Bufferless Bidirectional Multi-Ring Networks with Sharing an Optical Burst Mode Transceiver for Any Route

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SUMMARY Improvement of conventional networks with an incremental approach is an important design method for the development of the future internet. For this approach, we are developing a future aggregation network based on passive optical network (PON) technology to achieve both cost-effectiveness and high reliability. In this paper, we propose a timeslot (TS) synchronization method for sharing a TS from an optical burst mode transceiver between any route of arbitrary fiber length by changing both the route of the TS transmission and the TS control timing on the optical burst mode transceiver. We show the effectiveness of the proposed method for exchanging TSs in bidirectional bufferless wavelength division multiplexing (WDM) and time division multiplexing (TDM) multi-ring networks under the condition of the occurrence of a link failure through prototype systems. Also, we evaluate the reduction of the required number of optical interfaces in a multi-ring network by applying the proposed method.

key words: time division multiplexing, timeslot synchronization, bidirectional bufferless WDM/TDM multi-ring networks

1. Introduction

With the growing popularity of the internet, expectations for new applications and services in various fields such as multi-media and transportation have increased. These have motivated the development of the future internet, which will achieve higher bandwidth, lower delay, higher reliability, and greater intelligence to accommodate future services. To create the future internet, many research programs such as FI-PPP [1] of the EU, FIA-NP [2], and US Ignite [3] of the U.S. have been founded and several drastically new network architectures for the future internet proposed. However, these programs haven't led to any fundamental changes in the basic underlying architecture because of the difficulty in maintaining the same operation for the current system and the increase in capital expenditure (CAPEX) needed to replace the entire existing infrastructure with new architecture. Therefore, for the time being, it is expected that the incremental approach for the current network will be effective. This is why we are focusing on architecture based on the current network system.

The current network, which is a three-layer structure, consists of core, aggregation, and access network. The basic function of the core network is to accommodate large amounts of traffic by setting the optical path between edges

of core network. Currently, a 100 Gbps interface is commercially available for the bandwidth of a wavelength in the core network. Moreover, it is predicted that optical networks will be required to support Tbps class transmission in the near future [4]. In response to this, research and development are also progressing [5] according to these requirements. On the other hand, the requirements for the future internet will severely affect the access network and the aggregation network. Because this network equipment has to be implemented at lower CAPEX in terms of the number of accommodated users per unit. In the access network, fiber to the home (FTTH) based on the passive optical network (PON) [6] has grown rapidly. When FTTH deployment in the access network has been accelerating, the operators and vendors are looking ahead to meet the requirements of new applications. A promising solution is to develop a higher speed PON such as the 10 Gigabit Ethernet PON (10G-EPON) [7]. Recently, the standardization of the next generation of EPON (NG-EPON) [8] as a future access network has started to be discussed. These approaches are broadbanding of the access network. Other studies have applied optical burst control techniques used in the PON to the aggregation network. As one of these studies, an access aggregation convergence network has proposed by the application of long reach PON to the aggregation network in terms of the reduction of the aggregation network's CAPEX [9]. However, the application of long reach PON has resulted in several issues, such as optical burst mode amplifications to support long reach with lower CAPEX [10] and a decrease in the network delay caused by dynamic bandwidth allocation (DBA) [11].

As a different method to achieve a cost-effective aggregation network, rather than a converged approach for the access network in terms of current network architecture, we have been studying an approach to incorporate the optical burst control techniques used in the PON, such as 10G-EPON, to the aggregation network, specifically, the optical Layer-2 switch network (OL2SW-NW) [12]–[18]. OL2SW-NW was designed based on the application of bufferless optical time division multiplexing (TDM) and DBA to achieve a large-scale cost-effective aggregation NW. OL2SW-NW is named after the possession of the function of the Layer-2 switch (L2SW). In general, the L2SW switches data frames from input ports to output ports based on the Layer-2 destination address. Therefore, the L2SW learns Layer-2 addresses automatically to build a forwarding table that can

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be used to selectively forward data frames. In the same way, the OL2SW-NW acts as a large-scale L2SW covering the whole aggregation network in which the internal bandwidth for each destination is variable. OL2SW-NW can multiplex the traffic without increase in network delay through the application of a high speed timeslot (TS) allocation (TSA) algorithm [15], which expands the PON's DBA, for the large scale of the aggregation network. One of the advantages of applying these access network technologies to the aggregation network is that it makes it possible to reduce the CAPEX. Because access network devices are mass-produced, they must have a low CAPEX. Moreover, the OL2SW-NW can eliminate the internally located L2SW by aggregating the packet buffers to the entity of the edge node. As a result, the entity located at the edge of the OL2SW-NW has packet buffers and converts variable length Ethernet frames from the external network into optical burst mode signals in the same way as the PON. On the other hand, the inside of the OL2SW-NW switches the TSs with no packet buffer and without classifying the packet header. To achieve this architecture, it is necessary to synchronize the TS control timing among all nodes in the OL2SW-NW as there is no packet buffer in the internal node (Here, we use the term "TS_{Sync}" for "synchronization of TS control timing." A definition of the status of TS_{Sync} is described in Sect. 2.2.). Moreover, the aggregation network requires high reliability because it must accommodate larger number of users than the access network. Therefore, in this paper, we propose a reliable TS_{Sync} for the OL2SW-NW to achieve future aggregation networks. "Reliable TS_{Sync}" means that it is possible to continue to achieve TS_{Sync} with no packet buffer in internal nodes of arbitrary length and multiple routes when a link failure occurs.

1.1 Related Works

In current aggregation networks, optical add/drop multiplexer (OADM) systems based on wavelength division multiplexing (WDM) technology [19] have been widely deployed. However, an OADM performs add/drop at each wavelength and allocates the bandwidth by setting the optical path to fit the maximum amount of traffic from edge to edge of the aggregation network. Therefore, bandwidth utilization is a problem when accommodating a smaller traffic volume in comparison with the bandwidth of a wavelength. To overcome this problem, OADM systems are used in combination with traffic grooming technology to perform efficient traffic multiplexing. Traffic grooming is executed on mainly two levels: on the optical transport network (OTN) [20] as layer 1 and at the Ethernet switch as layer 2. The OTN can multiplex the traffic for all data units, which are called "optical data units (ODUs)," at an ODU cross-connect (XC). The Ethernet switch uses the media access control (MAC) address to decide where to forward Ethernet frames. These make it possible to reduce the number of optical interfaces (N_{IF}) connected to the ODU-XC or the Ethernet switch at the aggregation point.

However, to achieve traffic grooming by using these technologies, an inter-connection node that executes traffic grooming needs to drop the traffic in order to multiplex the traffic and retransmit the traffic to the next node. As a result, N_{IF} at the inter-connection node increases. One method for multiplexing traffic at the optical layer is to use a packet-optical add/drop multiplexer (P-OADM) system [21], [22]. P-OADM extracts the control information from a packet and transports the control information via a control channel so as not to have to demodulate all the wavelengths at each node. This control channel generates the control timing of TSs and allocates the bandwidth for each node. However, P-OADM only synchronizes the control timing of TSs at single ring networks using a control channel. Therefore, when P-OADM is applied to a multi-ring network, it requires packet buffers at intermediate nodes connecting each ring [21]. Addressing this problem, our proposed OL2SW-NW does not require packet buffers at intermediate nodes connecting each ring by achieving TS_{Sync} among all nodes. This can eliminate not only the packet buffers and packet classifiers but also N_{IF} in order to insert the packets in the TS to the packet buffers in the intermediate nodes. However, previous proposed network has only supported uni-directional multi-ring network [14], which are not restorable for link and node failures. Therefore, there remains a challenge for an increase in reliability.

In view of the above background, the contribution of this paper is the achievement of a reliable TS_{Sync} for the OL2SW-NW. Figure 1 shows the concept of the reliable OL2SW-NW. The concept of the proposed network is a buffer-less optical TDM network to increase reliability while avoiding a complicated operation. Specifically, the proposed network aims to keep exchanging TSs between any route of arbitrary fiber length in bufferless optical TDM multi-ring networks even if a link failure occurs. This can eliminate the need for the operation to adjust the length of fiber. To achieve this, the proposed method dynamically changes both the route of the TS transmission and the TS control timing due to link failure. With this mechanism, the proposed method can eliminate the need to adjust the length of the fiber between all nodes, which bothers network operators.

The remainder of this paper is organized as follows. The architecture of the proposed network is described in

Fig. 1 Concept of reliable optical Layer-2 SW network.

Sect. 2, and the proposed TS synchronization method, which is the key function for reliable OL2SW-NW, is described in Sect. 3. In Sect. 4, the accuracy and scalability of TS synchronization are described to evaluate the effective bandwidth for the proposed method. In Sect. 5, we explain the characteristic of N_{IF} for the proposed method compared with the conventional method; P-OADM, which has to prepare packet buffers in the intermediate nodes connecting rings. The experimental and simulation results are described in Sect. 6. We conducted the experiments on the speed of changing TS control timings and the accuracy of TS synchronization to show the feasibility of the proposed method and the effective bandwidth using prototype systems. Then we showed comparisons of the simulation results of required N_{IF} in the proposed method with those of P-OADM to evaluate the CAPEX. Finally, we concluded this paper in Sect. 7.

2. Architecture of Reliable OL2SW-NW

2.1 Overview

Figure 2 shows the architecture of a reliable OL2SW-NW that can cost-effectively accommodate traffic in future aggregation networks based on a 10G-EPON system [7]. The OL2SW-NW is a bidirectional bufferless WDM/TDM multi-ring network located between access and core networks. It can characteristically eliminate the L2SW located in the internal network, which is required for conventional aggregation networks, by aggregating the packet buffer to the entity of the edge node in the OL2SW-NW. This entity is called an “Ether-burst converter (EBC) [13],” and it converts variable-length 10G Ethernet (10GE) frames to TSs with a fixed length and transmits them according to the allocated TSs at a constant TDM frame (the length of TDM frame: L_{FR}). Each node deploys a WDM/TDM SW [12], which enables TS add/drop for any channel and any TS. To allocate the bandwidth for logical paths between EBCs, the OL2SW-NW has a TS scheduler that collects the traffic information on all logical paths for TSA calculated by a high speed TSA algorithm [13]. Then, the TS scheduler periodically allocates bandwidth at a constant cycle, T , which is an integral multiple of L_{FR} for achieving DBA for large-scale aggregation networks [18]. The TS transmission at the EBC and the WDM/TDM SW are controlled by a TS controller (TSC), which is implemented at each node. TSCs at all nodes have to be TS_{Sync} because there is no packet buffer in the internal entity of the OL2SW-NW. Therefore, the OL2SW-NW has to achieve TS_{Sync} for the whole network. To achieve this, it has a TS synchronizer, which is set to aggregately execute TS_{Sync} for all TSCs. The TS synchronizer controls the TS control timing for all entities of the OL2SW-NW of arbitrary fiber lengths and arbitrary routes. This means that the TS synchronizer sets the start timing of the TDM frame and T to all TSCs in consideration of the length of the routes of TS transmission. The method of communication between the TS synchronizer and all TSCs is using control channel (λ_c) to ensure reachability between each node connected by

Fig. 2 Reliable optical Layer-2 SW network; (a) network architecture and (b) example of TS transmission from A-nodes to an upper ring.

an active WDM/TDM SW. We use two kinds of λ_c : λ_{c1} to send the control packets from the TS synchronizer to the TSC and λ_{c2} to send the control packets from the TSC to the TS synchronizer. λ_{c1} carries the control packets to synchronize the TS control timings and to set the information of allocated TSs. By contrast, λ_{c2} carries the control packets to measure the delay between the TS synchronizer and TSCs, the traffic information from external nodes connected to OL2SW-NW. Each λ_c defines TSs, named control TS. Each TSC is allocated to a dedicated control TS in advance. All control information between the TS synchronizer and TSCs is carried using the control TSs.

As described in Sect. 1, the OL2SW-NW acts as a large-scale L2SW. To achieve this, the TS scheduler undertakes MAC learning [18], which is a necessary mechanism to perform as a L2SW. This mechanism is achieved as follows. The TSC checks the source MAC address from the arriving packets from external nodes connected to OL2SW-NW and compares it to its MAC table. If it is a new address, the TSC notifies the TS scheduler of this address. The TS scheduler creates a new MAC table based on both the new MAC address and the TSC which the new external node is connected to. Then, the TS scheduler sets this MAC table to each TSC.

Here, we label the nodes that constitute the OL2SW-NW; that is, the node connected to L2SWs in the access network is called an “A-node,” the node connected to IP routers in the core network is called a “C-node,” and the intermediate node connecting rings is called an “IC-node.” Also, we call the node that deploys the TS scheduler and the TS synchronizer a “master node (M-node).”

2.2 Definition of TS_{Sync}

An OL2SW-NW is required for TS_{Sync} in all nodes because of the elimination of packet buffers located in the internal network. Firstly, to explain the status of TS_{Sync} , we define the TS control timing that each node has to prepare. Each node has the TS control timing in order to both control the arrival TS from the other nodes and send the TS from its own node. Figure 3 shows the definition of TS control

timing, which is working at a node on a TDM frame consisting of four TSs. The length of TS (L_{TS}) is at a constant. TS control timing means the timing of each TS section which the node manages. Each node can produce the TS control timing according to its own clock frequency (Fq) by setting the start timing for the TDM frame, L_{TS} and L_{FR} . In the OL2SW-NW, there is no packet buffer in the internal network. This means the TS gets to the receiver in the propagation delay between the sender and the receiver after the sender sends this TS. Therefore, to exchange TS in the OL2SW-NW, the TS control timing at the receiver must be delayed by the propagation delay in comparison to that of the sender. We define this status as TS_{Sync} (synchronization of the TS control timing). Figure 4 shows the definition of TS_{Sync} between the sender and receiver to exchange TSs. The status of TS_{Sync} means that the TS control timing at the receiver is delayed by the propagation delay in comparison to that of the sender. Moreover, because of the application of DBA in the OL2SW-NW, it is required to synchronize the start timing of T .

2.3 Problem with TS_{Sync} in Reliable OL2SW-NW

A reliable OL2SW-NW has to change to a standby route that does not go through the failure point to resume communication, if a link failure occurs over a working route that has already done TS_{Sync} between all nodes. However, if there is a difference in the length of the route of TS transmission between the working and standby routes, the start timing of the TDM frame shifts according to the difference in the length of these routes in the case that each node keeps working at the TS control timing for the working route. As a result, the arrival timing of TS at each node via the standby route deviates from that of the controlling TS at each node. Therefore, each node cannot forward the arriving TS.

A method for achieving TS_{Sync} , which sets all fiber delays to an integral multiple of the TS between each node, was proposed [23]. To make this method a possibility, it is necessary to measure and adjust the delay between all nodes. However, it is complicated to adjust the length of a fiber, so this method is impractical for commercial

Fig. 3 Definition of TS control timing.

Fig. 4 Definition of TS_{Sync} .

networks. As a practical method, reference [14] proposed a method for supporting arbitrary fiber lengths between all nodes. This method executes TS_{Sync} between all nodes of arbitrary fiber lengths by separating the different TS control timings for the add and the drop at each node. This means that this method accommodates the different TS control timings for downstream and upstream traffic. However, when applying this method to bidirectional bufferless WDM/TDM multi-ring networks to enhance the reliability of an aggregation network, the required number of optical burst mode transceivers increases depending on the number of supportive routes. This means that [14] has to statically allocate both the transceivers for each TS control timing to all routes. Hence, the problem of [14] is reducing N_{IF} without dependence on the number of routes.

3. Proposed TS_{Sync} Method

To achieve TS exchange while sharing an optical burst mode transceiver between arbitrary routes in bufferless WDM/TDM networks, the proposed method dynamically changes the route of the TS transmission and the TS control timing of both the WDM/TDM SW and the EBC for a link failure. This allows a TS from an EBC to be shared sequentially between any route of arbitrary fiber length working on different TS control timings. These TS control timings are calculated on the basis of the measured delay between each node. This method is an extension of our previous method [14] for application to bidirectional bufferless multi-ring networks. This method can reduce the number of transceivers compared with [14].

3.1 TS_{Sync} in Arbitrary Fiber Lengths and Arbitrary Routes

The basic idea of the proposed method for achieving TS_{Sync} between all nodes in arbitrary fiber lengths and arbitrary routes is based on separating the different TS control timings for the add and the drop at both the C-node and A-node. Figure 5 shows the basic idea of the proposed method. In this

Fig. 5 Abstraction of proposed TS_{Sync} method.

Fig. 6 Required TS control timings on bufferless two-stage rings network (a) for CCW route on the upper ring and (b) for CW route on the upper ring.

scenario, the OL2SW-NW has two kinds of fibers in both the upper ring and the lower ring. Each fiber carries traffic in one direction: a clockwise route (CW; standby route) or counter-clockwise route (CCW; working route). Each route has both a Data plane (D-plane) and Control plane (C-plane). The CCW route for the D-plane is used for normal operation, and the CW route for the D-plane is for failure recovery in the case of single link failure. On the other hand, both the CCW route for the C-plane and the CCW route for the C-plane are used for normal operation. An up-/down-stream path pair is carried on at the same direction. Here, as an example of TS_{Sync} , the X-node belonging to the lower node executes TS_{Sync} for the IC-node. This means that the TS control timings at the X-node have to be synchronized to that of the IC-node via both the CCW route and the CW route of arbitrary lengths. The TS control timings are used according to the route of TS transmission. These TS control timings are set to each node in advance. The key point of the proposed method is how to set these TS control timings and how to change the TS control timing for a protection route when a link failure occurs. Figure 5 shows an example of the TS control timings which X-node has; namely TDM#X and TDM#Y. To synchronize the TS control timings among all the nodes, the TS synchronizer set a baseline TS control timing, which is TDM#X, to all nodes. Then, other TS control timings; TDM#Y, are set based on TDM#X. In the case of Fig. 5, TDM#X is used to drop the TS via the CCW route and TDM#Y is used to add the TS via the CCW route at the X-node (although the simplified explanation in Fig. 5 could not convey it, the X-node has as many TS control timings as the routes of TS transmission which are described in Sect. 3.2). Following, we show the relationship between the TS drop timing at the X-node via the CCW route and the TS add timing at the X-node via the CCW route. To synchronize the TS drop timing at the X-node to the TS control timing at the IC-node, the TS drop timing in the X-node is set to be delayed by the propagation delay from the IC-node to the X-node in comparison with that of the IC-node. This delayed is expressed as x . To synchronize the TS add timing

at the X-node to the TS control timing at the IC-node, the TS add timing at the X-node is set to be earlier by the propagation delay from the X-node to the IC-node in comparison to that of the IC-node. This is expressed as y . Also, we define the difference between x and y as z . If both the setting of TS drop timing as a baseline TS control timing and the calculation of z are achieved based on the propagation delay between each node, it is possible to acquire the TS control timings for each route at the X-node. For example, in the case that the propagation delay of the left-hand and right-hand routes are $D2$ and $D1$ as described in Fig. 5, respectively, the TS drop timing via the CCW route at the X-node is expressed as $x = D2$. Then, the TS add timings via the CCW route at the X-node are expressed as $y = D1$, respectively. Then, z for the TS add timing via the CCW route at the X-node is calculated as $z = L_{FR} - (D1 + D2) = L_{FR} - D_R$. On the other hand, z for the TS add timing via the CW route at the X-node is calculated as $z = L_{FR} - (D2 + D2) = L_{FR} - 2D2$. Here, D_R is the delay around the ring. In the case that X-node is C-node, D_R is set to the delay around the upper ring (D_{RU}). In the case that X-node is A-node, D_R is set to the delay around the lower ring (D_{RL}). Therefore, the TS drop timing is set to the X-node and the D_R and $D2$ are notified to the X-node. These TS add timings can be calculated at the X-node by shifting the delay time z after the TS drop timing. When a link failure occurs, the proposed method dynamically changes the route of the TS transmission and TS control timing of a WDM/TDM SW and an EBC at each node according to the above TS control timings. Thanks to this mechanism, the proposed method can achieve a TS from an optical burst mode transceiver shared between any route in bufferless WDM/TDM multi-ring networks.

3.2 Required TS Control Timings at Each Node

Figure 6 shows the required kinds of TS control timings (TDM1–TDM8) at each node for supporting bidirectional bufferless two-stage rings network with the proposed method applied. Here, for the sake of simplicity,

Table 1 Summarization of each parameter to set the TS control timings to the A-node.

TDM#X	TDM#Y	x	y	z
TDM1	TDM2	$D2$	$D1$	$L_{FR} - D_{RL}$ ($:\varepsilon$)
	TDM3	$D2$	$D2$	$L_{FR} - 2D2$ ($:\xi$)
	TDM4	$D2$	$L_{FR} - D1$	$D_{RL} - 2D2$ ($:\eta$)
TDM5	TDM6	$D1$	$D2$	$L_{FR} - D_{RL}$ ($:\theta$)
	TDM7	$D1$	$D1$	$L_{FR} - 2D1$ ($:\kappa$)
	TDM8	$D1$	$L_{FR} - D2$	$D_{RL} - 2D1$ ($:\nu$)

$D1$: Propagation delay of right-hand route in the lower ring

$D2$: Propagation delay of left-hand route in the lower ring

D_{RL} : Propagation delay around the lower ring ($=D1+D2$)

L_{FR} : Length of TDM frame

the D_{RU} is set to an integer multiple of the TDM frame. If D_{RU} is not an integer multiple of the TDM frame, the required TS control timings for the C-node are set in the similar way for the A-node. Therefore, we focus on the TS_{Sync} for the A-node. First, TDM1 and TDM5 work for the CCW route and CW route on the upper ring, respectively. Because the same mechanism is used in left-right reversal, we focus on only how to achieve TS_{Sync} from the TS control timings of A-node to TDM1 on the upper ring. On the upper ring, TDM1 is used for TS add/drop at the IC-node and the C-nodes via the CCW. Then, each A-node is set to four kinds of TS control timings (TDM1–TDM4) to synchronize to TDM1 on the upper ring. TDM1 and TDM4 at the A-node are used for dropping the TSs, which are sent from C-nodes via the CCW route and CW route on the lower ring, respectively. TDM2 and TDM3 at the A-node are used for TS add via the CCW route and CW route to synchronize the TS add timings at the A-node to TDM1 on the upper ring, respectively. That is, the TS add timing at the A-node via the CCW route is applied to TDM2 and that via the CW route is applied to TDM3.

In Table 1, we summarize each parameter to set the TS control timings to the A-node. As shown in Sect. 3.1, when the TDM1 as a baseline TS control timing is set to each node from the TS synchronizer via the CCW route, z to start TDM2, TDM 3, and TDM 4 can be determined if the length of each route of TS transmission is measured. Here, we define z for TDM2, TDM 3, and TDM4 as ε , ξ , and η , respectively. Then, ε , ξ , and η are calculated as $L_{FR} - D_{RL}$, $L_{FR} - 2D2$ and $D_{RL} - 2D2$, respectively. On the other hand, TDM5–TDM8 can also be calculated in the same way for TDM1–TDM4. When the TDM5 as a baseline TS control timing is set to each node from the TS synchronizer via CW route, z for TDM6, TDM 7, and TDM8 can be determined if the length of each route of TS transmission is measured. Here, we define z for TDM6, TDM7, TDM8 as θ , κ , and ν , respectively. Then, θ , κ , and ν are calculated as $L_{FR} - D_{RL}$, $L_{FR} - 2D1$ and $D_{RL} - 2D1$, respectively.

3.3 Sequence of Proposed Method

Here, we explain the sequence of the proposed method assuming the scenario described in Fig. 7. The assumed scenario is to execute TS_{Sync} at the A-node for TS control timing for the CCW route of the upper ring (TDM1). Then,

Fig. 7 Use case of required TS control timings for CCW route's failure on the lower ring.

the A-node changes the route of TS transmission and the TS control timing for sending a TS from the CCW route to CW route due to a link failure at the lower ring. In this case, the TS add timing at the A-node is changed from TDM2 to TDM3. To achieve this, the proposed method follows four steps as described in Fig. 8. The control information for achieving TS_{Sync} is sent using control TSs on $\lambda c1$ via the CCW route and $\lambda c2$ via the CW. Control TSs on $\lambda c1$ via the CCW route work on TDM1 and control TSs on $\lambda c2$ via the CW route work on TDM3.

(1) Setting of TDM1 (Step 1)

The TS synchronizer in the M-node synchronizes the TDM1 for the CCW route on the upper ring between all nodes. Synchronizing the TDM1 between all nodes is achieved by sending the control packet to set the baseline TS control timing (B-packet) attached with a time stamp from the TS synchronizer to the TSCs of other nodes. This B-packet is sent using control TS via the CCW route working on TDM1. When receiving the B-packet, each TSC starts the TDM1 by starting the counter for it. This counter increments at every Fq at each TSC. We assume that Fq is synchronized among TSCs using Synchronous Ethernet [24] on the $\lambda c1$, but the phase of Fq is not synchronized. As a result, the start timing of the TDM1 frame at each node is delayed by the propagation delay of the CCW.

(2) Measurement of delay between each node (Step 2)

To synchronize the required TS control timings at the A-node to the TDM1 at the IC-node, the IC-node measures the D_{RL} . The D_{RL} is measured by subtracting the value of the counter at (a) from that at (b), where (a) is the time of receiving the B-packet at the IC-node and (b) is the time of receiving the B-packet after going around the lower ring at the IC-node. Then, the IC-node sends measured D_{RL} to the M-node using a control TS. Moreover, the M-node measures the delay from the M-node to A-node# j and IC-node using the control packet (D-packet), which is attached with a time stamp and sent from the A-node and IC-node when the A-node and IC-node receive the B-packet. This D-packet is sent using control TS via the CW route working on TDM3. However, in the initial state, A-nodes and IC-nodes transmit the D-packets at random times after receiving the B-packet from the TS synchronizer until the TDM3 is set to each

Fig. 8 Sequence of the proposed TS synchronization method.

node, since TDM3 is still not being set to each node in the initial state. Then the M-node calculates the delay between the IC-node and A-node#j (D_j) using the above measurement values. Specifically, D_j is calculated by subtracting the measured delay between the M-node and IC-node from the measured delay between the M-node and A-node#j. Then, the M-node sets the TS control timings of TDM2, TDM3, and TDM4 to the A-node#j by starting ε , ξ , and η later than the start timing of TDM1, respectively. ε , ξ , and η are expressed as $L_{FR} - D_{RL}$, $L_{FR} - 2D_j$, and $D_{RL} - 2D_j$, respectively according to Table 1.

(3) Setting of other TS control timing (Step 3)

To start TDM2, TDM3, and TDM4 at each A-node, the IC-node sends a control packet to set other TS control timings (O-packet) attached with ε , ξ , and η to each A-node. This O-packet is sent using control TS via the CCW route working on TDM1. After receiving the O-packet, each A-node starts TS control timings on TDM2, TDM3, and TDM4 using ε , ξ , and η .

The proposed method can overcome the variation in fiber delay, which is mainly due to the variation in the temperature, by executing steps 1–3 periodically.

(4) Changing route of TS transmission and TS control timing (Step 4)

When detecting the link failure, the M-node sends a control packet to change the route of the TS transmission and TS control timing at the A-node (C-packet). This C-packet is sent using control TS via the CCW route working on TDM1. We assume that the M-node can identify the link failure depending on whether or not the C-plane's TS is received from each node. After receiving the C-packet at each A-node, the A-node changes the TS control timings and the route of the TS transmission according to information from the C-packet. Figure 9 shows the working TS control timings at the drop interface (IF) and add IF when receiving the C-packet at the A-node. In the initial status of Fig. 9, TDM1, TDM2, and TDM3 are set and working by receiving the O-packet. When receiving the C-packet from the M-node, the

Fig. 9 Working TS control timings at the drop IF and the add IF when receiving the C-packet at the A-node.

A-node changes the TS control timing at the add IF according to the information in the C-packet. In this case, the TS control timing working on the add IF is changed to TDM3 from TDM2. The timing of changing TS control timings is at the end of the TDM frame where the A-node receives the C-packet. Through this mechanism, the proposed method can share a TS from an optical burst mode transceiver between any route of arbitrary fiber length by changing both the route of the TS transmission and the TS control timing on the optical burst mode transceiver when a link failure occurs.

3.4 Detection for the Link Failure Using Control TSs

Here, we explain how to detect a link failure in the sequence of the proposed method as described in the previous Section. The point of how to detect a link failure in the proposed method is whether or not plural contiguous nodes detect the loss of control TSs simultaneously. This status is regarded as an occurrence of a link failure connected to the most upstream side's node in these contiguous nodes. Specifically, A-nodes and IC-nodes send control TSs attached the reception status of control TSs from the M-node. Then, M-node not only checks the reception status of control TSs

Fig. 10 Proposed method to detect a link failure.

from A-nodes and the IC-nodes but also checks the reception status of control TSs at the A-nodes and the IC-nodes. Through this mechanism, the proposed method can identify the link failure.

Following, we explain the proposed method to detect the link failure using Fig. 10, which shows a bidirectional two-stage ring network consisting of a M-node, an IC-node, and two A-nodes. IC-node, A-nodes#1, and A-nodes#2 are allocated control TS#1, #2 and #3, respectively. Case 1 and case 2 described in Fig. 10 are available and unavailable for the detection of a link failure in the proposed method, respectively. For case 1, a link failure between IC-node and A-node#1 occurs. On the other hand, for case 2, a link failure between IC-node and A-node#2 occurs. In case 1, M-node cannot receive the control TSs from the plural contiguous nodes A-node#1 and A-node#2. Then, the M-node recognizes the occurrence of the link failure between IC-node and A-node#1. On the other hand, in case 2, IC-node could not receive the control TS going around the lower ring. Therefore, the IC-node sends the control TS attached to the reception status of not receiving the control TS going around the lower ring from the M-node. Then M-node recognizes the occurrence of the link failure between A-node#2 and IC-node. However, in case 2, if a failure of the optical burst mode receiver for the control TS at the IC-node occurs, the IC-node also recognizes it falsely as an occurrence of an adjacent link failure at the IC-node. Therefore, this method could not distinguish between the failure of the optical burst mode receiver for control TS at the IC-node and the link failure between IC-node and A-node#2. There is a candidate method to address this issue, which is the deployment of two optical burst mode receivers for control TSs at the IC-node as active-active redundancy to increase the reliability of the optical burst mode receiver for control TS at the IC-node.

Fig. 11 Structure of each node.

3.5 Structure of Each Node

The structure of each node is shown in Fig. 11. This configuration is described only for supporting the CCW route on the upper ring to simplify the expression of figure. Each node has the TSC, which controls the TS control timing for a WDM/TDM SW and the EBC. To support the bidirectional routes on the upper ring, it is required that the TSC has to prepare the TS control timings for the CW route on the upper ring. Then, the EBC and WDM/TDM SW carry out the TS add/drop for each channel according to the TS control timing. Each TSC has an optical burst mode transmitter for sending the control TSs via the $\lambda c2$. The TSC at an IC-node deploys counters for TDM1 to control D-plane's TSs and TDM3 to transmit the D-packet via control TSs. Moreover, the TSCs at an IC-node and M-node deploy two receivers for the control TS to avoid collisions between the B-packet from the M-node and the B-packet after it goes around the lower ring and upper ring to measure the D_{RL} and D_{RU} , respectively. The M-node sends and receives the control packets to and from each node through control TSs via the $\lambda c1$ and $\lambda c2$. To compensate for the power loss of the λc , a fixed wavelength converter (FWC) is set to each port of the wavelength filter for the $\lambda c1$ and the $\lambda c2$.

In contrast, the A-node has add/drop interfaces connected to the EBC. The EBC and WDM/TDM SW interface at the A-node have to work at TDM1, TDM2, TDM3, and TDM4 according to the route of allocated TS transmission. To control the EBC and WDM/TDM SW's interface, the TSC at the A-node deploys the counters for TDM1, TDM2, TDM3, and TDM4. Then, according to the instructions from the M-node, the TSC changes the TS control timing

of the EBC and WDM/TDM SW's interface by switching the selector connected to each counter.

Here, we described how to realize the FWC and a candidate method to construct the FWC cost-effectively. As shown in Fig. 11, a FWC has to receive control TSs both from a FWC at an adjacent node and from its own node. Therefore, the FWC has to implement an optical burst mode receiver. Thus, a FWC consists of an optical burst mode receiver and a fixed-wavelength laser. In terms of cost-effectiveness for the FWC, there is further study for the construction of the FWC. However, as a candidate method to construct the FWC at a low cost, there is a method to apply a continuous mode receiver to the FWC. This concept is shown in [25]. This is achieved by adjusting the output power of an optical burst mode transmitter for the control TS at each node. This leads to the possibility of the application of a continuous mode receiver to a FWC. This means that further reduction of the CAPEX for the FWC may possibly be achieved in comparison to that for the FWC with application of an optical burst mode receiver.

3.6 Structure of WDM/TDM SW

Figure 12 shows the configuration of the WDM/TDM SW. The WDM/TDM SW has to execute TS add/drop operations for any route, any channel, and any TS. To achieve this, a WDM/TDM SW is composed of tunable wavelength converters (TWCs) at each input port and a wavelength filter. The WDM/TDM SW changes the route of TSs transmission by changing the wavelength of TS at the TWC, which can change the wavelength for every TS [12]. The TWC is controlled by the TSC based on the information of TSA and TS control timings set by M-node. A merit of the application of TWC is its ability to convert the wavelength to another one. This can avoid TS fragmentations and increase the efficiency of TS utilization [26].

Here, we show the implementation for the TWC. A practical way to directly convert wavelength at the optical level has not yet been established. Therefore, we use the TWC based on Optical-Electrical-Optical (OEO) conversion. In our approach, a TWC consists of a high-speed tunable laser and an optical burst mode receiver [12]. This optical burst mode receiver can recover the phase shift and loss imbalance for TSs from an adjacent node. This loss imbalance is caused by the combinations between the input

Fig. 12 Structure of WDM/TDM SW.

port and output port in the wavelength filter [27]. In this case, the TWC receives optical burst signals, which it converts to an electrical signal, and then transmits optical burst signals on the specified wavelength for every TS. Therefore, a TWC based on OEO conversion has to be deployed for each port of the WDM/TDM SW. As our previous study, we show our way of thinking for the CAPEX of this TWC [18]. In the reference to [18], to achieve the cost-effectiveness of the OL2SW-NW as the whole network system compared to the OTN as a conventional technology, the target value of the cost of TWC should be equal to the 3R regenerator of OTN. This 3R regenerator performs signal recovery by reamplifying, reshaping, and retiming the signal at the OEO processing. Currently, the tunable laser is still expensive. However, thanks to the progress of research and development of TDM/WDM-PON [28], which tunable lasers are applied for, tunable lasers will gradually come down in price.

4. Accuracy and Scalability for Proposed TS_{sync} Method

4.1 Accuracy of Proposed TS_{sync} Method

We estimate the accuracy of TS_{sync} (TS_{acc}) applied to the proposed method. This influences the effective bandwidth. Figure 13 defines TS_{acc} as the difference between the TS control timing at each node and the arrival timing of the TS. Therefore, the length of a guard band (L_{GB}) has to be set to be more than TS_{acc} to prevent TS collisions. The TS_{acc} consists of two factors: fluctuation of TS control timing and chromatic dispersion [18].

(1) Fluctuation of TS control timing

There are two factors that affect the fluctuation of TS control timing: (A) the processing of receiving and sending the control TS and (B) difference in the length of C-plane's and D-plane's route in a node (γ). (A) consists of (A1), which is the difference in the phase of Fq between each node (α), and (A2), which is 64B/66B encoding of the 10G-EPON [7] (β). (A1) is attributed to the difference between the arrival timing of the TS and the phase of Fq at the receiver. (A2) is attributed to the speed-conversion process of 64B/66B encoding, which transforms between 64-bit word at 161 MHz and 66-bit word at 156 MHz. Here, we discuss the degree of (A) and (B) for TS_{acc} at each step described in Sect. 3.3. We define N_L , N_U , and N_M as the number of A-nodes on a lower ring, C-nodes, and IC-nodes, respectively.

Step 1 is affected by (A) and (B) when sending and receiving the B-packet. (A) is generated by (A1) for receiving the B-packet and (A2) for sending/receiving the B-packet. Hence, (A) becomes $\alpha + 2\beta$. Meanwhile, (B) is generated at

Fig. 13 Definition of TS_{acc} .

every node the B-packet goes through. Then, (B) becomes $\gamma(N_U + N_M + N_L)$ at maximum.

Step 2 is affected by (A) and (B) when receiving the B-packet twice at the IC-node to measure D_{RL} and sending/receiving the D-packet between the A-nodes and M-nodes. For the B-packet, (A) is generated by (A1) and (A2) at the IC-node receiving the B-packet twice to measure D_{RL} . Hence, (A) and (B) for B-packets become $2\alpha + 2\beta$ and γN_L , respectively. (A) and (B) for D-packets are the same as those in Step 1. Hence, (A) and (B) for D-packets become $\alpha + 2\beta$ and $\gamma(N_U + N_M + N_L)$ at maximum. Note that Steps 3, which are the processes of setting TDM 2, TDM3, and TDM4 using the O-packet, do not affect TS_{acc} because TDM 2, TDM3, and TDM4 are set based on TDM1 at the A-node regardless of the arrival timing of the O-packets.

(2) Chromatic dispersion

In the assumed network model, it is impossible to ignore the effects of chromatic dispersion because the total length of fiber becomes several hundred kilometers at maximum. The delay time for each channel affected by the chromatic dispersion is described as $D_d \cdot W \cdot G_r \cdot L_{total}$; here, D_d is the chromatic dispersion, W is the number of wavelengths for a fiber, G_r is the channel spacing, and L_{total} is the maximum distance of a TS traversal. Then, TS_{acc} is expressed as Eq. (1).

$$TS_{acc} = (4\alpha + 6\beta) + 2\gamma\left(\frac{3}{2}N_L + N_M + N_U\right) + D_d B_{fiber} G_r L_{total} \quad (1)$$

As described in Sect. 3.3, the method to measure the propagation delay between each node is using control TSs. However, a difference occurs between the propagation delay for control TS and that for the desired data channel affected by chromatic dispersion. There are two methods to deal with this difference in propagation delay. One is to adjust the TS control timings according to the propagation delay of TS on each data channel. In this method, each TS control timing is corrected by calculating $D_d \cdot \Delta\lambda \cdot L_{total}$; $\Delta\lambda$ is the difference of wavelength between the control channel and the desired data channel. This approach can increase in the effective bandwidth caused by the achievement of the reduction of the guardband. However, this approach is required for adjusting TS control timings at every TS according to the TS's wavelength. Therefore, it leads to difficulty in controlling of TSs and the increase in the required hardware resources in the TSC. Another method is, in terms of the simplification for the implementation of the TSC, setting the guardband for absorbing the difference of the propagation delay between the control channel and the desired data channel to each TS. In this paper, we adopt the latter on grounds of simplification for the implementation of the TSC.

4.2 Scalability for Proposed TS_{Sync} Method

Following, we show the scalability for the number of stages and rings in the proposed method. Regarding the number of

stages, the greater the number of stages ($:N_{Stage}$) increase, the more the number of routes of TS transmission ($:N_{Route}$) increases according to $N_{Route} = N_{Stage}^2$. This means that the required number of TS control timings and wavelengths increase in proportion to N_{Route} . For the number of TS control timings, this affects the size of the TS table in the TSC to manage the TS control timings and the information of allocated TSs. Therefore, the more the number of stages increases, the more the required hardware resources in TSCs increases. Therefore, it is necessary to design the size of TS table in the TSC in accordance with the number of accommodated stages in the target network system. On the other hand, the increase in the number of rings leads to an increase in the number of IC-nodes. Therefore, the TS_{acc} deteriorates caused by increasing in the number of accommodated nodes which TS goes through. Therefore, it is necessary to design the effective bandwidth in accordance with the number of accommodated rings for the target network systems.

5. Characteristic of N_{IF} for OL2SW-NW

There is a probability of deteriorating TS_{acc} caused by TS_{Sync} for the whole network. Therefore, L_{GB} must be set at more than TS_{acc} for every TS to avoid TS collisions. That is to say, the larger L_{GB} is, the more N_{IF} increases under the condition that the volume of accommodated traffic is the same. In the following, we evaluate the required L_{GB} of the OL2SW-NW in the assumed network model and the N_{IF} .

5.1 Assumed Network Parameters

To evaluate L_{GB} , here we show the assumed network parameters. Figure 14 shows the assumed physical and logical network model of the OL2SW-NW, which is a bidirectional two-stage ring network aggregating traffic from 1000 SWs on the access network to 10 IP routers on the core network. This means that the OL2SW-NW accommodates 1000 A-nodes and 10 C-nodes. We assume that the maximum number of N_L is 25. In this case, N_M becomes 40 at maximum. The fiber lengths around the upper ring and the lower ring are 20 and 400 km, respectively. Also, we assumed that one L2SW has a 10 GE interface that accommodates 1000 users. Since the assumed calling rate is 10% at most, 100 users can simultaneously connect to the OL2SW-NW from

Fig. 14 Assumed network model; (a) physical network and (b) logical network.

an L2SW. Also, we assume that the average traffic from a user flows at 50 Mbps. Then, the total average traffic from an A-node becomes 5 Gbps. In this case, the traffic volume on average from one L2SW to a C-node (TR) becomes 0.5 Gbps. Other network parameters for evaluating L_{GB} are shown as follows. We set γ to be 1 m (equal to 5 ns), and α and β were 6.4 ns assuming that Fq was 156 MHz. Also, we assumed G_r , W , and D_d were 50 GHz, 100 wavelengths, and 17 ps/nm/km [29], respectively. Here, the TR was set at from 0.1 Gbps to 1 Gbps. In other words, the maximum amount of traffic from one L2SW was set to 1 Gbps or 10 Gbps, respectively.

Here, we described the required interface speed for the control channel. The OL2SW-NW has to both change the route of TS transmission when the link failure occurs and control the DBA. Therefore, it is desirable for the achievement of both the fast restore from the occurrence of the failure and shortened DBA cycle to increase the efficiency of the accommodated traffic [13]. The control information related to DBA and the detection of a link failure is transmitted using control TSs between each node. As an example, the size of control information for DBA becomes about 10 Kbytes in the assumed network model according to [13]. If the interface speed for the control plane is 1 Gbps, the required size of a control TS become about 100 μ s. In this case, the time to collect control information from 1000 A-nodes become about 100 ms. This value not only affects the effective bandwidth to accommodate the traffic in terms of DBA, but also has a significant impact on the required time to restore a link failure. In this case, our proposed method isn't sufficient for conventional ether ring protection to provide 50-ms protection [30]. Therefore, we adopt 10 Gbps interface speed for the control plane.

5.2 Characteristic of P-OADM and OL2SW-NW

Here, we show the characteristic of N_{IF} in the OL2SW-NW compared with that of the P-OADM as a conventional technology (Table 2). We define N_{IF} in the OL2SW-NW as N_{IF}^{OL2} and in the P-OADM as N_{IF}^{P-OADM} . We show the difference in characteristics between P-OADM and OL2SW-NW in Table 2.

P-OADM extracts the control information from a packet and transports the control information via a control channel so as not to have to demodulate all the wave-

lengths at each node. According to this control information, each node autonomously operates the transmission of optical slots. The control information also provides the timing of optical slot transmission to an adjacent node. Then, the size of L_{GB} for the P-OADM is equal to the difference in the length of the C-plane's and D-plane's route in a node. Therefore, the P-OADM can increase the effective bandwidth. However, it is required to adjust the fiber between each node to support a bidirectional multi-ring network. These fiber adjustments are required for the interconnection of rings to achieve TS_{Sync} between rings and for the link between each node to achieve TS_{Sync} between bidirectional routes. Moreover, the IC-node of the P-OADM requires the packet buffer because it is not a guarantee of optical slot collision between the upper and lower ring. If there is no contention from other incoming optical slots, the optical slot is switched to the output port, passing through the IC-node transparently. However, in the case of contention, the packets in the optical slot are stored to the shared packet buffers for temporary storage. Therefore, if TR is larger, N_{IF}^{P-OADM} at the IC-node is increased.

On the other hand, the OL2SW-NW can multiplex the traffic without applying an electrical L2SW for the whole network. This is achieved by applying TS_{Sync} for the whole network and controlling DBA. Thanks to this mechanism, the OL2SW-NW does not need the packet buffer at the IC-node. As a result, it is possible to reduce N_{IF}^{OL2} to insert the packet buffer at the IC-node. In contrast, the OL2SW-NW requires the increase in L_{GB} to avoid TS collisions for the TS_{Sync} for the whole network. Therefore, a slight decrease in effective bandwidth occurs.

5.3 Mathematical Expression for N_{IF} at Each Method

Here, we explain the mathematical expressions for N_{IF} at each method. We show the model of N_{IF}^{tech} when using the technology $tech \in \{OL2, P-OADM\}$. N_{IF}^{tech} for each method is expressed as

$$N_{IF}^{tech} = \sum_{i \in S} \left\lceil \sum_{j \in D} \left\lceil (T_{i,j} / B_{TS}) / BU_{eff}^{tech} \right\rceil / N_{TS} \right\rceil + \sum_{j \in D} \left\lceil \sum_{i \in S} \left\lceil (T_{i,j} / B_{TS}) / BU_{eff}^{tech} \right\rceil / N_{TS} \right\rceil + N_M N_{IF-JC}^{tech} \quad (2)$$

Here, $\lceil \cdot \rceil$ represents the ceiling function, S is the node sending the traffic, D is the node receiving the traffic from S , T is a matrix indicating the traffic, $T_{i,j}$ is the traffic from node i to node j , BU_{eff}^{tech} is the effective bandwidth for allocated TSs, B_{TS} is the capacity of a TS expressed in bps, N_{IF}^{tech} is the N_{IF} at an IC-node, and N_{TS} is the number of TSs on a wavelength in a L_{FR} . BU_{eff}^{tech} is expressed as $(N_{A-TS} \cdot L_{TS} - L_{GB}^{tech}) / (N_{A-TS} \cdot L_{TS})$. N_{A-TS} and L_{GB}^{tech} are the number of allocated TSs for a logical path and the length of the guard band for a TS with the application of $tech \in \{OL2, P-OADM\}$, respectively. N_{A-TS} increases in proportion to the accommodated TR . The first, second, and

Table 2 Comparison of P-OADM and OL2SW-NW.

	P-OADM	OL2SW-NW
Packet buffers and optical IF in intermediate node	[Poor] Need for packet buffers and optical IF in intermediate node to insert optical slots to packet buffers to avoid collision of TS between rings.	[Fair] No need to set packet buffers in intermediate node by synchronizing TSs in all nodes.
Effective bandwidth (BU_{eff})	[Fair] Guard band attributed to the TS_{acc} for whole network not required.	[Poor] Decreasing because of TS_{Sync} in whole network.
Fiber adjustment	[Required] For the fibers between bidirectional routes and between multi rings.	[Not required]

third terms of Eq. (2) denote N_{IF} at the source node, N_{IF} at the destination node, and N_{IF} at the IC-node, respectively. This formulation has two kinds of ceiling functions. The outer ceiling function represents the unit of an optical interface to accommodate the TSs. The inner ceiling function represents the unit of TS. The difference in BU_{eff}^{tech} between the P-OADM and OL2SW-NW is L_{GB}^{tech} caused by TS_{acc} . The TS_{acc} of the OL2SW-NW is deteriorated in order to require TS_{sync} for the whole network. However, the OL2SW-NW does not require N_{IF} to avoid TS collisions at the IC-node because of the achievement of TS_{sync} for the whole network.

6. Evaluation of Proposed Method & Discussion

We evaluated the effectiveness of our proposal from two perspectives; the first is (i) the feasibility of the proposed method, which changes TS control timing dynamically. The index of evaluation (i) is the time of changing TS control timing and TS_{acc} using prototype systems. These have an effect on the size of BU_{eff} , which affects the N_{IF} . The second is (ii) the evaluation of the required N_{IF} assuming the results of (i). This affects the CAPEX.

6.1 Experimental & Evaluation Conditions

(1) Experimental conditions for changing TS control timing and TS_{acc}

We conducted an experiment on TS exchange in a bidirectional bufferless WDM/TDM two-stage rings network using the prototype systems. We evaluated the speed of changing TS control timings (T_{timing}) and TS_{acc} . The experimental setup for evaluating T_{timing} and TS_{acc} is shown in Fig. 15. We set a M-node, an IC-node, and two A-nodes and set TSCs for these nodes. The scenario is that the A-node#1 sent a TS via the CCW route to the IC-node. Then, the A-node#1 changed the route of the TS transmission and TS control timing when a link failure between the A-node#1 and the A-node#2 occurred (Fig. 15(b)). We emulated a TWC in the WDM/TDM SW using both a 1x2 optical SW [31] and optical couplers. Figure 15(c) shows the prototype of TSC. This prototype of TSC has a 10G optical burst mode transmitter for the control plane and a 1GE IF for connecting to the EBC for the control plane. This TSC also connects to the 1x2 optical SWs using coaxial cables (Fig. 15(a)). If the TSC receive the C-packet from the TS synchronizer, the TSC send both the signal of changing the switched port to the 1x2 optical SW connected to the add IF via a coaxial cable and the signal of changing the TS control timing to the EBC via the 1GE. We used three wavelengths, one for the data channel (λ_1) and two control channels (λ_{c1} , λ_{c2}). To confirm that the TSs from an EBC are shared between the CW route and CCW route and do not collide at the IC-node, a real-time oscilloscope was set to the IC-node's interface. The TS numbers allocated to A-nodes#1 and #2 were TS#1 and TS#3. Moreover, to measure TS_{acc} while changing the TS control timing for an arbitrary fiber length between each

Fig. 15 Experimental conditions; (a) experimental setup, (b) experimental scenario, and (c) prototype of TSC.

node, we set the optical delay generator for the length between the IC-node and A-node#1 (D_2).

(2) Simulation conditions for required N_{IF}^{OL2}

To confirm the effectiveness of the OL2SW-NW, we evaluated N_{IF}^{OL2} on the basis of the experimental results and Eq. (2). Here, the TR described in Fig. 14 was set to three patterns: 0.1, 0.5, and 1 Gbps according to the assumed network parameters in Sect. 5.1. In other words, the amount of traffic from one L2SW was set to 1, 5, and 10 Gbps, respectively. Here, we define the ratio of N_{IF} (R_{IF}) as $N_{IF}^{OL2}/N_{IF}^{P-OADM}$. If R_{IF} is smaller than 1, this means that N_{IF}^{OL2} can be reduced more than N_{IF}^{P-OADM} when accommodating the same amount of traffic. When multiple TSs were allocated for the same destination, we applied a multi TS bonding technique [32], which allocates successive TSs. L_{FR} , L_{TS} and L_{GB} were 1 ms, 10 μ s, and 100 ns, respectively. To evaluate the applicable area for the OL2SW-NW, we changed $N_L = 1 - 25$, $N_M = 5, 40$, and $TR = 0.1, 0.5, 1$ Gbps, respectively.

6.2 Experimental Results of Speed of Changing TS Control Timings

Figure 16 shows the results of T_{timing} at A-node#1, which changed the TS control timing from TDM2 to TDM3. As you can see, the proposed method could achieve T_{timing} within one TDM frame (1 ms) from receiving the C-packet. This switching time is not the constraint of hardware specifications of TSC but the TS control timing that TSC switches to. This is determined by the difference in the delay between

Fig. 16 D-plane's TS signals from A-node #1 with changing TS control timings; (a) arrival timing of C-packet at A-node #1, (b) D-plane's TS signals with changing TS control timing from A-node #1, (c) TS control timing for add via CCW route (TDM2), (d) TS control timing for add via CW route (TDM3) at A-node #1, and (e, f) enlarged view of (b), (c), and (d).

Fig. 17 D-plane's TS signals from each A-node changing both routes of TSs transmission and TS control timings at IC-node; (a) D-plane's TS signals from different A-nodes, and (b, c) enlarged view of (a).

the routes of TS transmission. However, the time taken to identify a link failure was not taken into account in this experiment. This time is determined by the network size. If the D_R is several hundred km, the time taken to detect the link failure at the M-node is about the round trip time between an A-node and M-node. Therefore, this time becomes a few ms. Hence, this result could be sufficient for conventional ether ring protection to provide 50-ms protection [30]. Figure 17 shows the results of receiving the D-plane's TS signals at the IC-node from different A-nodes by changing both the route of the TS transmission and the TS control timing at $D2 = 2 \mu\text{s}$ for the above experiment. As you can see, these signals were multiplexed without TS collisions according to the TS control timing at the IC-node.

6.3 Experimental Results of TS_{acc}

Figure 18 shows the TS_{acc} with the proposed method at the IC-node for the length of $D2$ under the same conditions for the above experiment. It shows the maximum, minimum, and average values for 10 seconds measurement time at length $D2$ from 1 to 10 μs . At each length of $D2$, the width of the TS_{acc} means the fluctuations of TS control timings caused by 64B/66B encoding of the 10G-EPON described

Fig. 18 TS_{acc} with proposed method.

in Sect. 4.1; 6β ($= 38.4 \text{ ns}$ at maximum). The difference in the offset of the TS_{acc} between each length of $D2$ means the fluctuations of TS control timings caused by the difference in the phase of Fq between each node described in Sect. 4.1; 4α ($= 25.6 \text{ ns}$ at maximum).

In total, the TS_{acc} were within 60 ns of the length of $D2$. This result was almost equal to the designed value for the fluctuation in TS control timing: $4\alpha + 6\beta$ in the first term of the right part of Eq. (1) at $\alpha, \beta = 6.4 \text{ ns}$ without considering both the affection of the chromatic dispersion and the difference in the length of C-plane's and D-plane's route for all accommodated nodes.

Based on these experimental results, we evaluated the total TS_{acc} in the proposed method considering the assumed network parameters described in Sect. 5.1. Firstly, the maximum difference in the length of C-plane's and D-plane's routes in the whole network was calculated as 375 ns by considering the total number of accommodated nodes according to the description in Sect. 4.1 (1). Next, the maximum difference in the propagation delay for each channel affected by the chromatic dispersion was calculated as 286 ns considering the length of the ring according to the description in Sect. 4.1 (2). As a result, TS_{acc} becomes about 720 ns in total. This is equal to 92.8% of the effective bandwidth for L_{TS} ($: 10 \mu\text{s}$). In the following, we evaluate the required N_{IF} based on this effective bandwidth.

6.4 Simulation Results of N_{IF}

Finally, we evaluate the required N_{IF} for each method by calculating R_{IF} ($: N_{IF}^{OL2} / N_{IF}^{P-OADM}$) using Eq. (2). Figure 19 shows the R_{IF} when changing N_L (from 1 to 25), N_M ($: 5$ and 40) and TR ($: 0.1, 0.5$, and 1 Gbps), respectively. It is clear that the R_{IF} decreased as the TR increased. This is because, for the P-OADM, the larger the TR increases, the larger the number of collisions of TSs increases at the IC-node. Therefore, for the P-OADM, the required packet buffer and N_{IF} in the IC-node increase according to the increase in N_L and N_M . In comparison, for the OL2SW-NW, BU_{eff} increases as a result of the successive TSs allocations [32] according to the increase in TR . However, as a trade-off relationship, N_{IF}^{OL2} increases according to N_M and N_L because the OL2SW-NW requires the increase in L_{GB} , which is proportional to N_M and N_L . As a result, R_{IF} increases according to the increase in N_M and N_L .

From the above results, we found that the OL2SW-NW was effective in terms of the reduction of N_{IF} . In particular,

Fig. 19 R_{IF} when changing N_M (5 or 40) and N_L (from 1 to 25) at $TR = 0.1, 0.5, 1$ Gbps.

in this experimental condition, R_{IF} at minimum became 0.7 at $N_L = 25$, $N_M = 40$, and $TR = 1$ Gbps. This means the OL2SW-NW could reduce the N_{IF} by 30% at maximum. In view of the above results, we could find that the OL2SW-NW could be effectively applied to an aggregation network, which has to accommodate an ever-growing traffic volume while suppressing the CAPEX of aggregation networks.

7. Conclusion

In this paper, we proposed an OL2SW-NW for supporting bidirectional bufferless multi-ring networks to achieve a cost-effective and reliable aggregation network toward the future internet. The proposed network can eliminate both the packet buffer and optical interface at the IC-node by achieving TS_{Sync} for the whole network in the arbitrary lengths and arbitrary routes. To achieve this, we proposed a TS_{Sync} method that dynamically changes the routes of TS transmission and the TS control timing of a WDM/TDM SW and an EBC at each node according to the occurrence of a link failure. The important point of the OL2SW-NW is how to decrease L_{GB} , as this affects N_{IF}^{OL2} . To evaluate L_{GB} , we conducted experiments to measure TS_{acc} . Using prototype systems, we found that the required L_{GB} were about 60 ns caused by the fluctuation of TS control timing to achieve TS_{Sync} for the whole network. On the basis of the above experimental results, we conducted a simulation to evaluate N_{IF}^{OL2} when changing N_M , N_L and TR in comparison with N_{IF}^{P-OADM} . For the assumed network model, we found that the OL2SW-NW could reduce the N_{IF} by 30% at maximum. In view of the above results, we could find that the OL2SW-NW could reduce N_{IF} . Therefore, we concluded that the OL2SW-NW could effectively aggregate the

traffic while suppressing the CAPEX of future aggregation networks.

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