Synchronous Bidirectional Transmission (DASBT) Scheme is proposed to solve issues arised in the previous chapter. First, system model and overall operational procedure is described. Then, essential algorithm, Sleep Boundary Adjustment (SBA) is explained that considers uplink and downlink traffic status and delay requirement. Also, synchronized uplink and downlink transmission is described. Finally, overall algorithms for DASBT is explained.

3.1 System Model

3.1.1 Operational Assumptions

In proposed DASBT solution, ONU operates in several modes (e.g. active, sleep, etc). To manage sleep mode in ONU, ONU has a new component called as MCL (Mode Controller Logic) . MCL dedicatedly turns on and off ONU components to reduce energy consumption in specific cases (e.g in the absence of uplink or/and downlink traffic, etc). OLT also have new components to calculate sleep parameters to manage each ONUs [6]. In the following section, the functional block diagram of the OLT and an ONU is explained. Then, different modes are described in which an ONU operate.

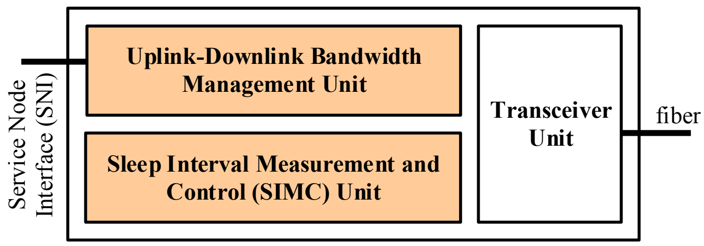


Figure 3.1: Functional block diagram of OLT in DASBT

OLT Functional Block Diagram

Like previous schemes [6,12–14], DASBT OLT takes part of calculating sleep interval for ONUs that are connected to the OLT. Unlike previous schemes that calculate the length of sleep interval directly, the OLT decides the sleep interval boundary T_min and T_max. In this solution, DASBT OLT is assumed to be composed of a Transceiver Unit, an Uplink-Downlink Bandwidth Management Unit, and a Sleep Interval Measurement and Control (SIMC) Unit. Figure 3.1. shows a diagram of an OLT. In the following part, the main modules are explained:

- **Transceiver Unit**: This unit takes charge of transmission and reception related activities. It has components like avalanche photodiode, Burst Mode CDR (BM-CDR) [15].
- **Sleep Interval Measurement and Control (SIMC) Unit**: This unit take great part in calculating sleep parameters. It obtains uplink and downlink traffic information through the optical interface and the Service Node Interface (SNI). In the absence of uplink and downlink traffic, it decides T_min and T_max using Sleep Interval Length (SLID) algorithm. OLT, also, finds sleep interval boundary T_min and T_max based on the novel Sleep Boundary Adjustment (SBA) algorithm using uplink and downlink arrival rates (λ_{UL} ,λ_{DL}) within a predefined Sample Time Window (STW).
- **Uplink-Downlink Bandwidth Management Unit**: This unit allocates uplink and downlink bandwidth for each ONUs based on uplink and downlink traffic and their sleep schedule.

ONU Functional Block Diagram

As shown in Figure 3.2, DASBT ONU diagram is depicted including all the basic components that can be found in previous schemes [6,10–12]. The ONU is mainly composed of analog and digital circuitry. In sleep modes, digital parts are on and analog parts are managed dedicately via Mode Control Logic (MCL) unit. That logic calculate sleep interval within sleep interval boundary T_min and T_max. Then, the ONU sleeps with DSM or LSM based on sleep interval length. In other words, ONU turns off suitable components in Transceiver Unit. Also, the ONU buffers uplink traffic when ONU is in sleep mode.

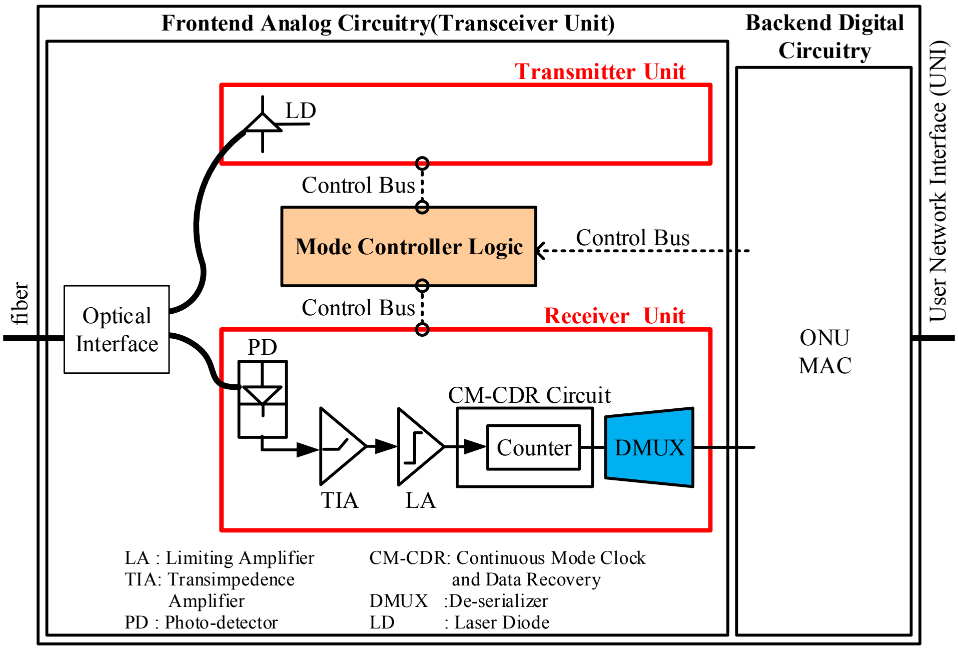


Figure 3.2: Functional block diagram of ONU in DASBT

3.1.2 ONU Modes

In this proposed solution, ONU operate in 5 modes as listed below. In each mode, MCL turns off adequate components shwon in Figure 3.2. and their power consumption is shown in Figure 3.3.

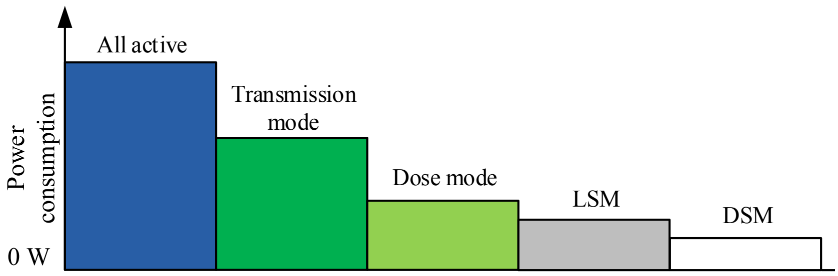


Figure 3.3: Energy Consumption Level of ONU

- **Active mode (4.69W)**: It is the state that no component is off. ONU transmits uplink traffic and receives downlink traffic together.

- **Transmission mode (2.99W)**: It is the state that RM(Receiver Module) is off. ONU transmits uplink traffic only.

- **Dose mode(Receive mode) (1.7W)**: It is the state that TM(Transmitter Module) is off. ONU receives downlink traffic only.

- **Light Sleep Mode (1.28W)**: It is the state that TM is off and DMUX in RM is off. ONU does not loose its clock. ONU can synchronize with OLT within 125μs from this mode.

- **Deep Sleep Mode (0.75W):** It is the state that RM and All components in TM are off; PD, TIA, LA, CM-CDR, counter, DMUX are off. ONU should recover clock with OLT before transmitting and receiving traffic. It takse 5.125ms.

3.2 Proposed Delay Aware Synchronous Bidirectional Transmission (DASBT) Operational Procedure

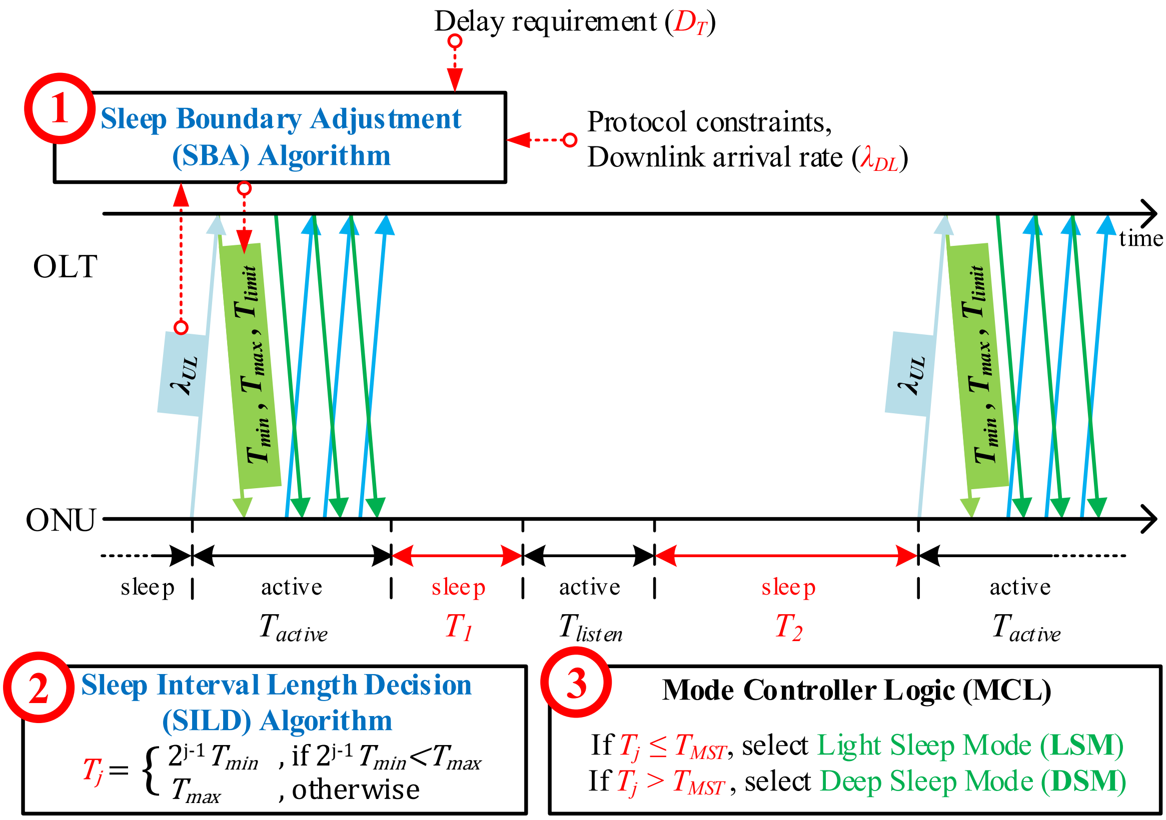


Figure 3.4: Overall message flow in DASBT

In Figure 3.4., essential procedure of DASBT is explained. First, OLT runs Sleep Boundary Adjustment (SBA) Algorithm when ONU wakes up from sleep mode. Based on Uplink rate, downlink rate, delay requirement, it calculate sleep boundary, T_{min} and T_{max}, and transmit it to ONU. Second, ONU

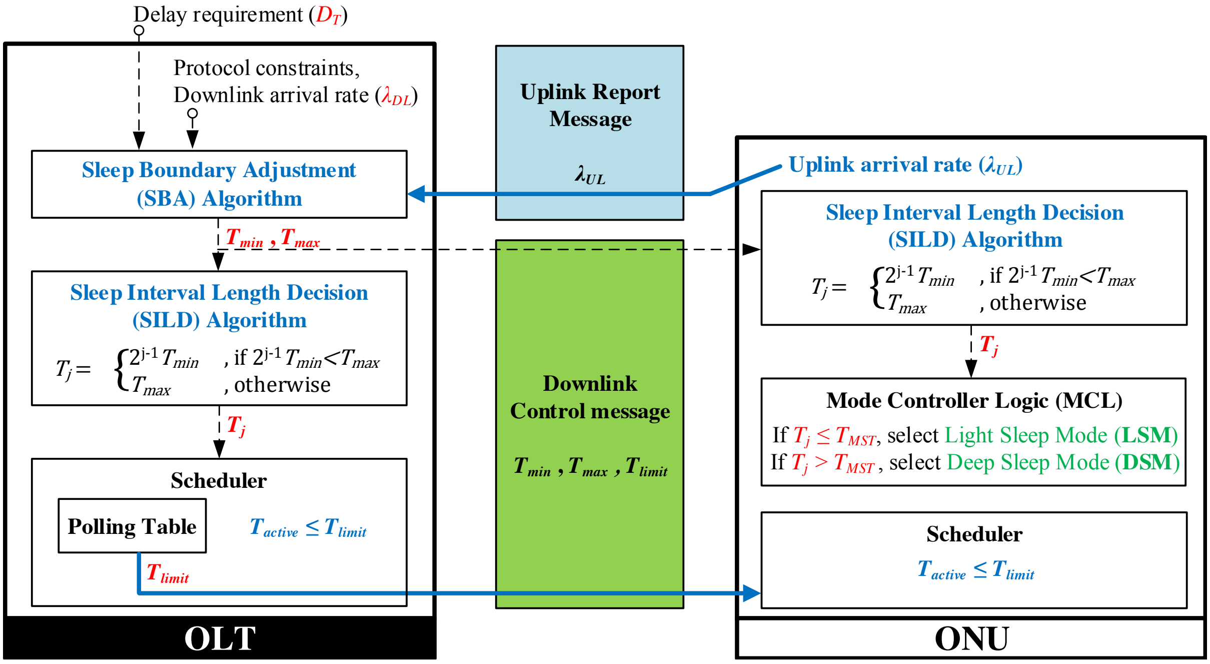


Figure 3.5: Overall functional diagram with message flow in DASBT

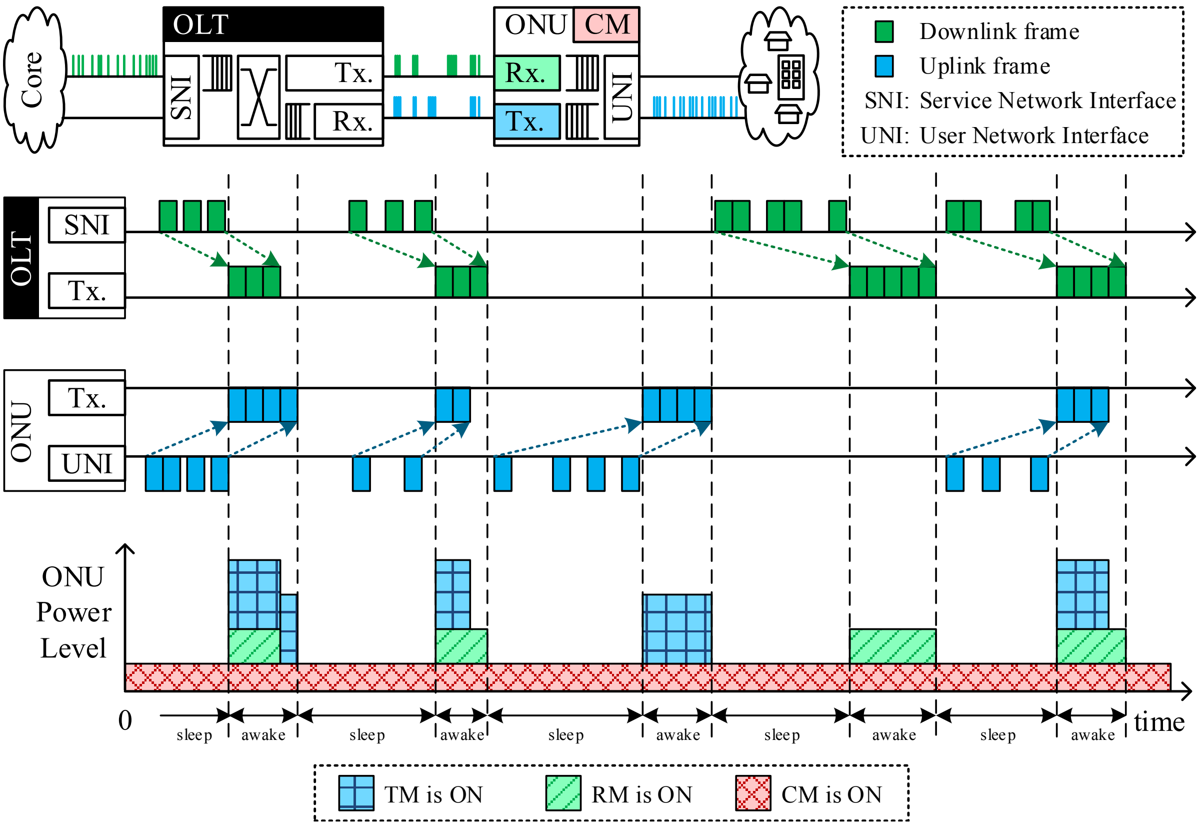


Figure 3.6: Overall transmission scheme in DASBT

runs Sleep Interval Length Decision (SILD) algorithm. No frame on the first sleep interval T_1 and the next sleep interval T_2 becomes twice of it. Third, Mode controller Logic (MCL) choose energy efficient sleep mode between DSM or LSM when new sleep interval is calculated.

Figure 3.5. maps those functionalities with ONU or OLT. Difference with ADAEE solution [6] is colored by deep blue; (i) Uplink arrival rate λ_{UL} is reported via Uplink Report Message and (ii) Sleep Boundary Adjustment (SBA) algorithm calculate sleep boundary (T_{min} and T_{max}) using both uplink arrival rate λ_{UL} and downlink arrival rate λ_{DL}. (iii) Also, the schduler manages ONUs sleep and informs closest wake-up time T_{limit} of other ONU to ONUs. Until T_{limit}, ONU can transmit uplink traffic and receive downlink traffic.

During sleep intervals, the ONU bufferes uplink traffic and the OLT bufferes downlink traffic on their queues. After the ends of those sleep intervals, the ONU and the OLT transmit their uplink and downlink queues at the same time. Figure 3.6. describes this synchronous bidirectional transmission scheme. Sparsely arrived uplink and downlink traffics are merged in bufferes in the ONU and the OLT and transmitted to them. When both uplink and downlink transmissions end, the ONU sleeps based on the schemes above. In the absense of uplink or downlink traffic, the ONU and the OLT also transmit their traffic and sleeps.

The OLT operates in the following procedure shwon in Figure 3.7. (i) The OLT looks up the polling table to check whether it is time to wake up ONU_i. (ii) The OLT checks other ONU's wake up schedule and set T_{limit} as the nearest wake-up time and BW_{limit} as the amount of bytes can be trasmitted until T_{limit}. The ONU can be in active mode to transmit and receive traffics until T_{limit}. (iii) In the case that the size of downlink buffer exceed BW_{limit}, BW_{limit} is allocated as uplink and downlink bandwidth for ONU_i. In the other case, the size of downlink buffer BW_i is allocated as downlink bandwidth for ONU_i. (iv) The OLT transmit Downlink Notification to ONU_i that contains T_{limit} and the sleep boundary (T_{min} and T_{max}) obtained by SBA algorithm that explained in the next section. (v) The OLT receives Uplink notification that contains $\lambda_U L$ and update the polling table. Then, the OLT transmits downlink

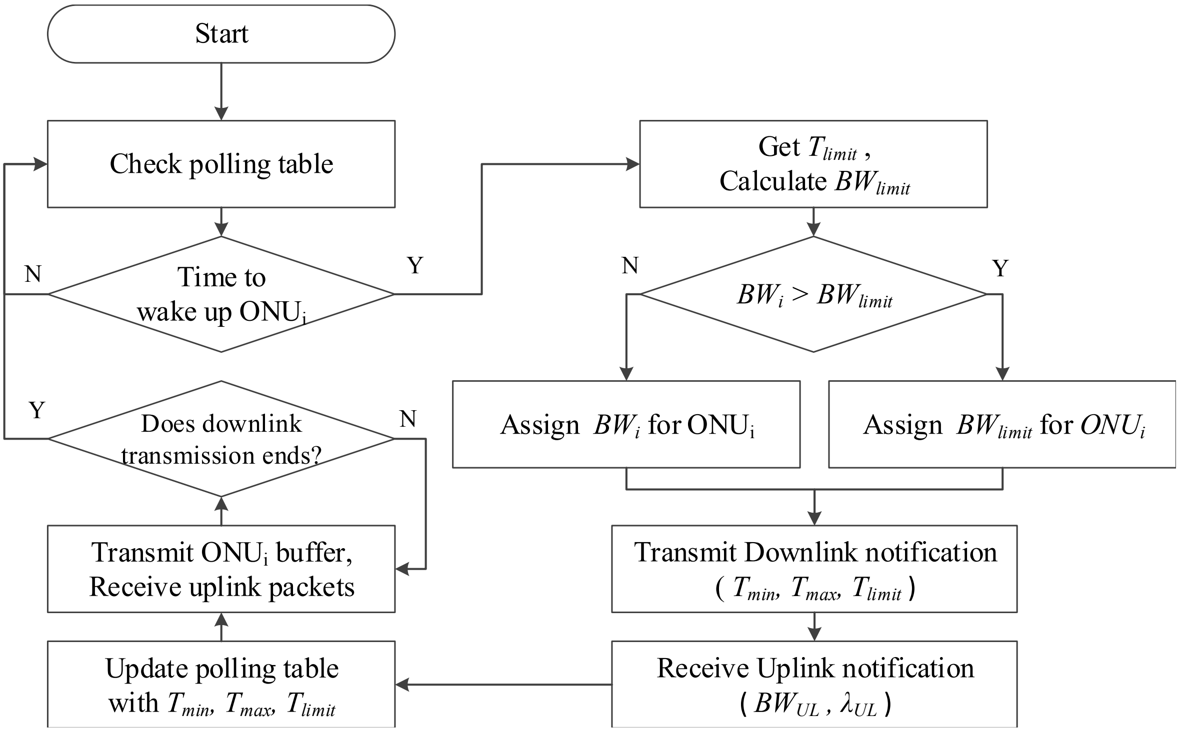


Figure 3.7: Flowchart of the algorithm designed in OLT

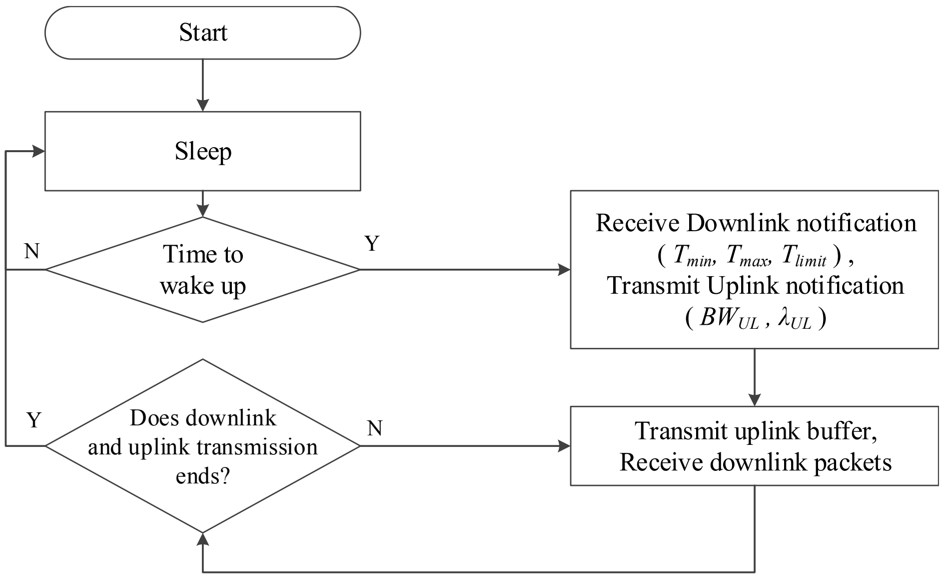


Figure 3.8: Flowchart of the algorithm designed in ONU

traffic and receives uplink traffic.

In Figure 3.8, operational procedure of an ONU is described. (i) The ONU wakes up and receives Downlink notification and transmits Uplink notification. (ii) The ONU transmits uplink traffic and receives downlink traffic until the time that is written in Downlink notification. After transmission ends, the ONU sleeps in adequate mode.

3.3 Proposed Sleep Boundary Adjustment (SBA) Algorithm

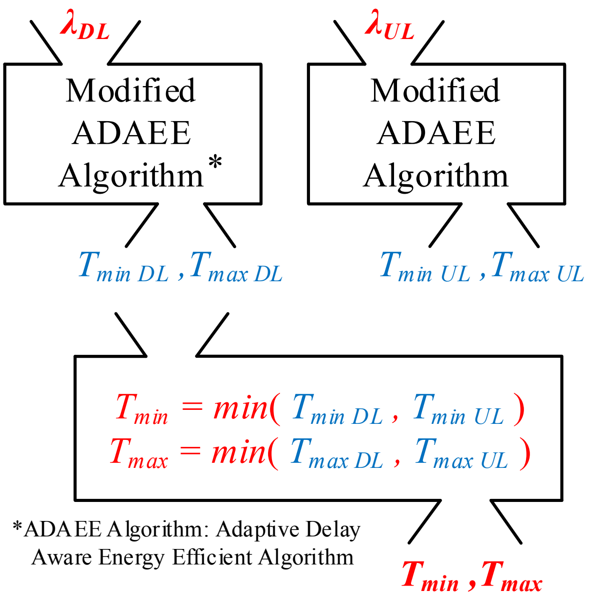


Figure 3.9: Overall proposed Sleep Boundary Adjustment (SBA) Algorithm

In this section, most essential algorithm is explained. In previous ADAEE solution, there are considerations on downlink traffic only [6]. In DASBT, as shown in Figure 3.9, two modified ADAEE algorithm runs to calculate sleep mode parameter for uplnik and downlink each. Then, those parameters are merged by selecting minimum values.

In ADAEE algorithm, estimated frame delay is used for maximizing sleep interval. However, they it not consider service time of each frames. In Sleep Boundary Adjustment (SBA) algorithm, frame delay estimation is modified to consider service time on each frames.

3.3.1 Formulation of Estimated Frame Delay

In this section, frame delay is estimated when sleep boundary (T_{min} , T_{max}) and traffic arrival rate λ are given and sleep intervals follows Sleep Interval Length Decision (SILD) with Equation 3.1.

$$T_j = \begin{cases} 2^{j-1}T_{\min} & , 2^{j-1}T_{\min} < T_{\max} \\ T_{\max} & , otherwise \end{cases} \tag{3.1}$$

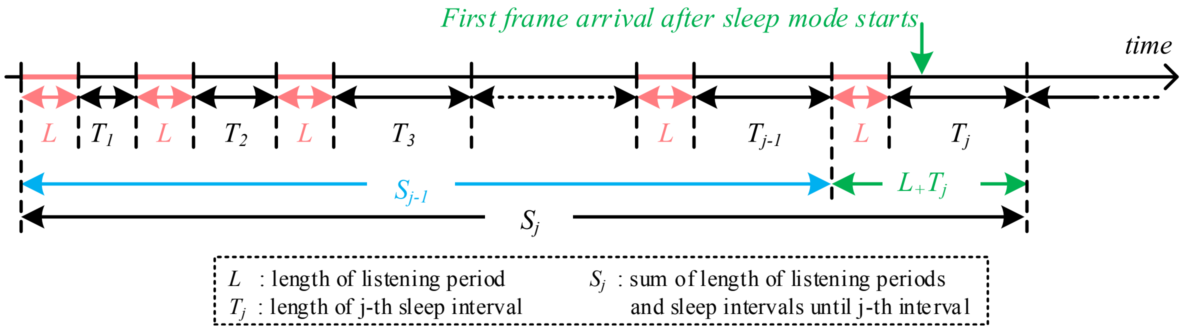


Figure 3.10: An example that the first frame arrives in j_{th} sleep period

First, probability, $P(j)$, that the first frame arrives in j_{th} sleep interval and its adjacent listening interval is derived.

The input traffic is assumed as Poisson process with arrival rate λ. Let L is the length of listening interval and T_j is the length of j_{th} sleep interval. And S_j, the total sleep length until j_{th} sleep interval, is defined as $S_j = \sum_{i=1}^{j} (L + T_i)$. Then, probability is:

$$P(j) = P(\text{ no frame in } S_{j-1})P(\text{ at least one frame in } (L + T_j)) \tag{3.2}$$

To calculate those probabilities, exponential distribution is used. Let T is frame interval. Then, T follows exponential distribution with arrival rate λ and its CDF is the following:

$$f(T; \lambda) = 1 - exp(-\lambda T) \tag{3.3}$$

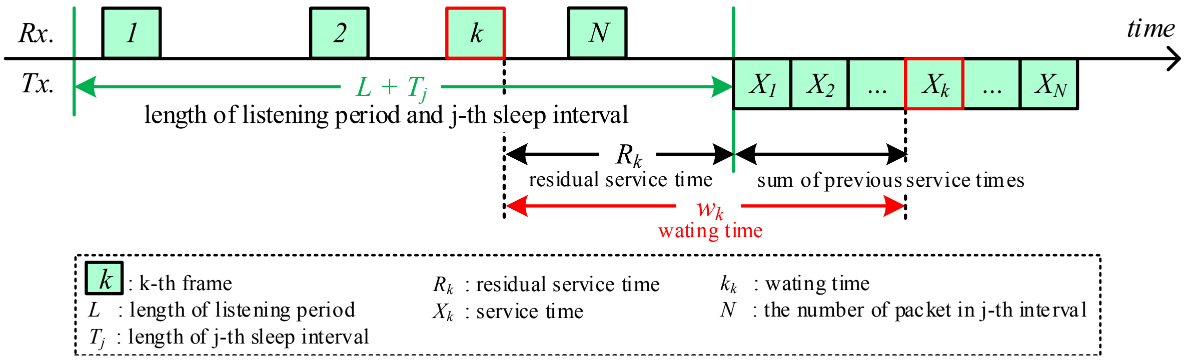


Figure 3.11: An example of residual analysis on j_{th} sleep interval and its adjacent listening interval

This means the probability that frame interval is below T. And, those probabilities can be calculated.

$$P(\text{ no frame in } T\ ) = P(\text{ frame interval exceed } T\ ) \tag{3.4}$$

$$= exp(-\lambda T) \tag{3.5}$$

$$P(\text{ at least one frame in } T\ ) = P(\text{ frame interval is below } T\ ) \tag{3.6}$$

$$= 1 - exp(-\lambda T) \tag{3.7}$$

Using above Equation 3.5 and 3.7,

$$P(j) = P(\text{ no frame in } S_{j-1}\ )P(\text{ at least one frame in } (L + T_j)\ ) \tag{3.8}$$

$$= exp(-\lambda S_{j-1})(1 - exp(-\lambda(L + T_j))) \tag{3.9}$$

Second, average waiting time W_j of frames received in listening interval and j_{th} sleep interval is derived. To derive average waiting time, residual analysis is used.

$$W_j = E\left[w_k\right] \tag{3.10}$$

$$= E\left[w_k + \sum_{i=1}^{k-1} X_i\right] \tag{3.11}$$

$$= E[R_k] + E\left[\sum_{i=1}^{k-1} X_i\right] \tag{3.12}$$

Due to Poisson Arrivals See Time Averages (PASTA) property, average residual service time becomes:

$$E[R_k] = \frac{L + T_j}{2} \tag{3.13}$$

Using iid (independent and identically distributed) property of the service times and conditioning by N (the number of frames in jth sleep interval), the sum of previous service times become:

$$\begin{aligned}
E\left[\sum_{i=1}^{k-1} X_i\right] &= E\left[\sum_{i=1}^{k-1} E[X]|N\right] && (3.14)\\
&= E[(k-1)\bar{X}|N] && (3.15)\\
&= E[k-1|N]\bar{X} && (3.16)\\
&= \frac{E[N]}{2}\bar{X} && (3.17)\\
&= \frac{\lambda(L+T_j)\bar{X}}{2} && (3.18)
\end{aligned}$$

Therefore, average waiting time in j_{th} sleep interval becomes:

$$\begin{aligned}
W_j &= E[w_k] && (3.19)\\
&= \frac{L+T_j}{2} + \frac{\lambda(L+T_j)\bar{X}}{2} && (3.20)\\
&= \frac{(1+\lambda\bar{X})(L+T_j)}{2} && (3.21)
\end{aligned}$$

Using Equation 3.9 and 3.21, average waiting time becomes:

$$E[W_j] = \sum_{j=1}^{\infty} W_j P(j) \tag{3.22}$$

$$= \sum_{j=1}^{\infty} \frac{(1+\lambda\bar{X})(T_{listen}+T_j)}{2} exp(-\lambda S_{j-1})\{1-exp(-\lambda T_j)\} \tag{3.23}$$

$$= \sum_{j=1}^{\infty} \frac{(1+\lambda\bar{X})(T_{listen}+T_j)}{2} exp\left(-\lambda\sum_{i=1}^{j-1}(T_{listen}+T_i)\right)\{1-exp(-\lambda(T_{listen}+T_j))\} \tag{3.24}$$

$$= \sum_{j=1}^{\infty} \frac{(1+\lambda\bar{X})(T_{listen}+T_j)}{2} \left\{exp\left(-\lambda\sum_{i=1}^{j-1}(T_{listen}+T_i)\right) - exp\left(-\lambda\sum_{i=1}^{j}(T_{listen}+T_i)\right)\right\} \tag{3.25}$$

3.4 Proposed Overall Algorithm

This section covers with overall algorithm that runs on the proposed DASBT OLT for calculating T_{min} and T_{max}. Algorithm 1 is Sleep Boundary Adjustment (SBA) and it is same as Figure 3.9. The OLT calculate T_{min} and T_{max} for every end of uplink and downlink transmission. Algorithm 2,3,4 are same as those of previous ADAEE solution [6]. In algorithm 5, Equation is changed to consider service time in estimated delay.

Algorithm 1: T_{min} / T_{max} calculation with DL / UL arrival rates

```
Data: λ_DL, λ_UL, λ_T, D_T
Result: T_min, T_max
begin
    while t_present − T_last DL sent,ONU−k ≥ SS  &&  t_present − T_last UL recv,ONU−k ≥ SS do
        [T_min DL, T_max DL] = Modified_ADAEE(λ_DL, λ_T, D_T)
        [T_min UL, T_max UL] = Modified_ADAEE(λ_UL, λ_T, D_T)
        if T_min DL > T_min UL then
            T_min = T_min UL
        else
            T_min = T_min DL
        if T_max DL > T_max UL then
            T_max = T_max UL
        else
            T_max = T_max DL
```

Algorithm 2: Modified_ADAEE Function: T_{min} / T_{max} measurement with an arrival rate

Data: $\lambda, \lambda_T, D_T, T_{min\,threshold}, T_{max\,threshold}$
Result: T_{min}, T_{max}
begin
  if $D_T > strict\,delay\,requirement$ **then**
    $T_{min} = T_{min\,threshold}$
    $T_{max} = getTmax(\lambda)$
  else
    if $\lambda > \lambda_T$ **then**
      $T_{min} = getTmin(\lambda)$
      $T_{max} = T_{max\,threshold}$
    else
      $T_{min} = T_{min\,threshold}$
      $T_{max} = getTmax(\lambda)$

Algorithm 3: getTmin Function: Algorithm for finding maximum T_{min}

Data: $\lambda, T_{max\,threshold}, \{T_{min\,i}\}$
Result: $T_{min}/2$
begin
  while $D_T \geq D$ **do**
    $D = f(\lambda, T_{min\,i}, T_{max\,threshold})$
    $i = i + 1$
  return $T_{min}/2$

Algorithm 4: getTmax Function: Algorithm for finding maximum T_{max}

Data: $\lambda, T_{min\,threshold}, \{T_{max\,i}\}$
Result: T_{max}
begin
  while $D_T \geq D$ **do**
    $D = f(\lambda, T_{min\,threshold}, T_{max\,i})$
    $i = i + 1$
  return T_{max}

Algorithm 5: f Function: Algorithm for estimated frame delay

Data: $\lambda, T_{min}, T_{max}$
Result: $EstimatedDelay$
begin
  $EstimatedDelay$

$$= \sum_{j=1}^{\infty} \frac{(1+\lambda\bar{X})(T_{listen}+T_j)}{2} \left\{ exp\left(-\lambda \sum_{i=1}^{j-1} (T_{listen}+T_i)\right) - exp\left(-\lambda \sum_{i=1}^{j} (T_{listen}+T_i)\right) \right\}$$

  (Equation 3.25.)
  where: $T_k = min(2^{k-1}T_{min}, T_{max})$
  return $EstimatedDelay$

Chapter 4. Performance Evaluation

4.1 Performance Criteria and Evaluation Assumptions

In this chapter, performance of propsed DASBT scheme is presented. Based on real network traces, performance of DASBT solution is measured in the aspect of frame delay and energy consumption compared with always on scheme with various delay requirements; $D_T = 10ms, 40ms, 80ms$. Then, DASBT is compared with previous three schemes; ADAEE, FTS-LOOA, FTS-SOOA [6,14]. FTS stands for Fixed T_{min} and T_{max} Solution. LOOA for Long Overhead ONU Architecture, that considers Deep Sleep Mode only. SOOA for Short Overhead ONU Architecturem that considers Light Sleep Mode only.

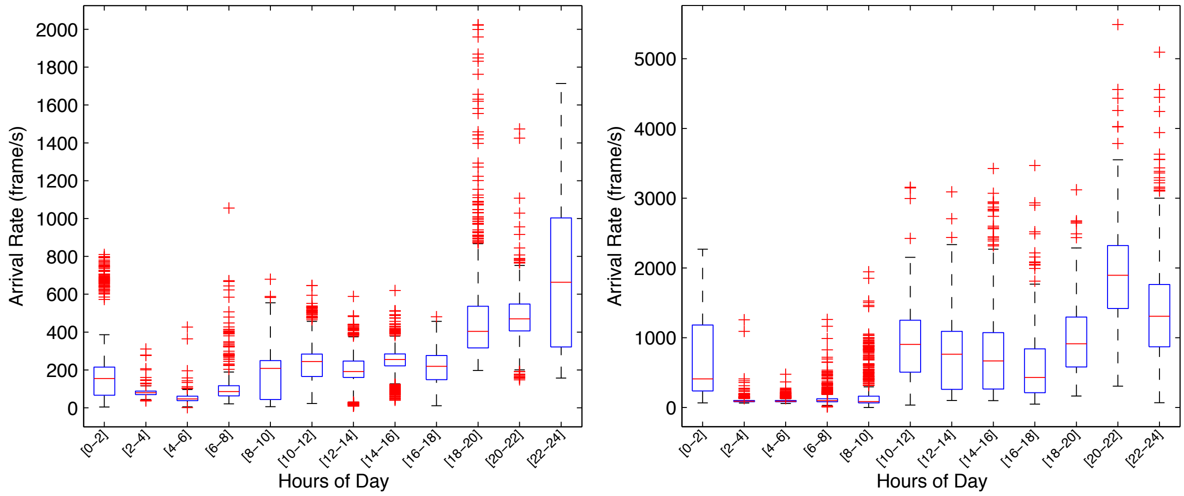
To evaluate DASBT, the real network traffic trace during 24 hours is used as shown in Figure 4.1. This one is also used in the previous work [6]. That trace captures network traffic of 16 users within 24 hours by network monitoring tool (Microsoft Network Monitor 3.4) [16]. In capturing this trace, numerous kinds of applications was running. In the traffic trace in Figure 4.1, traffic rates are low at dawn, between 2 to 6, and traffic rates are high after dinner around 18 to 24.

It is also assumed that ONU and OLT has large buffer. Simulation was performed by C++ discrete evnet simulator. Table 4.1 represents parameters used in the simulation.

4.2 Simulation Results

Figure 4.2 depict CDFs of the frame transfer delay and the energy savings with respect to various delay requirements.

In delay aspect, downlink frame delay of DASBT solution is nearly similar to that of ADAEE solution. As downlink frame arrival rates is higher than uplink frame arrival rates in input traffic traces in Figure 4.1, T_{min} and T_{max} follows $T_{min\,DL}$ and $T_{max\,DL}$ in SBA algorithm.



(a) Uplink traffic traces

(b) Downlink traffic trace

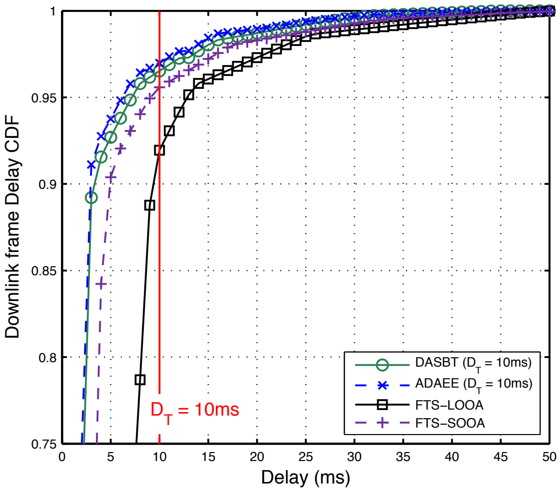
Figure 4.1: Traffic traces for performance evaluation

In energy aspect, DASBT solution is most energy efficient solution. DASBT reduces energy consumption up to maximum 15% compared to ADAEE soultion.

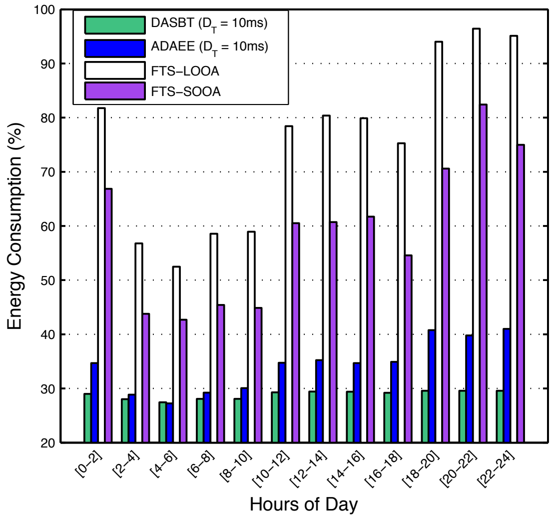
In the small delay requirement case in Figure 4.2a, 98% of frames satisfy delay requirement in DASBT and 92.5% in FTS-LOOA. Deep sleep takes long transition time and it is not adequate for small delay requirement.

In low arrival case (4 to 6), energy consumption of DASBT and ADAEE are similar as ONUs does not wake up frequently in low uplink rates. In high arrival case in (18 to 20), difference of energy consumptions in DASBT and ADAEE is large as ONUs with ADAEE wake up frequently in high uplink rates.

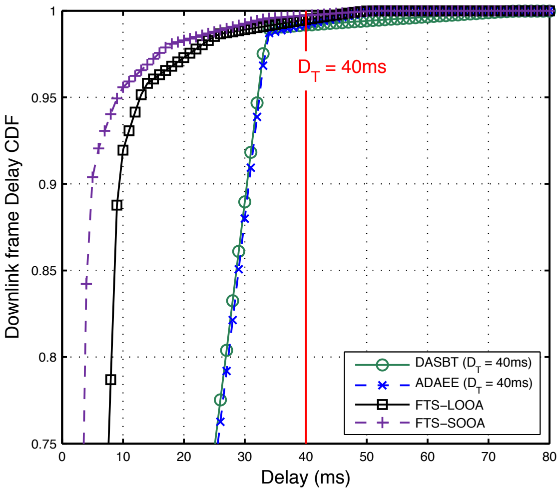
Figure 4.3 shows that DASBT adjusts sleep intervals and gets similar delay distributions in different delay requirements. It can be found that delay cdf in low utilized time is slightly lower than cdf in high utilized time. The probability of sleep with long sleep interval in low utilized time is greater than that in high utilized time. Frames arrived in long sleep interval usually get experienced longer frame delay.



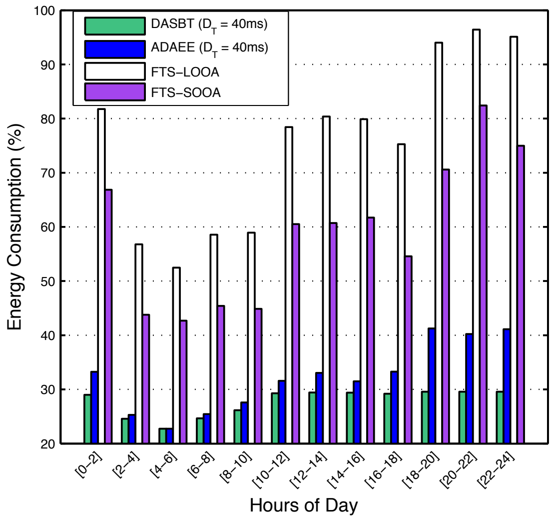
(a) Delay CDFs ($D_T = 10ms$)



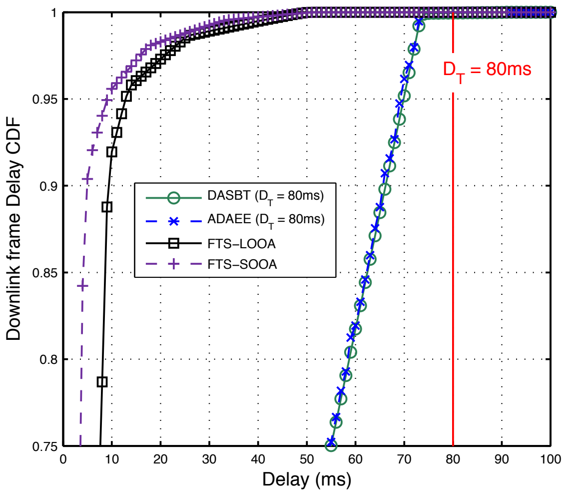
(b) Energy consumptions ($D_T = 10ms$)



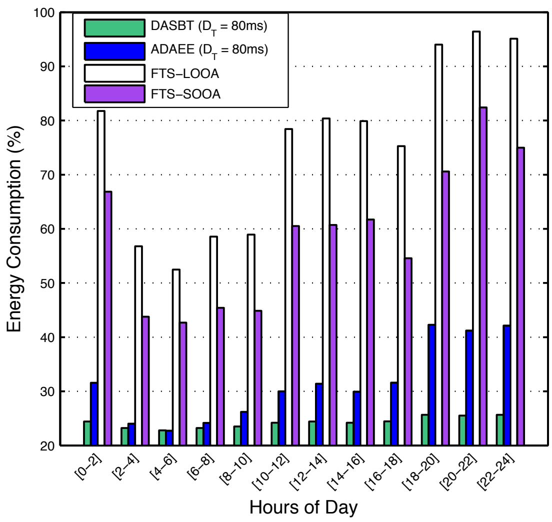
(c) Delay CDFs ($D_T = 40ms$)



(d) Energy consumptions ($D_T = 40ms$)



(e) Delay CDFs ($D_T = 80ms$)

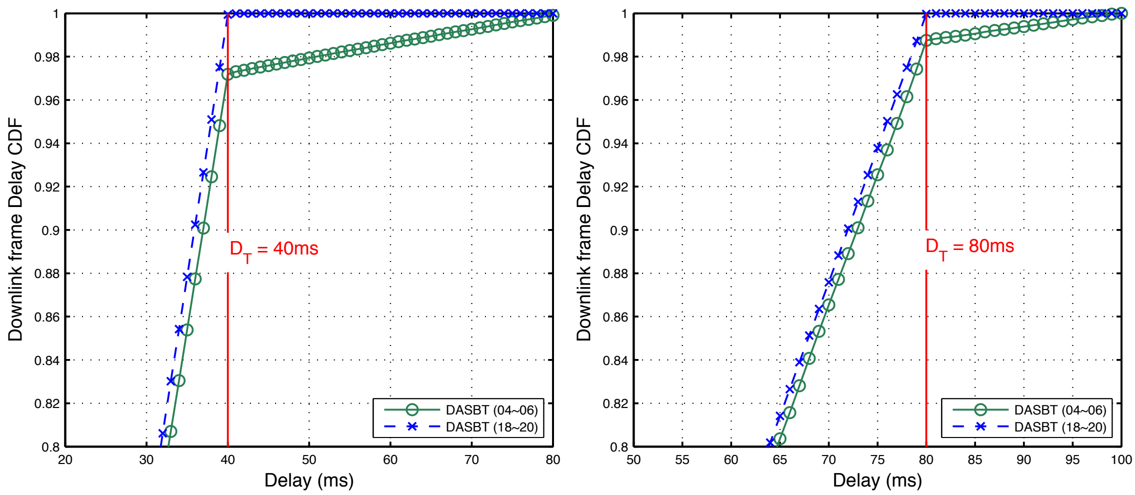


(f) Energy consumptions ($D_T = 80ms$)

Figure 4.2: Delay CDF and energy saving with various delay requirement

Table 4.1: Simulation parameters for performance evaluation

Description	**Values**
Power consumption in active mode	4.69 W [17].
Power consumption in doze mode	1.7 W [17].
Power consumption in Deep Sleep Mode (DSM)	0.75 W [11].
Power consumption in Light Sleep Mode (LSM)	1.28 W [11].
Transition time in Light Sleep Mode	125 μs [11].
Transition time in Deep Sleep Mode	5.125 ms [11].
Value of T_{min} in FTS-SOOA	1 ms
Value of T_{min} in FTS-LOOA	6 ms
Value of T_{max} in FTS-SOOA	50 ms
Value of T_{max} in FTS-LOOA	50 ms
$T_{threshold}$	16 ms
λ_T	0.05 $frames/ms$
$T_{max\,Threshold}$ (for proposed DASBT)	100 ms
$T_{min\,Threshold}$ (for proposed DASBT)	1 ms
Downlink and uplink data rate	1 $Gbps$
Transmission delay between an ONU and the OLT	0.2 ms [13]
Sampling Ttime Window (STW)	10 s



(a) Delay CDFs on 5˜6 and 19˜20 ($D_T = 40ms$) (b) Delay CDFs on 5˜6 and 19˜20 ($D_T = 80ms$)

Figure 4.3: Adaptively adjusted frame delay in low and high arrival rates via DASBT

Chapter 5. Conclusions and Future Works

Reducing energy in access networks becomes important issues due to fast deployment of internet service all around the world. However, energy efficient proposals in TDM-PON can be considered useful when they can save energy, also guarantee QoS performance together. Proposed DASBT solution shows that energy consumption of ONUs can be reduced by considering both uplink and downlink traffic status within constrait delay requirement. This proposal is evaluated under real traffic traces and compared with previous proposals. The obtained results demonstrate that the proposed approach is the most energy efficient solution and it guarantees QoS performance in terms of delay. In future study, multicast and broadcast services also should be considered to make energy efficient network base on TDM-PON environment.

Summary

Delay Aware Synchronous Bidirectional Transmission Scheme for Energy-efficient TDM-PON

인터넷의 빠른 보급으로 인해 ICT 분야의 에너지 절감이 이슈화 되었다. 엑세스 네트워크의 에너지 소비는 전체 인터넷 에너지 소비의 70%에 달하는 큰 부분을 차지한다. 하지만, 액세스 네트워크의 많은 부분을 차지하는 TDM-PON 장비들은, 하루 중 대부분의 시간 동안 낮은 utilization을 보인다. 때문에 액세스 네트워크에서 에너지를 줄이려는 많은 연구들이 진행되었다. 대부분의 에너지 절감형 TDM-PON 연구들은 다운링크 트래픽만을 고려하였다. ONU가 사용자 네트워크로부터 업링크 트래픽을 수신하면, ONU의 슬립은 중단되고 슬립모드에서 깨어나 업링크 트래픽을 전송한다. 이로 인한 잦은 상태 전환은 추가적인 에너지 소비를 유발한다. 또한, 다운링크와 업링크가 별개로 관리되기 때문에, 동시에 관리되었을 때와 대비하여 추가적인 컨트롤 메시지 오버헤드가 발생한다. 이러한 문제를 해결하기 위해 업링크와 다운링크 전송을 주기적으로 동기화하는 방식이 몇몇 연구를 통해 제안되다. 하지만 이들 연구는 트래픽 요구사항을 고려하지 않아 여전히 에너지를 절감할 수 있는 부분이 있다. 때문에 이 논문에서는 TDM-PON 환경에서 ONU의 에너지를 절감함과 동시에 만족할만한 트래픽 성능 제공하는 지연을 인지한 양방향 동기 전송방식을 제안하였다. 세부적으로는 업링크와 다운링크 트래픽 상태, 그리고 지연 요구사항을 모두 고려한 새로운 슬립 구간 결정 알고리즘을 제안하였다. 또한 업링크와 다운링크를 동시에 전송하여 에너지를 절감하도록 하였다. 시뮬레이션의 결과, 주어진 지연 요구사항을 반족하면서 제안한 방식이 기존 방식에 비해 최대 15%가량 성능이 향상되었음을 확인하였다.

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학 회 활 동

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연 구 업 적

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