A Flexible Low-Latency Metro-Access Converged Network Approach Based on Time-Synchronized TWDM-PON

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Abstract: A flexible time-synchronized TWDM-PON (TS-TWDM-PON) architecture is proposed and implemented for low-latency metro-access communication. Results show that a two-order-of-magnitude reduction in end-to-end delay can be achieved with the new TS-TWDM-PON architecture.

OCIS codes: (060.4250) Networks; (060.0060) Fiber optics and optical communications

1. Introduction

Cloud computing may fail to satisfy the required level of latency for new technologies, such as virtual reality, smart vehicle communication, health-related services, etc. For example, the self-driving car test from Google implies that nearly one gigabyte data will be generated by a car every second and it requires real-time processing to make instant instructions [1]. Edge computing, where computing resources are deployed at the edge of the network, is a promising technology to provide better service for the delay-sensitive applications [2]. However, two main factors will introduce extra latency in practical operation. On one hand, the required source for some users might not be stored in the nearest Micro Data Center (MDC) due to the limited storage capacity, which could boost the latency when the users access the resource in a remote MDC or a centralized data center. Resource provisioning could be applied to alleviate the latency in some degree, but it could not solve the problem entirely [3]. On the other hand, when a user leaves the area served by the current MDC, the corresponding virtual machine is needed to be migrated to the new nearest MDC, resulting in excessive latency and heavy burden in the core network. These two main practical problems should be handled carefully to ensure the quality of service.

Passive Optical Network (PON) has been widely deployed in metro-access networks for its passive features and easy management. Time and Wavelength Division Multiplexing PON (TWDM-PON) is regarded as one of the most promising candidate for the next generation optical access networks [4]. Optical Network Units (ONUs) provide network service to subscribers through the user interface and Optical Line Terminals (OLTs) are located in the central office. Between ONU and OLT lies the passive equipment. A PON-enabled programmable access and edge cloud architecture was proposed in [5], where central office is re-architected as MDC. The computing resources are more close to users in this architecture, and users will get low-latency connections when the wanted resources are stored in the MDC that the ONU connects to directly. However, a user still needs to undergo grooming delay when the user wants to connect to a remote MDC that belongs to another PON system. In this case, the problems mentioned above still exist.

In this paper, we propose a Time-Synchronized TWDM-PON (TS-TWDM-PON) architecture. ONUs from different PON systems are time synchronized and data could be transmitted without going through the processing time in MDC. Simulation results demonstrate that the new architecture could provide lower-latency connections compared to the conventional system. Furthermore, we conduct an experiment to validate the feasibility of the architecture.

2. Time-synchronized TWDM-PON

Fig. 1 depicts the TS-TWDM-PON architecture, which is composed of two MDCs and two PONs. The whole architecture can be divided into two parts: metro and access networks. In the metro network, the OLTs locate in the MDCs. As for the access network, Optical Distribution Network (ODN) is at the user side. Colorless ONUs can use any wavelength due to the deployment of tunable transmitters and receivers. Through user interfaces deployed in ONUs, users could get access to the resource in MDCs. From the picture, we could learn that the most difference between the conventional TWDM-PON and the new TS-TWDM-PON is the deployment of Cross-PON Switches (CPSs). In the conventional TWDM-PON, a PON system connects to its specific MDC, and the MDCs are communicated with each other through the metro network. It would be easy for an ONU to get the resource in the MDC which it directly connects to. However, when an ONU needs to connect to a remote MDC, e.g., an ONU from PON #1 wants to get the

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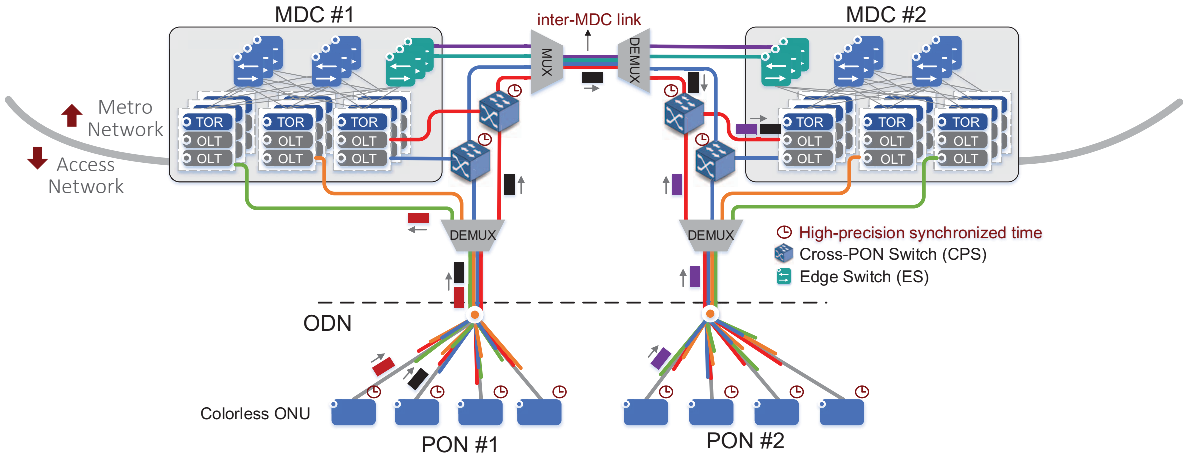


Fig. 1. TS-TWDM-PON architecture.

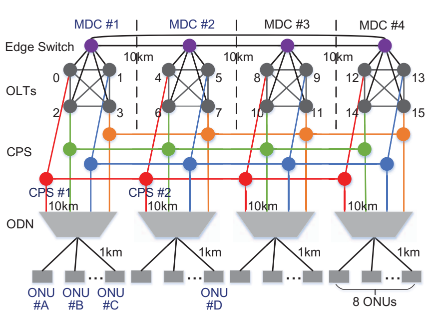
resource in MDC #2, data need to traverse MDC #1 first and then be transmitted to MDC #2 through the edge switches of both the two MDCs, which brings excessive processing delay. In the TS-TWDM-PON approach, data can be sliced and all-optically switched by CPSs directly and need not go through the edge switches. In this way, only propagation delay exists and thus end-to-end latency can be reduced.

Here we discuss the feasibility of the new architecture. In Fig. 1, three upstream data flows, marked red and black respectively in PON #1, and purple in PON #2, are generated by their corresponding ONUs. The destination of the red flow is MDC #1 while the black and purple flows are aggregated at MDC #2. In this case, the time of the CPSs needs to be synchronized with that of the ONUs belonging to different PONs to avoid collision. The traditional PON systems can only synchronize the OLT and ONUs inside a PON via distance measurement [6], but this method is not applicable to cross-PON synchronization. The proposed TS-TWDM-PON approach uses mature sub-microsecond network time synchronization technology [7] to realize cross-PON synchronization. Time synchronization technology enables collaborative time slot assignment within different PONs. Furthermore, 10-ns-level optical switches [8] can be used in CPS to achieve fine-grained optical time slice switching.

3. Performance evaluation and experiment validation

We develop a simulation platform to evaluate the latency performances. Fig. 2(a) shows the simulation topology. The number of MDCs is four and each MDC contains four OLTs. There are four PONs in total and each PON system is deployed with four wavelengths. The capacity of a single wavelength is set to 10 Gb/s. Both propagation delay and grooming delay are considered in the simulation. We assume that each grooming node brings about 5 ms end-to-end delay for simplicity. In the traditional PON architecture, inter-MDC data flows are forwarded through the electrical edge switches deployed in MDC, while for the new TS-TWDM-PON approach, they are switched all-optically at CPSs.

Fig. 2(b) describes the Wavelength and Time Slice Allocation algorithm (WTSA) for TS-TWDM-PON. We adopt first-fit algorithm for time-slice allocation. The computational complexity of WTSA is $O(WN^2)$, where W and N represent the number of wavelengths and time slice granularity (the length of an upstream frame divided by the minimum length of a time slice), respectively.

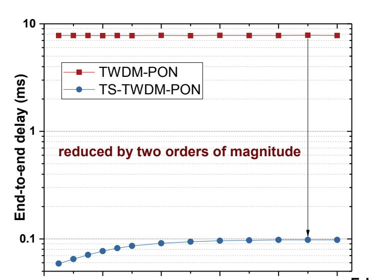


(a)

Algorithm 1 : Wavelength and Time Slice Allocation Algorithm (WTSA)

```
Require:
    R ← the set consisting of requests;
    W ← wavelength set of each PON system;
for each request in R do
    for each wavelengths in W of the corresponding PON system do
        if total traffic load does not exceed the capacity then
            use this wavelength to accomodate the request;
            latency = propagation delay + grooming delay; //TWDM-PON
        end if
    end for
    for each wavelengths in W of the PON system containing end node do
        if unoccupied time slice can accomodate the required bandwidth then
            use this wavelength to accomodate the request;
            latency = propagation delay; //TS-TWDM-PON
        end if
    end for
end for
return latency;
```

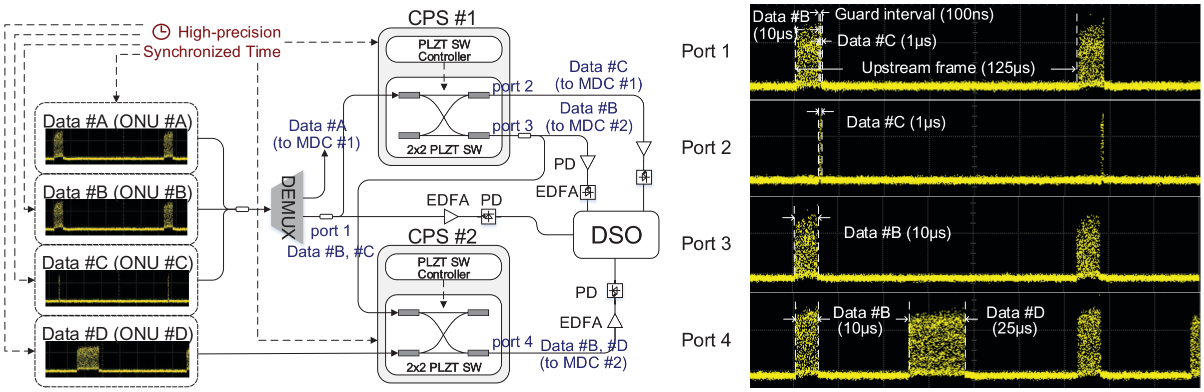
(b)



(c)

Fig. 2. Simulation setup and results. (a) topology; (b) WTSA algorithm; (c) latency performances.

Fig. 2(c) compares the latency performances between the traditional TWDM-PON and the new TS-TWDM-PON under various load conditions. It can be seen that end-to-end delay is around 8 *ms* in traditional PON, while is less than 0.1 *ms* for TS-TWDM-PON, reduced by almost two orders of magnitude.



(a) (b)

Fig. 3. Experimental setup and results. (a) experimental setup; (b) results.

We also conduct a prototype experiment to validate the feasibility of the proposed architecture. Fig. 3(a) shows the experimental setup. Four data flows, marked Data #A, #B, #C, and #D, are generated by ONUs #A to #D (marked in Fig. 2(a)) with the lengths of 10 μs, 10 μs, 1 μs, and 25 μs, respectively. ONU #A, #B, and #C are from the same PON system while ONU #D belongs to another PON. The CPSs are realized by two PLZT switches.

Fig. 3(b) presents the experimental results. Port 1 shows the aggregation of Data #B and #C after going through a WDM DEMUX. The length of the upstream frame and the guard interval are set to 125 μs and 100 *ns*, respectively. Data #B and #C are separated at a PLZT switch (CPS #1), and Port 2 and Port 3 show the received data at MDC #1 and MDC #2, respectively. In Port 4, Data #B and #D are aggregated correctly through CPS #2. This experiment shows that data flows from different PONs could be transmitted accurately with time synchronization, which validates the feasibility of the proposed architecture.

4. Conclusions

Computing resources are more close to users in edge computing to provide a better quality of experience. However, users may experience an excessive delay when they want to get access to a remote MDCs in traditional architecture. To tackle this problem, we propose a new TS-TWDM-PON architecture based on time synchronization. In this architecture, users could get access to a remote MDC without processing delay in relay MDCs. Simulation results show that the end-to-end delay is reduced by almost two orders of magnitude. Furthermore, we successfully validate the feasibility of the new architecture through a prototype experiment.

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