Delay-Aware Dynamic Wavelength Bandwidth Allocation in Time- and Wavelength-Division-Multiplexed Passive Optical Network

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Abstract: Most research works related to dynamic wavelength bandwidth allocation in a time- and wavelength-division–multiplexed passive optical network are based on bin packing algorithm and present many advantages in terms of bandwidth utilization and energy efficiency. However, delay performance can be significantly degraded by frequent wavelength changes. In this paper, we propose a delay-aware dynamic wavelength bandwidth allocation algorithm. First, we theoretically analyze queuing delay corresponding to the tuning time, decision cycle, and the number of optical network units. And then, we show that the queuing delay is decreased by setting the limit value of the number of optical network units in a wavelength channel. In addition, we derive the threshold ratio of the tuning time to the decision cycle as 0.004.

1 INTRODUCTION

As user bandwidth requirements are escalating to support multimedia streaming services such as high-definition television (HD-TV), 3D TV, and mobile services, the bandwidth capacity of optical access networks needs to be expanded by upgrading legacy PONs to the next-generation passive optical network 2 (NG-PON2). Among various types of system architectures for NG-PON2, time- and wavelength-division-multiplexed passive optical networks (TWDM-PON) are known as the best technology in terms of power budget, key component maturity, and especially system coexistence with legacy PONs. Full Service Access Network (FSAN) has studied TWDM-PONs since 2010, and this technology has been specified as an ITU-T G.989 recommendation (Yuanqui and Frank, 2013).

1.1 TWDM-PON

TWDM-PONs increase upstream and downstream bandwidth capacity by stacking four or eight (optional) XG-PONs with wavelength division multiplexing (WDM) technology. An optical line terminal (OLT) consists of four or eight fixed optical transceivers and can manage network resources more flexibly than legacy PONs owing to the tunability of the optical network unit (ONU), which is composed of a tunable transmitter and receiver. Figure 1 shows the block diagram of a general TWDM-PON architecture (ITU-T Study Group 15, 2013, Yuanqiu, Xiaoping, Frank, Xuejin, Guikai, Yinbo and Yiran, 2013).

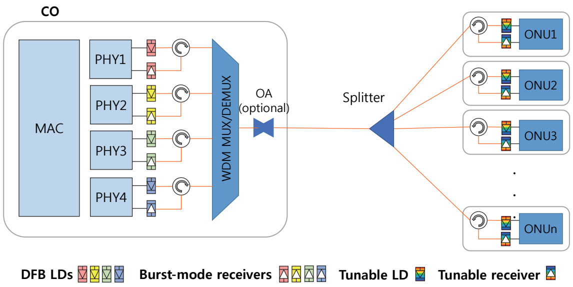

Figure 1: The general architecture of a TWDM-PON (CO: Central Office, OA: Optical amplification for long reach or high-split-application system).

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1.2 Dynamic Wavelength Bandwidth Allocation (DWBA)

The general requirements of TWDM-PONs are specified in the ITU-T G.989.1 recommendation. However, there have not been specifications related to system management and bandwidth allocation mechanisms in the transmission convergence (TC) layer yet. Ideal methods of dynamic wavelength and time slot allocation at the same time, well known as DWBA, have been studied by many researchers. As a result of extensive research, many algorithms have been introduced to research societies related to optical access networks. Most algorithms originate from the conventional bin packing (BP) algorithm, whose objective is to achieve an efficient resource distribution with the minimum number of channels.

There are several types of algorithms, including first fit (FF), first fit decreasing (FFD), next fit (NF), and best fit (BF). Among these algorithms, FFD is known as the most optimal algorithm in terms of the minimum number of wavelength channels utilized. According to the principle of FFD, OLT collects reported information, including ONU bandwidth requirements, and rearranges it in descending order. Then, the OLT checks the channel capacity from the first to last wavelength channels and finds an available channel to support the ONU bandwidth requirement. After finding a supportable wavelength channel, the OLT makes the ONU change a previously allocated wavelength to a new wavelength and allocates as many time slots as the ONU requires. Figure 2 shows the operating principle of FFD with a flow chart.

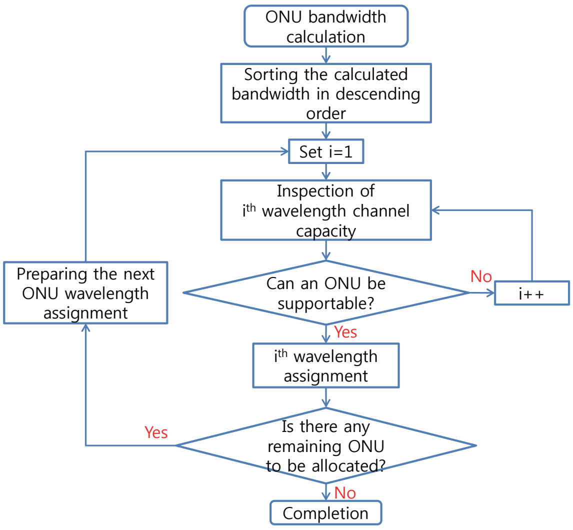

Figure 2: Flow chart of FFD.

Although DWBA has many advantages, including flexibility of bandwidth allocation, load balancing, and the possibility of saving energy, there are also limitations caused by a long wavelength tuning time. Several milliseconds are required for the ONU to change its wavelength (Jens and Edmond, 2006). Because the wavelength tuning time is long compared to the service interval (typically 125 µs in an XG-PON), at least approximately 80 or more frames should be accumulated in the buffer. Thus, the degradation of the delay performance can be caused by a large number of accumulated frames. Although the wavelength tuning time of an optical tunable component cannot be negligible for this reason, there have been few studies on DWBA with consideration of this factor. For the realization of a delay-aware DWBA algorithm, we should analyze the relation between several parameters related to wavelength tuning and queuing delay.

In this paper, we find important parameters that affect delay performance degradation and reveal the theoretical relation between the parameters and delay. We also propose a DWBA algorithm to reduce delay. Then, we evaluate the system performance in terms of the queuing delay through simulation and compare the results with conventional DWBA algorithms.

2 APPROXIMATION ANALYSIS

Before analyzing the relation between wavelength tuning and delay, we assume that OLT should check ONU buffer occupancy and make a decision whether ONU changes its wavelength or not every period T (wavelength tuning decision cycle). All decision points are synchronized simultaneously. ONU changes a wavelength channel during tuning time τ as soon as it receives a wavelength tuning message from the OLT. After ONU wavelength tuning is finished, ONU notifies OLT of its tuning completion by sending wavelength tuning completion message. And then, OLT allocates the time bandwidth to ONU

We assume that ONU has a stochastic tendency p of wavelength tuning. If there is no limitation of wavelength change, ONU changes its wavelength frequently. As a result, a stochastic tendency of ONU is increased and approximately same as 1. However, if OLT allocates wavelength channel with some restrictions that prevent ONU from changing wavelength channel time to time, p is decreased. In the case that ONU's wavelength channel is fixed like WDM PON, p is equal to 0.

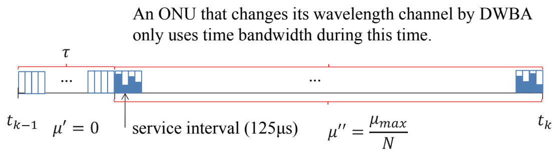

Figure 3: Utilization of time bandwidth during decision cycle when ONU changes its wavelength.

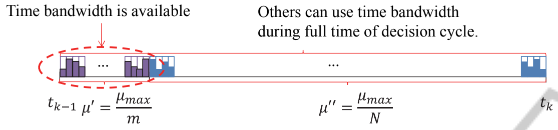

Figure 4: Utilization of time when ONU maintains its wavelength.

To approximately analyze the relation, we divide the situation into two cases, as shown in the above figures. The first is the case that the ONU changes its wavelength. The second is the case that the ONU does not participate in wavelength tuning. When the ONU participates in wavelength tuning, it cannot transmit upstream signals during tuning time *τ*. After completing wavelength tuning, adequate time slots with the consideration of fairness among N ONUs belonging to the same wavelength channel group are assigned to the ONU. On the other hand, ONUs that do not participate in wavelength tuning can transmit an upstream signal during not only *τ* but also the remaining time *T* - *τ*. A total of *m* nontuning ONUs belonging to the same wavelength group share the time bandwidth during *τ*, and N ONUs, including tuning ONUs, share the bandwidth during *T* - *τ* evenly.

Generally speaking, μ is occasionally changed by the network situation in a real PON system. However, we consider only the effective service rate (μ) during T to simplify the calculation. The effective service rate can be calculated by the following equations:

$$\mu_{tuning} = \frac{\mu_{max}}{N} \times \frac{(T-\tau)}{T} \qquad (1)$$

$$\mu_{not\_tuning} = \frac{\mu_{max}}{m} \times \frac{\tau}{T} + \frac{\mu_{max}}{N} \times \frac{T-\tau}{T} \qquad (2)$$

μ_{tuning} is the effective service rate of ONUs needed to participate in wavelength tuning, and μ_{not_tuning} is the effective service rate of other ONUs. μ_{max} is the maximum service rate of a wavelength channel, typically, 2.5 Gbps.

On the basis of an M/M/1 queuing model (Henry and John, 1994.), the number of accumulated packets in the ONU buffer is derived by the following equation:

$$B = \frac{\lambda}{\mu - \lambda} \qquad (3)$$

For our system, B should be modified to a new equation that reflects the wavelength tuning condition with stochastic tuning tendency *p*. Therefore, the expected accumulated number of packets β is derived as follows:

$$\begin{aligned}\beta &= E[B] \\ &= B_{tuning} * p + B_{not_{tuning}} * (1-p) \\ &= \frac{\lambda p}{\mu_{tuning} - \lambda} + \frac{\lambda(1-p)}{\mu_{not\_tuning} - \lambda}\end{aligned} \qquad (4)$$

The queuing delay (*D*) is derived by Little's Theorem and converted into a simple form by inserting equations (1) and (2) into equation (4).

$$D = \frac{\beta}{\lambda} = \frac{p}{\gamma_1 \mu_{max} - \lambda} + \frac{(1-p)}{\gamma_2 \mu_{max} - \lambda} \qquad (5)$$

$$\gamma_1 = \frac{1-\delta}{N}, \quad \gamma_2 = \frac{\delta}{m} + \frac{1-\delta}{N} \qquad (6)$$

$$\delta = \tau / T \qquad (7)$$

Because the queuing delay is improved as δ and N are decrease, we have to set the limit value of the maximum number of ONUs in the same wavelength group (N_{th}) for efficient DWBA realization.

3 PROPOSED ALGORITHM

In the previous section, we explained why the limit (N_{th}) is required for wavelength assignment and bandwidth allocation. We propose the modified FFD algorithm reflecting N_{th} under the following assumptions: (1) all ONU bandwidth requirements are bounded between R_{min} and R_{max}, and (2) the sum of every bandwidth requirement is lower than the sum of the capacity of all wavelength channels. Briefly speaking, the system can always support all bandwidth requirements.

To satisfy the assumption, the value of R_{max} is

$$R_{max} = \frac{C}{I/J} \qquad (8)$$

C is the channel capacity of a single wavelength channel, *I* is the total number of ONUs, and *J* is the number of wavelength channels in the system.

R_{min} can be changed by a system operator corresponding to the target service rate in the system because it depends on the decision of the system operator.

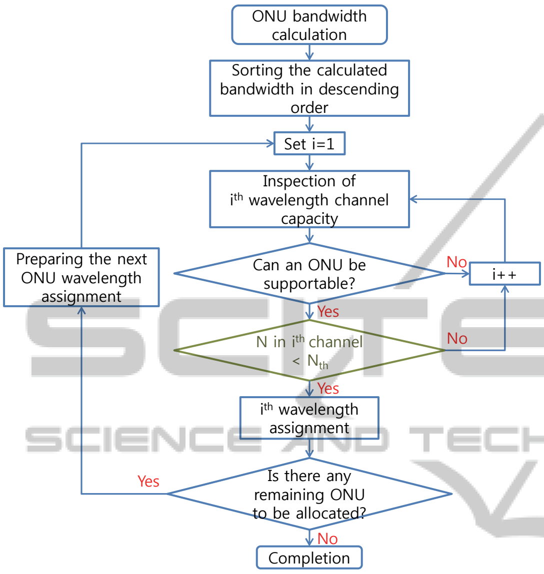

Figure 5: Flow chart of the proposed algorithm.

As shown in Figure 5, the basic principle of the algorithm is similar to FFD except for checking the wavelength availability condition. Although the ONU bandwidth requirement is lower than the capacity of a wavelength channel, the ONU cannot be assigned to the wavelength channel if the number of accommodated ONUs in the channel is equal to N_{th} because we should avoid a biased wavelength assignment that causes severe degradation of the delay performance.

4 SIMULATION RESULTS

We evaluate the performance of the proposed algorithm by conducting simulations. We only consider the case in which 32 ONUs exist in a TWDM-PON system that utilizes eight wavelength channels (2.5 Gbps for upstream line rate, 10 Gbps for downstream line rate per single wavelength channel). The wavelength tuning time is 10 ms, and the decision cycle of wavelength assignment is fixed to 1 s. The optical link distance between the OLT and ONU is 20 km (The distance value is a general requirement of TWDM-PON). The ONU generates frames randomly, and the load is followed by a Poisson distribution. We control the mean offered load of the ONU from 100 Mbps to 600 Mbps when we evaluate the queuing delay of the system. Because the ONU queuing delay values differ from each other as a result of the randomness of the simulation, we acquire the mean value of the delay to show a tendency and compare values that result from FFD and the proposed algorithm.

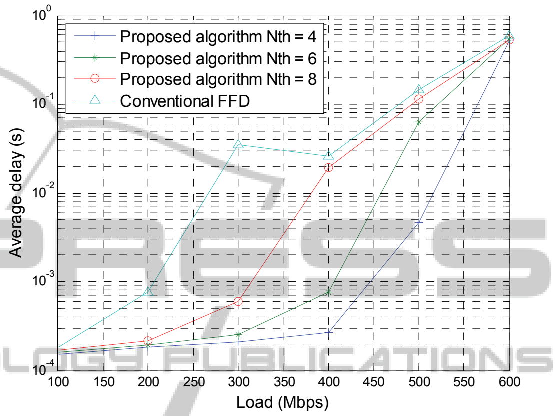

Figure 6: Performance comparison of mean queuing delay correspoding to offered loads.

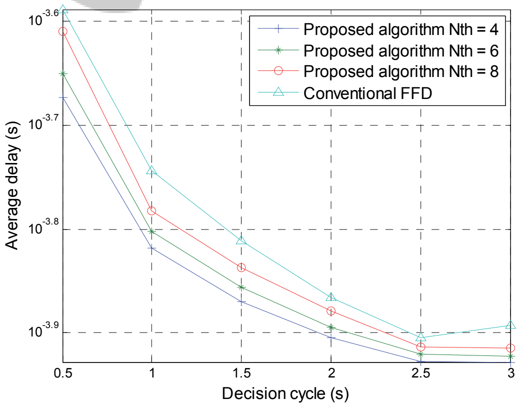

Figure 7: Average queuing delay corresponding to *T*.

As shown in Figure 6, the delay performance grows worse as N_{th} increases. Because of the randomness of traffic generation, many ONUs can be assigned to the same wavelength channel if there is no limitation on N_{th}. Consequently, the OLT cannot allocate time slots when many time slots are simultaneously required. On the other hand, the proposed algorithms exhibit significantly better results than the conventional algorithm. Secondly, we also evaluate the average queuing delay corresponding to the decision cycle (*T*) to study the effect of *T*. The result is plotted in Figure 7 under the assumption that the mean offered load of the ONU is equal to 96 Mbps. As shown in Figure 7, there exists trade-off relation between the decision cycle time and delay. To improve delay performance, long decision cycle time should be set.

When the offered load is 400 Mbps, there is a dip in the graph of conventional FFD because more wavelength channels are allocated compared to the case of the 300-Mbps load. That is because the long and fixed decision cycle in simulation framework prevents OLT from reacting to network traffic condition instantly. When traffic condition is extremely changed compared to the beginning of wavelength decision, channel under-utilization or overflow problem can happen in the system which uses conventional FFD. In this case, when the load is 300 Mbps, four wavelength channels are required. However, six wavelength channels are required when the load is 400 Mbps. This difference of the number of wavelength channels during fixed cycle time makes a peak at the point of 300-Mbps load.

As explained in section 2, δ decreases as the decision cycle duration increases. As a result, the queuing delay is inversely proportional to the decision cycle, which means that many packets that accumulate during the wavelength tuning time cannot be completely transmitted within a shorter decision cycle. Therefore, it is important to set a proper decision cycle length to compensate for the defect caused by wavelength tuning. In this simulation with the assumption mentioned earlier, the saturation value of T is 2.5 s ($\delta = 0.004$).

5 CONCLUSIONS

We proposed a DWBA algorithm with a limitation on the number of ONU assignments to prevent the queuing delay from increasing. By theoretical simulations, we reveal the relation between the number of ONUs in a wavelength channel and the queuing delay and ensure that N_{th} is an important parameter affecting the delay performance through the simulation. In addition, we found that the optimized value of δ should be lower than 0.004 for efficient DWBA in TWDM-PON.

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