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Pipelined Architecture of Dynamic Bandwidth Allocation for Energy Efficiency in XG-PON

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Abstract

This paper proposes a pipelined architecture for a dynamic bandwidth allocation (DBA) in 10-gigabit-capable passive optical networks (XG-PONs). In the proposed architecture, the DBA operation is performed in multiple stages for high energy efficiency. Also, the proposed architecture forwards requests to next stages to obtain high performance. Using simulations, we evaluate performance of the proposed architecture.

Keywords: Pipeline, DBA, XG-PON, Energy Efficiency

1 Introduction

A 10-gigabit-capable passive optical network (XG-PON) is an emerging solution for a recent access network since it supports 10 and 2.5 Gbps in the upstream and downstream directions, respectively. An XG-PON consists of a single optical line termination (OLT) and a number of optical network units (ONUs). The OLT receives requests from ONUs and performs dynamic bandwidth allocation (DBA) to allocate non-overlapping transmission slots to ONUs. An XG-PON is a synchronous system that every operation is synchronized with a frame duration (FD) which is fixed to 125 μs [1]. The DBA operation must be completed within an FD.

An energy consumption of an access network is 80% of the energy consumed in the Internet [2]. To save energy of XG-PONs, an ONU with a sleep mode was proposed in [3]. The sleep mode means that an idle ONU sleeps until the ONU receives sufficient amount of packets. Also, a DBA algorithm was introduced that exploits the sleep mode in [3]. However, the power consumption of an OLT was not considered in [3]. When the number of ONUs is large, the operation speed of an OLT must be high to complete the DBA operation within an FD. It is well known that the power consumption of a digital circuit is proportional to the operation speed [4]. To save power of the OLT, the operation speed must be lowered.

In this paper, we propose two pipelined DBA schemes to save power of XG-PONs. To the best of our knowledge, a pipelined DBA has never been studied in XG-PONs. The first scheme is a basic pipelined DBA (BPD) which completes the DBA in four FDs. The BPD has a drawback that some of requests are not immediately used. The second scheme is a pipelined DBA with forwarding (PDF) that overcomes the drawback of the BPD. Using simulations, we evaluate the mean delays of the BPD and the PDF and show performance of the PDF is better than that of the BPD.

2 Pipelined DBA

An XG-PON system consists of a single OLT and N ONUs. To support QoS, three service classes are used in the system. The service class is known as a T-CONT type in XG-PON technology [1]. Each ONU has three queues for T-CONT types 2, 3 and 4, respectively. A packet arrived from a user side to an ONU is saved to a queue based on its T-CONT type. Since a static bandwidth allocation is used for the T-CONT type 1, we do not consider the T-CONT type 1 in this paper. Each queue has a unique identifier called an Allocation Identifier (AllocID). Every operation of the XG-PON system is synchronized with an FD which is fixed to 125 μs [1].

The OLT dynamically allocates a dynamic bandwidth report upstream (DBRu) field to a queue. Only when a queue receives the DBRu field, the queue reports its total queue length to the OLT using the DBRu field [1]. The OLT gathers requests from ONUs and then updates the request status for the upcoming DBA operations. In each FD, the OLT performs the DBA operation to produces grant results for all queues based on the saved requests. The DBA operation is performed in the order of T-CONT type priorities. During the DBA operation, the OLT allocates the DBRu field to each queue. Then the OLT makes a bandwidth map (BWmap) by calculating the transmission start time of each queue based on the grant results and the DBRu field assignments [1]. Then the OLT notifies the BMmap to each queue.

To complete the DBA, the required operations of the OLT in each FD are (a) the update of request status for each queue, (b) the grant allocations in the order of T-CONT types 2, 3 and 4, (c) the assignment of a DBRu field for each queue, (d) the BWmap generation. If the total number of ONUs is large then the operation speed of the OLT must be high to complete the DBA within a single FD. The maximum number of ONUs in an XG-PON system is 1023 [1]. In addition, the maximum number of queues in an XG-PON system is 15,360 [1]. One possible solution for the DBA of the large system is a pipelined DBA whose operations are completed in multiple FDs.

The pipelined DBA has a benefit in power saving. The dynamic power consumption, P_d, of a digital circuit is given by [4]

$$P_d = \alpha C_L V_{DD}^2 f.$$

The symbol α means a switching activity factor, the symbol C_L is a load capacitance, the symbol V_{DD} is a supply voltage, and the symbol f is a clock frequency. In general, if V_{DD} or f is decreased then the power consumption is decreased. The operational speed of a digital circuit is proportional to the supply voltage [4]. The pipelined operation will decrease the required operational speed and the required clock frequency. Therefore, the pipelined DBA will reduce the power consumption. The pipelined DBA can be used even when the total number of ONUs is not large if the power consumption is a primary object in an XG-PON system.

2.1 Basic pipelined DBA

Fig. 1 shows the proposed BPD scheme which consists of four stages, T2, T3, T4 and B. One stage is completed in an FD. At the beginning of the T2 stage, the requests of the queues of the T-CONT type 2 are updated. Then the grant operation for the queues of the T-CONT type 2 is performed at the T2 stage. Also, at the beginning of the T3 stage, the requests of the queues of the T-CONT type 3 are updated. Then the grant operation for the queues of the T-CONT type 3 is executed at the T3 stage. Similarly, at the T4 stage, the update of requests and the grant operation of the T-CONT type 4 are performed. The final stage B is for the BWmap generation. In Fig. 1, t_i denotes an FD where i = 0,…,6. At the FD t_0, the T2 stage is executed. The remaining upstream bandwidth at the T2 stage will be used at the next stage T3. At the FD t_1, the T3 stage is executed with the remaining upstream bandwidth. Similarly, at the FD t_2, the T4 stage is executed with the remaining upstream bandwidth at the T3 stage. Finally, at the FD t_3, the BWmap is generated based on the grant and DBRu field results. At the beginning of the FD t_4, the OLT sends the BWmap to every ONU.

At the FD t_1, when the T3 stage starts, also the T2 stage starts with the new requests and the new upstream bandwidth resource as shown in Fig. 1. Similarly, when the T4 stage starts at the FD t_2, T2 and T3 stages start. Also, at the FD t_3, all stages operate. After the FD t_3, the BWmap is produced in every FD. The DBA operation is completed in four FDs but the DBA result is produced in every FD.

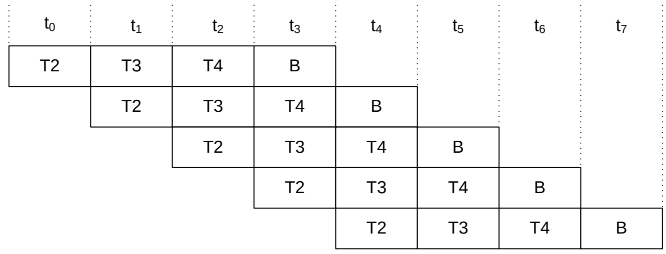
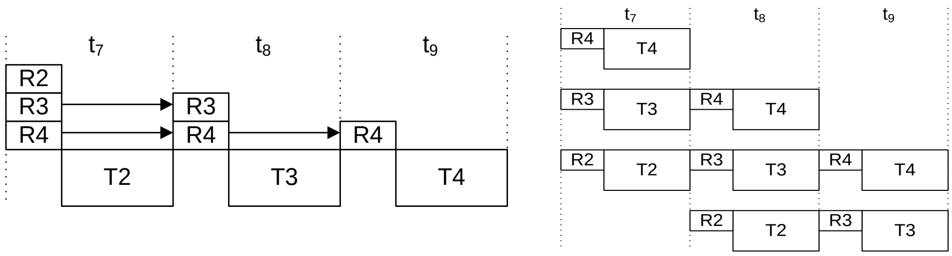


Fig. 1. Proposed basic pipelined DBA scheme

As the number of pipeline stages increases, the power consumption decreases since the required operational speed decreases. Also DBA performance decreases as the number of pipeline stages increases since the waiting time of requests increases. The number of pipeline stages can be varied based on how much DBA performance is important than the power consumption. For instance, a two-stage pipelined DBA scheme has better performance but a worse power consumption compared to the four-stage pipelined DBA scheme. In this paper we assume that the number of pipeline stages is four.

2.2 Pipelined DBA with forwarding

The BPD has a drawback that requests are not immediately used for T-CONT types 3 and 4. Fig. 2 (a) shows the request update timing diagram of the BPD. At the FD t_7, the R2, R3 and R4 are the requests of T-CONT types 2, 3 and 4 arrived at the FD t_6, respectively. At the FD t_7, only the request R2 is used for updating in the T2 stage and other requests R3 and R4 are transferred to the T3 stage. At the FD t_8, only the request R3 is used for updating in the T3 stage and the request R4 is transferred to the T4 stage. As a result, the request R3 has to wait one FD to be used and the request R4 has to wait two FDs to be used.



(a) (b)

Fig. 2. Request update timing diagram

To overcome the drawback, we propose a PDF scheme. The request update timing diagram of the PDF is illustrated in Fig. 2 (b). At the FD t_7, the R2, R3 and R4 are the requests of T-CONT types 2, 3 and 4 arrived at the FD t_6, respectively. At the FD t_7, the request R2 is used for updating in the T2 stage. Also, the requests R3 and R4 are forwarded to the T3 and T4 stages, respectively. The requests R3 and R4 are immediately used for updating in the stages T3 and T4, respectively. At the FD t_8, the R2, R3 and R4 are the requests of T-CONT types 2, 3 and 4 arrived at the FD t_7, respectively. In a similar way to the FD t_7, the requests R2, R3, and R4 are immediately used for updating in the stages T2, T3 and T4, respectively, at the FD t_8. Unlike the BPD, the requests R3 and R4 does not wait but are immediately used in the PDF.

We now describe how the request is updated in the PDF. Fig. 3 shows the request update mechanism of the PDF when the maximum distance between the OLT and an ONU is 20 km. Let G2 (t_i), G3 (t_i), and G4 (t_i) be the grant result at the FD t_i for the T-CONT types 2, 3 and 4, respectively. At the end of the FD t_0, the T2 stage produces the grant result G2 (t_0). Also, the T3 and T4 stages produce the grant results G3 (t_1) and G4 (t_2) at the FDs t_1 and t_2, respectively. At the FD t_3, the B stage builds a BWmap using the grant results, G2 (t_0), G3 (t_1) and G4 (t_2). Then the BWmap is sent to all ONUs at the beginning of the FD t_4. The symbol M denotes the BWmap in the Fig. 3. At the FD t_5, the ONU reports its request using the DBRu field, which is represented by the symbol R in the Fig. 3. The request R is the total packet length of a queue of the ONU. The OLT collets the requests of ONUs during the FD t_6, then the requests are used at the FD t_7 to update the requests of T-CONT types 2, 3 and 4.

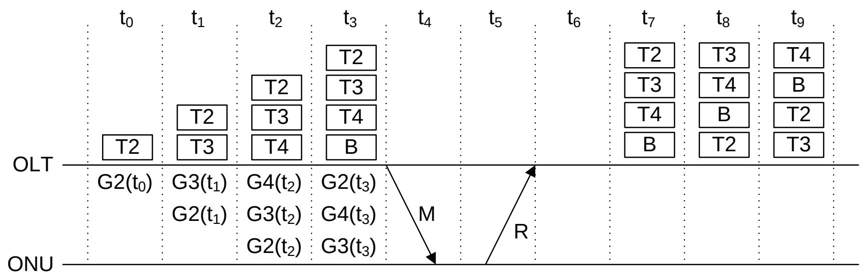


Fig. 3. Request update mechanism of PDF

We explain the request update mechanism for the T-CONT type 2. Because of the pipelined scheme, at the end the FD t_1, the T2 stage generates the grant result G2(t_1) which may contain the grant for the ONU. Suppose the request R is the request of a queue of T-CONT type 2 in the ONU. When the ONU sends the request R, the grant result G2(t_1) has not been delivered to the ONU. It means that the grant result G2(t_1) is not reflected in the request R. Similarly, G2(t_2),…, G2(t_6) are not reflected in the request R. Since the ONU sends the DBRu field before it transmits its packets [1], the grant result $G2(t_0)$ is not reflected in the request R. Therefore, to get the correct request of the queue of the T-CONT type 2, the OLT needs to remember the most recent seven grants and then subtract them from the request R at the beginning of T2 stage. That is, the correct request is calculated by

$$r_2 = R - \sum_{i=0}^{6} G2(t_i) \quad (1)$$

where the variable r_2 is the true request for a queue of the T-CONT type 2.

In a similar way to the request update of the T-CONT type 2, we compute the true request for the T-CONT type 3. Assume that the request R in Fig. 3 is the request of a queue of T-CONT type 3 in the ONU. The six grants, $G3(t_1),\ldots,G3(t_6)$ are not reflected in the request R. Therefore, the true request for a queue of the T-CONT type 3, r_3, is given by

$$r_3 = R - \sum_{i=1}^{6} G3(t_i). \quad (2)$$

Also, suppose that the request R in Fig. 3 is the request of a queue of T-CONT type 4 in the ONU. Then the true request for a queue of the T-CONT type 4, r_4, is obtained by

$$r_4 = R - \sum_{i=2}^{6} G4(t_i). \quad (3)$$

To get a correct request, the OLT must remember the most recent 7, 6 and 5 grants for T-CONT types 2, 3 and 4, respectively. Then the OLT subtracts the 7, 6 and 5 grants from a new request delivered from an ONU in the request update operation for T-CONT types 2, 3 and 4, respectively.

Finally, we explain the DBA algorithm of the PDF. We modify the efficient bandwidth utilization (EBU) algorithm of [5] for the PDF. Let queue(j) be the queue having AllocID j. The queue(j) has two service parameters, SI(j) and AB(j). The parameter SI(j) is the service interval of queue(j) in the unit of an FD. The parameter AB(j) is the maximum allocation bytes of the queue(j) during SI(j). The queue(j) has two counters, ST(j) and VB(j). The counter ST(j) is decreased by 1 in each FD and recharged to SI(j) when ST(j) has expired. The counter VB(j) is the remaining service bytes of queue(j) during SI(j). When ST(j) has expired, the counter VB(j) is charged to AB(j). Let request(j) and grant(j) be the request and the grant of queue(j), respectively. Note that request(j) is calculated by one of Eqs. (1), (2) and (3) based on the T-CONT type of queue(j). The pseudo code of the DBA algorithm is shown in the following code.

```
If request(j)> 0 and FB > 0 then
    grant(j) = min(AB(j),request(j),FB);
    AB(j) -= grant(j);
    request(j) -= grant(j);
    FB -= grant(j);
end if;
```

The variable FB is the remaining frame byte and its initial value at the T2 stage is 38,880 bytes when the upstream speed is 2.5 Gbps. The variable FB confines the sum of the grants to be less than the size of an FD. The remaining value of FB is transferred to the next pipeline stage. For instance, if the remaining value of FB is 1,000 bytes at the end of the T2 stage, the initial value of FB at the T3 stage is 1,000 bytes. For simplicity, we do not use the utilization of unused bandwidth scheme of the EBU algorithm. Other details of the EBU algorithm can be found in [5].

3 Performance Evaluations

In this section we evaluate performance of the BPD and the PDF using simulations. The request update of the BDF is similar to Eq. (1) for all T-CONT types. Also the DBA algorithm of the PDF is used for the BPD. We consider an XG-PON system with 64 ONUs. The distance between the OLT and an ONU is 20 Km. The input rate of an ONU from users is 50 Mbps and the size of a queue of an ONU is 4 Mbytes. For queue(j) of T-CONT type 2, we set SI(j) = 4, AB(j) = 1564, which is equivalent to 25 Mbps. For queue(j) of T-CONT type 3, we have SI(j) = 5, AB(j) = 1953, which is equivalent to 25 Mbps. For queue(j) of T-CONT type 4, we set SI(j) = 10. AB(j) = 3906, which is equivalent to 25 Mbps. The initial value of FB at the T2 stage is 38,880 bytes.

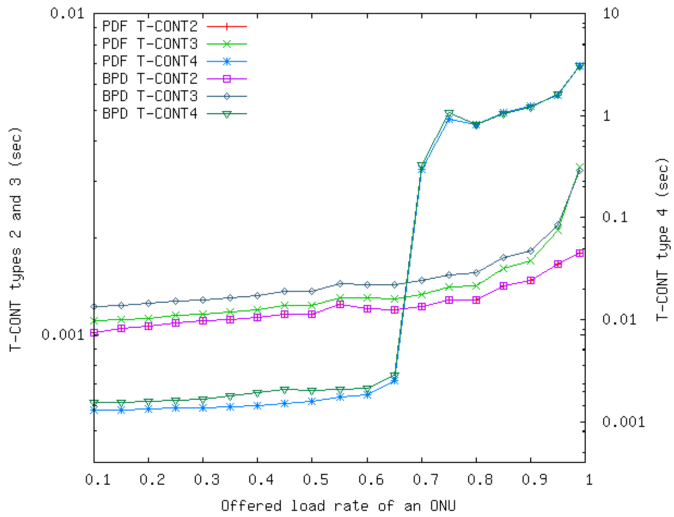


Fig. 4. Mean delay of BPD and PDF

We use the self-similar traffic of [5] with the Hurst parameter of 0.8. The packet sizes follow the tri-modal distribution that packet sizes are 64, 500 and 1500 bytes with fractions of 0.6, 0.2 and 0.2. The input load rates of ONUs are balanced so that each ONU has an identical input load rate. The load fractions of T-CONT types 2, 3 and 4 are 1/3, 1/3 and 1/3, respectively. Simulation is performed until the number of packets received by the OLT exceeds 10^9 for each plot point. Fig. 4 shows the mean delay of each T-CONT type for the BPD and the PDF. As we can see from Fig. 4, the mean delays of the PDF are improved up to 10% and 26% compared to the BPD for the T-CONT types 3 and 4, respectively, thanks to the request forwarding scheme of the PDF. For the T-CONT type2, the requests are immediately used at the T2 stage in the BPD and the PDF as we explained in Section 2.2. This explains that the mean delays are almost identical for the T-CONT type 2 in Fig. 4.

4 Conclusions

We proposed the BPD and the PDF for power saving of the XG-PON system. Using the pipelined DBA operation, the BPD and the PDF decrease the operation speed of the OLT. Also by forwarding the requests of the T-CONT types 3 and 4, the PDF improves the mean delays compared to the BPD.

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