Traffic Accommodation Methods
for Optical Compression TDM/WDM Ring Networks

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Abstract

High–speed optical ring networks can be recently realized by an optical pulse compression/expansion technology based on a TDM (Time Division Multiplexing) technique (OCTDM). We first consider the path accommodation method for the OCTDM ring. We derive a theoretical lower bound on the numbers of slots and frames in order to allocate all paths among nodes. Three path accommodation algorithms for the all–optical access are next proposed to achieve the lower bound as closely as possible. Some numerical results show that at least one of those algorithms which we propose as A1, A2, and A3 for OCTDM ring can offer a good result close to the theoretical lower bounds, but there is no best one that always yields the shortest superframe. Thus, our recommendation is that all our proposed algorithms should be performed and the best one is chosen to set up the optical paths. Path splitting is next considered to improve the traffic accommodation. Finally, we analyze the packet delay time for given numbers of slots/frames, which are decided by our proposed algorithms. Numerical examples are also shown to examine the effectiveness of our proposed algorithms including path accommodation and path splitting methods.

To provide more bandwidth, it can be combined with a WDM (Wavelength Division Multiplexing) technology where OCTDM is applied to each wavelength. In this paper, we next consider the optical ring where the combination of OCTDM and WDM is utilized. When constructing OCTDM/WDM rings, we need to consider the balance of the network resources including the number of wavelengths, the traffic volume between every node pair, the packet I/O processing capability (the numbers of optical compression devices and optical expansion devices) at each node, and the optical compression ratio. The latency of tuning the wavelength used for the packet transmission is another important factor when the OCTDM/WDM ring is considered. We first analyze the theoretical lower bound on the superframe length of the OCTDM/WDM ring network by taking into account the above parameters including the tuning latency. We next propose a path accommodation method to assign each path of the source–destination pair to the optical slot. We evaluate our proposed method by comparing with the theoretical lower bound to see how well our algorithm can provide the path accommodation. The packet delay times are also investigated to see the influence of the tuning latency. Some numerical results show that our algorithm which we propose as APW+APTRS for OCTDM/WDM ring can provide reasonable path accommodation in the sense that the number of slots which are needed for accommodation by our algorithm is close to the theoretical lower bound. Furthermore, we can observe that the algorithm is effective for both of uniform and nonuniform traffic load cases with almost all conditions.

Keywords

Optical Compression/Expansion Technology

OTDM (Optical Time Division Multiplexing)

WDM (Wavelength Division Multiplexing)

Traffic Accommodation Method

Optical Unidirectional Ring Network

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1 Introduction

Very high–speed optical networks are expected for establishing the next–generation broadband data communications. In this paper, we treat the optical ring networks, which are widely used for the metropolitan area networks (MAN). In a last few years, it becomes evident that an optical pulse compression/expansion technology [1-3] is useful for the optical time–division multiplexing (OTDM) rings, which we will call OCTDM (Optical Compression TDM). OCTDM can provide high–speed backbone networks with one to tens of Gbps [4, 5]. As described in [4], when the optical node of the OCTDM ring receives a packet from LAN, bit intervals of the packet are shortened to fit the time–slot length of the backbone ring. Also, when receiving the packet at the destination node, it is lengthened to fit the LAN speed.

In OCTDM, we need a path accommodation method to decide how each slot within a frame is used by every node pair. In the conventional TDM, it is easy to accommodate the traffic on the ring. Suppose that the ring has N nodes, numbered from 0 to $N-1$. The ith slot within the frame (consisting of N slots) is allocated to the ith source node. The ith source node always transmits the packet on the ith slot. The destination node retrieves the packet by observing the destination address in the header. It implies that the destination node can receive at most $N-1$ packets within the frame time. In OCTDM, on the contrary, the number of slots transmitted (and received) within the frame is limited by the numbers of optical compression devices (and optical expansion devices), since it employs the optical pulse compression/expansion for ring access [6]. We will show the path accommodation methods suitable to the bidirectional OCTDM rings consisting of 2 fibers (clockwise and anti-clockwise) in [7, 8].

In this paper, we first propose the path accommodation methods for unidirectional rings with OCTDM [9, 10]. The methods for all–optical access are described by which we try to obtain the minimum number of required slots close to the theoretical lower bound. If this is not possible, we allow some all–optical paths to be split in order to achieve higher performance. A similar idea of path splitting is presented in [11] for WDM rings. The path splitting method is then investigated to improve the degree of path accommodation. An ideal realization of optical networks is achieved by all–optical connection between every node pair. However the performance of OCTDM rings can actually be improved by carefully splitting several paths at intermediate nodes, unless OE/EO conversion is not a bottleneck.

Against further bandwidth demands, an introduction of a WDM (Wavelength Division Multiplexing) technology is promising. Fortunately, OCTDM and WDM are not independent technologies, but both can be combined. One way is that WDM provides multiple channels of the wavelength on the fiber, and OCTDM does a channel access mechanism. In this paper, we propose an effective path accommodation method for such an OCTDM/WDM ring network. For TDM/WDM networks, several researches have already been made [12-14]. The path accommodation method for the TDM/WDM star-based networks is shown in [13], and the medium access control protocol for the TDM/WDM ring networks is proposed in [15]. On the contrary, OCTDM/WDM ring networks that we treat in this paper can be expected to provide much larger capacity. However, the number of slots that can be accessed by nodes during the frame is limited due to the optical pulse compression/expansion, which may inhibit the performance improvement. Therefore, we need to newly develop a path accommodation method suitable for the OCTDM/WDM ring networks. Following [13], we also consider the latency of wavelength tuning, which is necessary in order to change the wavelength used for packet transmission. It is important for the WDM technology to be applied in our system [16].

The rest of the paper is organized as follows. In Section 2, we first describe an OCTDM/WDM ring structure and the optical pulse compression/expansion technology. Our model is next presented in Section 3. In Section 4, we first show the derivation of the minimum number of slots needed to accommodate traffic, and we propose and evaluate the traffic accommodation method for the unidirectional OCTDM rings. In Section 5, our traffic accommodation method is proposed and discussed for the unidirectional OCTDM/WDM rings. Conclusions and future works are summarized in Section 6.

2 Technologies and Structures of the Optical Compression TDM/WDM Ring

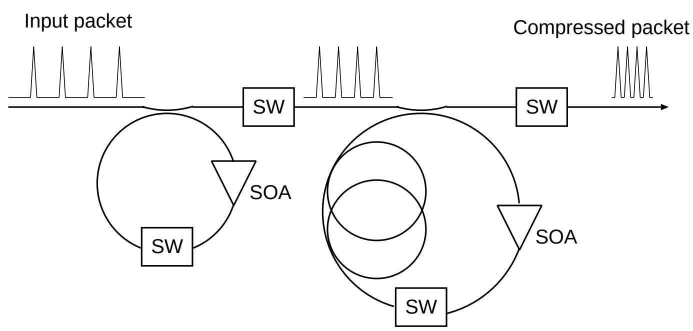


Figure 1: Optical Compression Device

In this section, we first present the technologies of optical pulse compression/expansion in Section 2.1. In Section 2.2, the access method to the OCTDM ring consisting of single wavelength is shown. We next consider the OCTDM/WDM rings. Compared with the OCTDM ring, the structure of the OCTDM/WDM ring becomes complicated because, in the access method, we have to consider the management of multiple wavelengths. In Section 2.3, we introduce a structure of each node for the management of multiple wavelengths. The access method to the OCTDM/WDM ring consisting of multiple wavelengths is also described.

2.1 Optical Pulse Compression/Expansion Technologies

An optical pulse compression/expansion is promising to realize the very high-speed backbone ring [6]. When a packet with fixed-size is put on the optical line, a bit interval is compressed by using the fiber delay loop (Figure 1). Since the compression rate with one loop is limited, several steps may be necessary to achieve a high compression rate if it cannot be realized at a time. The compression/expansion frequency at each compression/expansion device is also limited, and multiple optical compression/expansion devices are necessary at each access point if consecutive packets are compressed/expanded at the node.

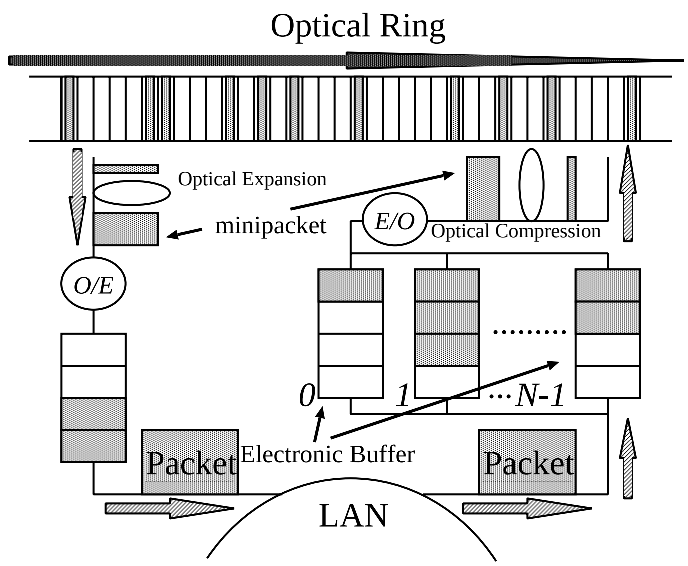


Figure 2: Node Stfucture of the Optical Compression TDM Ring

To compensate the loss on the fiber delay loop, a semiconductor optical amplifier (SOA) and the switch (SW) are inserted on the loop. The packet is then transmitted onto the ring. When the receiver node receives the packet from the optical line, a bit expansion is performed by a reverse procedure of the bit compression. More details of the optical pulse compression technique are described in [1-3].

2.2 Access Method to Optical Compression TDM Ring

In this subsection, we describe the access method of the unidirectional OCTDM ring consisting of single wavelength. Figure 2 shows the access method to the ring at each node. Packets arriving at the node from LAN are first queued at electronic buffers. Separate buffers are prepared according to the destination node. The arriving packet is divided into minipackets to be fitted into one time slot. After the minipacket is optically compressed by the fiber delay loop, it is put into the slot, which is allocated to the source/destination node pair in advance. After receiving the packet (consisting of several minipackets) from the ring, the packet is reconstructed and forwarded to the destination LAN.

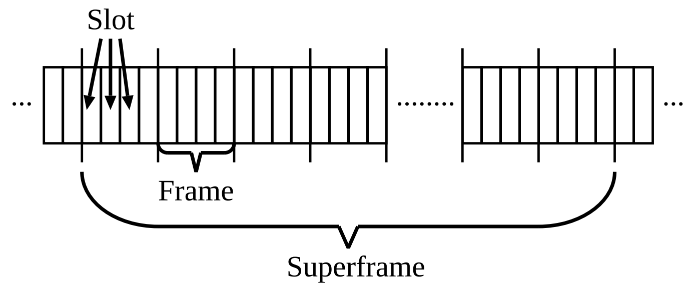


Figure 3: The Relation of Slots, Frames, and Superframes

The transmission speed of the minipacket is identical to that of the backbone OCTDM ring. However, there is a limit on the number of minipackets that the transmitter can put into the slot, due to speed mismatch between the backbone ring and LANs. More precisely, each optical compression device can place only one minipacket during the fixed time duration, which is referred to as the *frame* (Figure 3) in this paper. The number of minipackets that each receiver can receive within one frame is also limited to one. The number of slots required to accommodate all the paths between every source–destination pair is called the *superframe* (Figure 3). The superframe may consist of several frames. The superframe is cyclically carried on the ring.

If some node has a multiple number of optical compression devices (optical expansion devices), it can transmit (receive) more than one minipacket within the frame, which possibly results in a shorter length of the superframes. However, optical compression/expansion devices are costly, and they are limited resources in the OCTDM ring.

2.3 Access Method to Optical Compression TDM/WDM Ring

When the ring network has multiple wavelengths, we must decide the structure of each node by carefully considering the cost, effectiveness, and future extension. If every node is equipped with enough optical components to access to all wavelengths at the same time, each node can communicate with the others without wavelength conversion. However, it is not realistic especially when we consider the network cost, and we follow [13] that we assume each node has a pair of Tuning Transmitter and Fixed Receiver (TT-FR). By using optical compression/expansion, one wavelength can provide the bandwidth of 10 to 100Gbps, and multiple wavelengths can increase the line bandwidth. However, since we only have one set of TT-FR, the tuning latency with TT should be considered. For example, by a wavelength with bandwidth of 40Gbps and a packet size (being identical to time slot) of 100byte, each time-slot becomes $\frac{100\times 8}{40\times 10^9} = 20$ ns. Since today's TT requires the tuning latency to be in the almost same order of time-slots, the tuning latency should be explicitly taken into account. In this paper, we consider the unidirectional OCTDM/WDM ring network. It is assumed that a wavelength is time-slotted, and every slot is synchronized over wavelengths. Except the wavelength tuning latency at each transmitter described above, the access method to multiple wavelengths is same as the one for single wavelength in Section 2.2.

The access method to the ring is as follows. When each node has a packet to be transmitted to the optical ring, the packet is first queued in the electric buffer according to its destination address. It is then divided into several minipackets. Each minipacket is transmitted using a preassigned slot. If the wavelength of that slot is different from the current tuned wavelength, wavelength tuning is performed. A determination of the slot that the minipacket for the source–destination pairs is transmitted is performed by a path accommodation method. The minipacket is optically compressed by optical compression device for its transmission. In a similar way, when receiving the compressed minipacket at a destination node, the original packet is reconstructed after expanding each minipacket by using an optical expansion device. Each node must be equipped with at least one optical compression/expansion device for the access to the ring, and the access capacity is decided by the number of such devices and optical compression/expansion rate. As noted above, each optical compression (expansion) devices can compress (decompress) one minipacket at a time. We assume that each optical compression device (and expansion device) can access only one slot during one frame due to a limitation of optical compression/expansion. Since all paths cannot be always accommodated within one frame, we also introduce superframe as the case of the OCTDM ring with a single wavelength. In our path accommodation method, we will try to effectively assign slots and wavelengths to all the paths so that the superframe length is minimized. Then, the network throughput is maximized.

3 Network Model and Traffic Demands

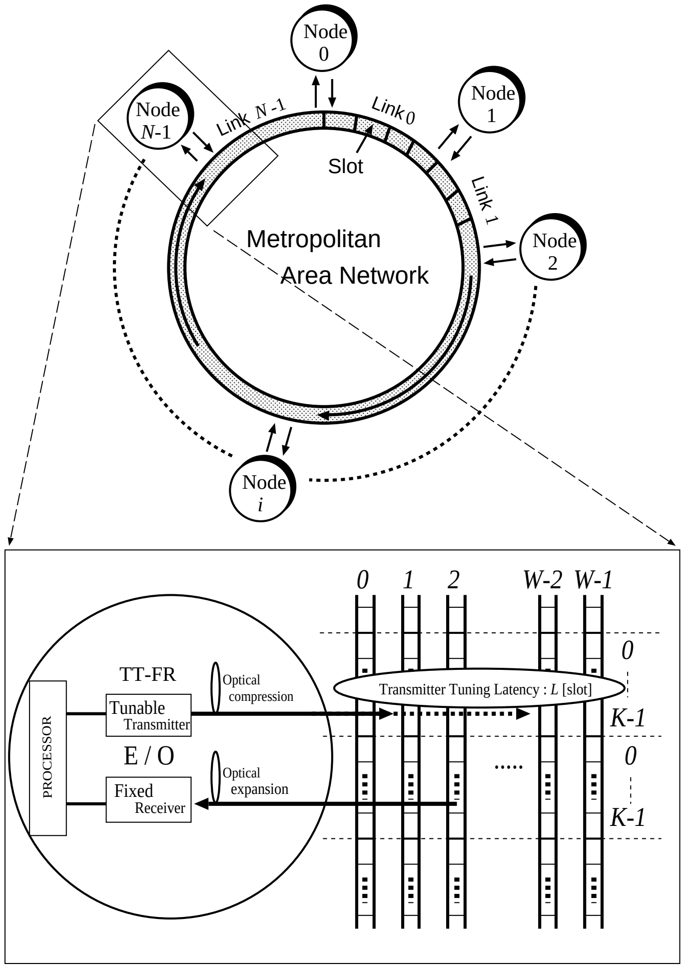


Figure 4: Network Model of the Optical Compression TDM/WDM Ring

3.1 Network Model

In this subsection, we introduce our network model of the OCTDM/WDM ring. See Figure 4 for its structure. We assume a unidirectional OCTDM(/WDM) ring with N nodes, which are numbered clockwise from 0 to $N-1$. As shown in Figure 4, the link n connects nodes n and $n+1$. On the link, there are the number W of wavelengths. Each capacity of wavelengths is B_R [bps]. A length of one frame is denoted as K, during which each of optical compression/expansion device can access only one time to the optical ring. The tuning latency is represented by L slots.

That is, after transmitting the minipacket on some wavelength, say λ_1, L slots are needed to begin transmitting the next minipacket if it should be put on another wavelength λ_i ($i \neq 1$). Assuming that node i is equipped with T_i optical compression and R_i optical expansion devices, let $\mathcal{T} = \{T_0, T_1, \cdots, T_{N-1}\}$ and $\mathcal{R} = \{R_0, R_1, \cdots, R_{N-1}\}$ be the sets of optical compression and optical expansion devices, respectively.

The path from source node i to destination node $(i+s)$ is represented by (i,s), where s is a clockwise distance between two nodes in hop counts. We will use k $(\geq N)$ to represent the node number in order to simplify the presentation. In such a case, k should be read as $\mathrm{mod}(k,N)$.

3.2 Traffic Demands

Our main purpose in this subsection is to determine the number of slots for each source/destination pair within a superframe. For this, we assume that an $N \times N$ traffic load matrix $F = \{f^{(i,s)}\}$ is given, where $f^{(i,s)}[\mathrm{bps}]$ is the traffic demand from source node i to destination node $i+s$. The total sum of traffic loads should not exceed the capacity of the backbone ring so that it will always be possible to accommodate all paths. That is, the following three conditions should be satisfied.

- Traffic load on each link should not exceed the link capacity.

$$(\forall i) \qquad \sum_{j=i+2}^{i+N} \sum_{s=(i+N+1)-j}^{N-1} f^{(j,s)} \leq B_R W \tag{1}$$

- Traffic load at node i should not exceed the transmission capability at that node.

$$(\forall i) \qquad \sum_{s=1}^{N-1} f^{(i,s)} \leq B_R \times \frac{T_i}{K} \tag{2}$$

- Traffic load reception at node i should not exceed the receiving capability at that node.

$$(\forall i) \qquad \sum_{k=0,k\neq i}^{N-1} f^{(k,i-k)} \leq B_R \times \frac{R_i}{K} \tag{3}$$

Since we treat the accommodation methods of slots within the frame, we represent the traffic demand matrix in units of slots. The $N \times N$ matrix $C = \{c^{(i,s)}\}$ that we will actually use below is determined by

$$C = \{c^{(i,s)}\} = \left\{ \left\lceil \frac{f^{(i,s)}}{h} \right\rceil \right\}, \tag{4}$$

where h is some positive real number ($0 < h \le \max f^{(i,s)}$). Matrix C should satisfy

$$(\forall i \forall s) \quad \frac{B_R}{LBS(N, \mathcal{T}, \mathcal{R}, K, W, L, C)} \cdot c^{(i,s)} \ge f^{(i,s)}, \tag{5}$$

where $LBS(N, \mathcal{T}, \mathcal{R}, K, W, L, C)$ is the theoretical lower bound of the superframe length expressed in terms of slots. Since it is not determined a priori, some iterations are needed to obtain the final result. However, for brevity of presentation, we will assume that the traffic matrix C is given below.

4 Traffic Accommodation Methods for Optical Compression TDM Ring

4.1 Theoretical Lower Bound of the Superframe

In this subsection, we derive the theoretical lower bound of the superframe length for given N (number of nodes), $\mathcal{T}$ (set of the numbers of optical compression devices), $\mathcal{R}$ (set of the numbers of optical expansion devices), K (number of time slots within the frame), W (the number of wavelengths), L (the tuning latency), and C (traffic load matrix). We define it as $LBS(N, \mathcal{T}, \mathcal{R}, K, W, L, C)$. Note that in the OCTDM ring, we do not have to consider the parameters W and L, i.e., $W = 1$ and $L = 0$. The theoretical lower bound in WDM rings was investigated in [17] under the conditions (1) that the numbers of transmitters and receivers provided by all nodes are identical, and (2) that the traffic load is uniform. The case of the bidirectional OCTDM rings is treated in [7]. We extend those methods to our unidirectional OCTDM ring below.

(A) The case where $\mathcal{T}$ and $\mathcal{R}$ are infinite, and K is finite

We first consider the case where the numbers of optical compression/expansion devices at every node are infinite, but that of time slots K is finite. We denote the total number of paths on link i by $n^{(i)}$, which can be determined from the traffic load matrix C as

$$n^{(i)} = \sum_{j=i+2}^{i+N} \sum_{s=(i+N+1)-j}^{N-1} c^{(j,s)}. \tag{6}$$

Since each frame has K slots, K paths can be set up in each frame on link i. It requires $\left\lceil \frac{n^{(i)}}{K} \right\rceil$ frames to allocate all paths on link i. The theoretical lower bound of the superframe length, $LBS(N, -, -, K, 1, 0, C)$, is thus given as

$$LBS(N, -, -, K, 1, 0, C) = \max_{0 \le i \le N-1} \left\lceil \frac{n^{(i)}}{K} \right\rceil \cdot K. \tag{7}$$

(B) The case where K is infinite, but $\mathcal{T}$ and $\mathcal{R}$ are finite

In this case, the total number of paths from sender node i to other receiver nodes is given by

$$s_p{}^{(i)} = \sum_{s=1}^{N-1} c^{(i,s)}. \tag{8}$$

Similarly, the total number of paths from sender nodes (except node i) to the receiver node i is given by

$$r_p{}^{(i)} = \sum_{k=0}^{N-1} c^{(k,i-k)}. \tag{9}$$

Since the number of slots in each frame is infinite, the number of paths allocated for node i is bounded by the numbers of optical compression devices (T_i) and optical expansion devices (R_i). That is, $LBS(N, \mathcal{T}, -, K, 1, 0, C)$ and $LBS(N, -, \mathcal{R}, K, 1, 0, C)$ are derived as

$$LBS(N, \mathcal{T}, -, K, 1, 0, C) = \max_{0 \le i \le N-1} \left\lceil \frac{s_p^{(i)}}{T_i} \right\rceil \cdot K, \tag{10}$$

$$LBS(N, -, \mathcal{R}, K, 1, 0, C) = \max_{0 \le i \le N-1} \left\lceil \frac{r_p^{(i)}}{R_i} \right\rceil \cdot K. \tag{11}$$

From the above two cases (A) and (B), we can determine $LBS(N, \mathcal{T}, \mathcal{R}, K, 1, 0, C)$ using Eqs. (7), (10) and (11) as follows:

$$LBS(N, \mathcal{T}, \mathcal{R}, K, 1, 0, C) = \max_{0 \le i \le N-1} \left(\left\lceil \frac{n^{(i)}}{K} \right\rceil, \left\lceil \frac{s_p^{(i)}}{T_i} \right\rceil, \left\lceil \frac{r_p^{(i)}}{R_i} \right\rceil \right) \cdot K. \tag{12}$$

From Eq. (12), we can infer that the length of the superframe can become smaller if terms in Eq. (12) are uniformly distributed for given numbers of optical compression/expansion devices and the number of time slots in the frame. Then we achieve a ring with higher throughput.

4.2 Path Accommodation Algorithm

In this subsection, we propose four path accommodation methods. Each of these path accommodation algorithms decides an allocation order of paths within frames. The lower bound developed in the previous section could be achieved if the algorithm works well and optical compression devices and optical expansion devices are effectively used. In what follows, we will first present three algorithms for the path accommodation method in the case of all–optical access in Subsections 4.2.1, 4.2.2, and 4.2.3. The case of path splitting access is then treated in Subsection 4.2.4, where some paths are split at some node between source/destination nodes in order to achieve the shorter superframe. Subsection 4.2.5 presents numerical examples.

To achieve the lower bound, we will first describe algorithm A1, where the longest path is always examined in path allocation. In algorithm A2, the weights of links and the number of optical compression/expansion devices are taken into account. Algorithm A3 reflects the accommodation balance for the effective use of the slots. Finally, algorithm PS is proposed for the path splitting access.

4.2.1 Algorithm A1: Longest Traffic First with All-Optical Access

We first show algorithm A1, which attempts to assign slots to the longest path first. It is simple in the sense that it does not consider the traffic load condition on every link and node. Algorithm A1 first finds the source/destination pairs requesting the path with longest distance (i.e., $s = N - 1$). For those paths, the slot is assigned from source node 0 to $(N - 1)$ if the source/destination pair requests such a path. The optical compression device for the source node and the optical expansion device for the destination node are assigned to accept those paths. Then, next longest paths with distance $s = N - 2$ are assigned. All paths are examined until paths with distance 1 are assigned slots.

The algorithm is summarized in Figure 5(a). The attempt to set up the path first checks to see if optical compression/expansion devices and slots are available on path (i, s) when $c^{(i,s)} \geq 1$ (see Line 7). If it is true, path (i, s) is actually set. Then, $c^{(i,s)}$ is reduced by one.

4.2.2 Algorithm A2: Heaviest Traffic First with All-Optical Access

We next present algorithm A2, which first attempts to set the path using the largest elements of the traffic weight matrix with respect to links and optical compression/expansion devices. Here, the

```
Init:  the_superframe_length = 1
while (every path cannot be set up)
 if (a path cannot be set up at all)
  the_superframe_length++
 for (s= N-1; s >= 1; s--)
  for (i=0; i <= N-1; i++)
    Attempt to set the path (i, s)
finally obtain the_superframe_length
```

(a) Algorithm A1

```
Init:  the_superframe_length = 1
while (every path cannot be set up)
 C_W is updated from C
 while (a path can be set up)
   try to set the path with
       a maximum element of C_W
   if cannot, set the element value to be 0
 the_superframe_length++
finally obtain the_superframe_length
```

(b) Algorithm A2

```
Init:  the_superframe_length = 1
while (every path cannot be set up)
  if (a path cannot be set up at all)
      the_superframe_length++
    for (i=0 ; i <= ⌊N/2⌋ - 1; i++)
      attempt to set each path (i, N/2) and (i + N/2, N/2)
    for (s=1; s <= ⌊N/2⌋ - 1; s++)
      for (i=0 ; i <= N-1 ; i++)
        set each path (i, s) and (i + s, N - s)
finally obtain the_superframe_length
```

(c) Algorithm A3

Figure 5: Path Accommodation Algorithms with All-Optical Access for the Optical Compression TDM Ring

traffic weight matrix $C_W = \{w^{(i,s)}\}$ is defined as

$$w^{(i,s)} = \begin{cases} \frac{\sum_{k=i}^{i+s-1} n^{(k)}}{K} + \frac{s_p{}^{(i)}}{T_i} + \frac{r_p{}^{(i+s)}}{R_{i+s}}, & \text{if } c^{(i,s)} > 0, \\ 0, & \text{otherwise.} \end{cases} \tag{13}$$

The setup is first tried for the path with the element with a maximum value in C_W. During algorithm execution, the traffic load matrix C is updated such that the paths that have been set up are excluded. The traffic weight matrix C_W should also reflect changes of C. The algorithm is summarized in Figure 5(b).

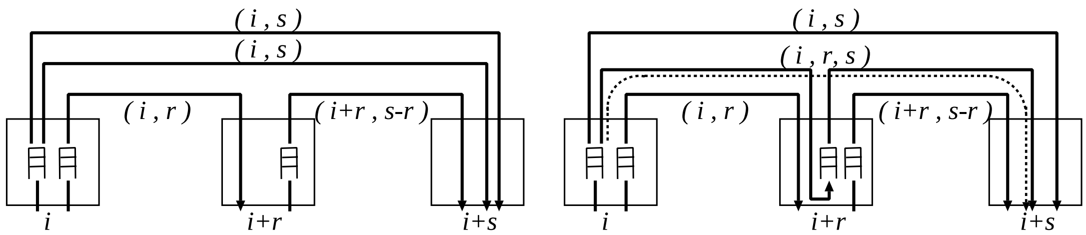
4.2.3 Algorithm A3: Balance Assignment with All-Optical Access

In the third algorithm A3, we consider the accommodation balance for the most effective use of each slot on every link. Namely, the first step in algorithm A3 is to set the two paths between two nodes which are located on the opposite side of rings. Two paths between two arbitrary nodes are also chosen at the same time. When the traffic load is nonuniform, all paths are not always set up at the same time. Thus, each path should be set up independently. The algorithm is summarized in Figure 5(c).

4.2.4 Algorithm PS: Path Splitting Access

In the previous three subsections, we proposed path accommodation algorithms for all–optical access. They aim at achieving the theoretical lower bound of the superframe length as closely as possible. However, they often fail. See the next subsection for numerical examples. In this subsection, we therefore consider the path splitting access by dividing several paths in order to attain the lower bound more closely.

As an example, see Figure 6. Suppose that in the case of all–optical access (Figure 6(a)), two all–optical slots with two hops are set up between two nodes i and $i+s$ (path (i,s)), and one–hop paths are set up between nodes i and $i+r$ (path (i,r)), and between nodes $i+r$ and $i+s$ (path $(i+r, s-r)$). If there exists more traffic between nodes i and $i+r$, and less traffic between nodes i and $i+s$, it is natural to split one direct optical path (i,s) into two paths, as shown in Figure 6(b).



(a) All–Optical Paths (b) Path Splitting

Figure 6: Difference between All–Optical and Path Splitting Accesses

Then, we still need only three slots within the frame. We refer to such a path (i, s) divided into path (i, r) and path $(i + r, s - r)$ as a splitting path (i, r, s). By splitting a path into two paths, an OE/EO conversion becomes necessary at node $i + r$ for the traffic between nodes i and $i + s$. This means that packet relaying delay is incurred at node $i + r$. However, we can expect a shorter length of the superframe if path splitting is adequately established.

In our path splitting method, we use the set of paths established by one of the three path accommodation methods described in the previous subsection. Then, we choose the path with the maximal value of C_W as a candidate for path splitting. Then, the node with the optical compression/expansion devices having the lowest weight along the path is selected as its splitting point. Consequently, the splitting node $i + r$ is chosen if

$$\min_{1 \le r < s} \frac{r_p^{(i+r)}}{R_{i+r}} + \frac{s_p^{(i+r)}}{T_{i+r}}. \tag{14}$$

In this way, the traffic matrix is reconstructed. After our proposed algorithm (A1, A2 or A3) is applied, the path splitting is finally performed so that the superframe length becomes smaller than the input. The superframe length approaches the theoretical lower bound by repeating the above procedure. If it does not, the iteration is terminated.

$$
\begin{array}{cc}
 & \begin{array}{cccccccccc} 0 & 1 & 2 & \cdots & 15 & 16 & \cdots & 29 & 30 & 31 \end{array} \\
\begin{array}{c} 0 \\ 1 \\ 2 \\ \vdots \\ 15 \\ 16 \\ \vdots \\ 29 \\ 30 \\ 31 \end{array} &
\begin{pmatrix}
0 & 1 & 1 & \cdots & 1 & 1 & \cdots & 1 & 1 & 1 \\
0 & 1 & 1 & \cdots & 1 & 1 & \cdots & 1 & 1 & 1 \\
0 & 1 & 1 & \cdots & 1 & 1 & \cdots & 1 & 1 & 1 \\
\vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\
0 & 1 & 1 & \cdots & 1 & 1 & \cdots & 1 & 1 & 1 \\
0 & 1 & 1 & \cdots & 1 & 1 & \cdots & 1 & 1 & 1 \\
\vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\
0 & 1 & 1 & \cdots & 1 & 1 & \cdots & 1 & 1 & 1 \\
0 & 1 & 1 & \cdots & 1 & 1 & \cdots & 1 & 1 & 1 \\
0 & 1 & 1 & \cdots & 1 & 1 & \cdots & 1 & 1 & 1
\end{pmatrix}
\end{array}
$$

(a) C_1

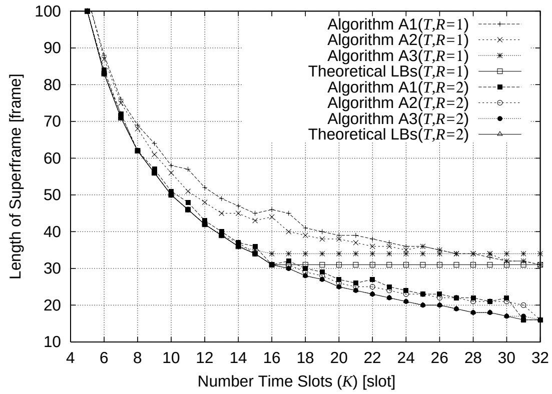
$$
\begin{array}{cc}
 & \begin{array}{cccccccccc} 0 & 1 & 2 & \cdots & 15 & 16 & \cdots & 29 & 30 & 31 \end{array} \\
\begin{array}{c} 0 \\ 1 \\ 2 \\ \vdots \\ 15 \\ 16 \\ \vdots \\ 29 \\ 30 \\ 31 \end{array} &
\begin{pmatrix}
0 & 1 & 1 & \cdots & 1 & 1 & \cdots & 1 & 1 & \mathbf{2} \\
0 & 1 & 1 & \cdots & 1 & 1 & \cdots & 1 & \mathbf{2} & 1 \\
0 & 1 & 1 & \cdots & 1 & 1 & \cdots & \mathbf{2} & 1 & 1 \\
\vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\
0 & 1 & 1 & \cdots & 1 & \mathbf{2} & \cdots & 1 & 1 & 1 \\
0 & 1 & 1 & \cdots & \mathbf{2} & 1 & \cdots & 1 & 1 & 1 \\
\vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\
0 & 1 & \mathbf{2} & \cdots & 1 & 1 & \cdots & 1 & 1 & 1 \\
0 & \mathbf{2} & 1 & \cdots & 1 & 1 & \cdots & 1 & 1 & 1 \\
0 & 1 & 1 & \cdots & 1 & 1 & \cdots & 1 & 1 & 1
\end{pmatrix}
\end{array}
$$

(b) C_2

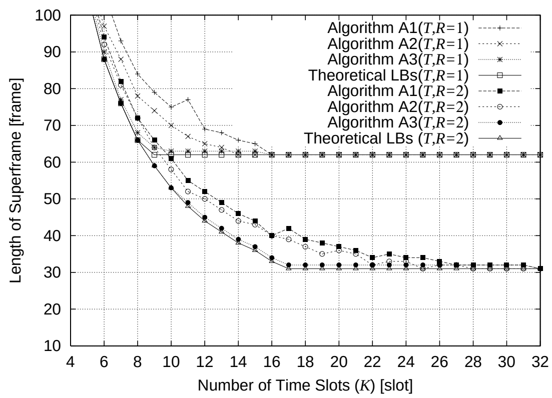
$$
\begin{array}{cc}
 & \begin{array}{cccccccccc} 0 & 1 & 2 & \cdots & 15 & 16 & \cdots & 29 & 30 & 31 \end{array} \\
\begin{array}{c} 0 \\ 1 \\ 2 \\ \vdots \\ 15 \\ 16 \\ \vdots \\ 29 \\ 30 \\ 31 \end{array} &
\begin{pmatrix}
0 & 0 & 3 & \cdots & 2 & 1 & \cdots & 3 & 3 & 1 \\
0 & 3 & 2 & \cdots & 0 & 3 & \cdots & 0 & 1 & 2 \\
0 & 1 & 3 & \cdots & 1 & 2 & \cdots & 2 & 2 & 0 \\
\vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\
0 & 2 & 0 & \cdots & 3 & 0 & \cdots & 1 & 3 & 2 \\
0 & 1 & 3 & \cdots & 1 & 2 & \cdots & 2 & 1 & 0 \\
\vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\
0 & 1 & 3 & \cdots & 1 & 2 & \cdots & 2 & 2 & 3 \\
0 & 2 & 0 & \cdots & 3 & 0 & \cdots & 3 & 0 & 1 \\
0 & 1 & 2 & \cdots & 0 & 2 & \cdots & 1 & 2 & 2
\end{pmatrix}
\end{array}
$$

(c) C_3

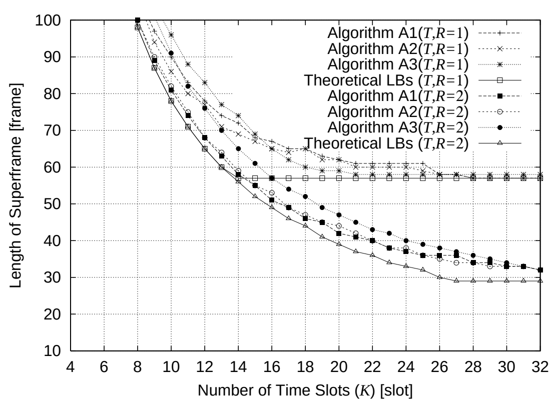
Figure 7: Traffic Matrices for Numerical Examples



(a) Traffic matrix C_1



(b) Traffic matrix C_2



(c) Traffic matrix C_3

Figure 8: Comparisons of Lower Bounds and Superframe Lengths obtained by applying Algorithms A1, A2 and A3

4.2.5 Numerical Examples and Discussions

In this subsection, we first compare three algorithms A1, A2 and A3 presented in the previous subsections. The number of nodes, N, is fixed at 32. For the traffic load matrices, we will consider C_1 (Figure 7(a)), C_2 (Figure 7(b)) and C_3 (Figure 7(c)). The characteristics of those traffic matrices are summarized below.

- C_1: a uniform traffic load.
- C_2: all paths except the ones with destination node 31 are uniform. The load of paths from any source node to destination node 31 is twice as large as that of others.
- C_3: the load of each path is randomly decided between 0 and 3.

We assume that the numbers of optical compression/expansion devices per node are identically set; i.e., $T = R$.

Figures 8(a), 8(b) and 8(c) show the superframe lengths obtained by applying algorithms A1, A2 and A3 to the traffic matrices C_1, C_2 and C_3 for all–optical access, respectively. In obtaining these figures, two cases of the number of optical compression devices are considered: $T = R = 1$ and $T = R = 2$. The horizontal axis ($4 \leq K \leq 32$) shows the number of slots within the frame, and the vertical axis the length of the superframe in slots. From those figures, we can observe that algorithm A3 gives good results for matrices C_1 and C_2. On the other hand, algorithms A1 and A2 are better than A3 for matrix C_3, especially in the case of $T = R = 2$. That is, the figures show that at least one of those algorithms can offer a good result close to the theoretical lower bounds, but there is no best one that always yields the shortest superframe. This was confirmed through extensive evaluation of other cases with various combinations of parameters. Thus, our recommendation is that all three algorithms should be performed and the best one is chosen to set up the optical paths.

In the figure, it can also be observed that in several parameter regions, none of the three methods can approach the theoretical lower bounds. In those cases, we can expect an effect of

Table 1: Results by Path Splitting for Traffic Load Matrix C_2

# of T_i, R_i	# of slots (K)	LBS [slot]	All-Optical Access			Path Splitting Access					
			A1	A2	A3	A1	# of split	A2	# of split	A3	# of split
1	11	682	847	737	693	704	13	726	1	682	1
1	12	744	828	780	756	780	4	756	2	744	1
1	13	806	884	832	819	819	5	806	2	806	1
2	11	528	605	572	539	561	13	550	5	528	1
2	12	528	624	600	540	564	10	576	5	528	1
2	13	533	637	611	546	585	11	572	6	533	1
2	14	532	644	616	546	574	12	574	7	532	1
2	15	540	660	645	555	585	13	585	10	540	1
2	16	528	640	640	544	592	5	608	4	528	1
2	26	806	858	832	832	832	1	806	3	806	2

path splitting access. The results for matrix C_2 are shown in Table 1. Values in the first two columns correspond to the parameters with which none of the three path accommodation methods achieved good results for the superframe length. As stated above, algorithm A3 exhibits better results for matrix C_2 than did the other algorithms. This can be confirmed under the column labelled "All–Optical Access." The last column labelled "Path Splitting Access" shows the results of path splitting. We find that path splitting access can decrease the superframe length to the theoretical lower bound in these cases. For example, in the case of $T = R = 2$ and $K = 14$, the all–optical path $(14, 17)$ is split at node 15 into two paths $(14, 1)$ and $(15, 16)$, as shown in the table. One possible problem of path splitting is that the packet transmission delay is increased by introducing the packet relay time at the intermediate node even though the superframe length is shortened. We therefore must examine the packet transmission delay, which will be done in the next subsection.

4.3 Packet Delay Times

In Subsection 4.3.1, we analyze the packet delay time for both all–optical and path splitting accesses. The case of uniform traffic load in all–optical access is first treated. The result is then modified to derive the approximate packet delay time for the nonuniform traffic load. The packet delay time for path splitting access is next considered. We will derive the packet delay time from source node i to destination node $i+s$ (i.e., on the path (i,s)). Numerical examples are finally provided in Subsection 4.3.2.

4.3.1 Analysis of Packet Delay Times

(A) Packet Delay Times for Uniform Traffic Load with All–Optical Access

By setting the capacity of the unidirectional ring to be B_R [bps], one slot time denoted by t [s] is given by

$$t = \frac{(S_h + S_p)\cdot 8}{B_R}, \tag{15}$$

where S_h [byte] and S_p [byte] are the header and payload sizes of the minipacket. The propagation delay between nodes i and $(i+s)$ is denoted by $W_p^{(i,s)}$ [s]. Furthermore, the number of frames in the superframe is represented by r, which has been determined using our path accommodation algorithms presented in the previous section. Then, the number of slots contained in the superframe, D, is given by $K \cdot r$, where K is the number of time slots per frame.

We assume that at source node i, packets destined for node $(i+s)$ arrive according to a Poisson distribution with rate $\lambda^{(i,s)}$. Hereafter, we will derive the mean packet delay time for this stream. The packet length in bytes has a general distribution with probability function f, and we represent its mean by P_B [byte]. The traffic load (in bps) for path (i,s) is then given by

$$B_f^{(i,s)} = \frac{\lambda^{(i,s)} \cdot P_B \cdot 8}{t}. \tag{16}$$

Furthermore, we introduce the random variable P_m, representing the number of minipackets in the packet. Its probability function, $g(n)$ $(n = 1, 2, \ldots)$, is given by

$$g(n) = \text{Prob}[P_m = n] = \sum_{x=S_p(n-1)+1}^{S_p \cdot n} f(x). \tag{17}$$

Our objective is to derive the packet delay time $W^{(i,s)}$ [s] on path (i,s), which consists of four components:

$$W^{(i,s)} = \left[\frac{D}{2} + W_q^{(i,s)} + (E[T_F] - (D-1))\right] \cdot t + W_p^{(i,s)}. \tag{18}$$

The last term, $W_p^{(i,s)}$, is the propagation delay from source node i to destination node $(i+s)$. The first term within brackets is necessary because we consider the random arrival of packets, and the packet should wait for half the superframe length on average, which corresponds to the time duration during which the first minipacket can be put on the slot assigned to that path since it reaches the head of the packet buffer. We next examine the third term in brackets. The random variable T_F [slots] in the term shows the mean time required to transmit all minipackets in the packet from the time the designated packet reaches the head of the queue. Since it needs $E[P_m]$ superframes, the following equation holds:

$$E[T_F] = D \cdot E[P_m]. \tag{19}$$

The subtraction of $D-1$ from $E[T_F]$ is necessary since we consider the time interval until the last minipacket is put onto the ring. The second term on the right–hand side in Eq. (18), $W_q^{(i,s)}$, corresponds to the queueing time at the source node buffer until the packet reaches the head of the queue. By applying the Pollaczek–Khinchin formula, it can be obtained by

$$W_q^{(i,s)} = \frac{\lambda^{(i,s)} E[T_F^2]}{2(1-\lambda^{(i,s)} E[T_F])}, \tag{20}$$

where $E[T_F^2]$ is given by $D^2 E[{P_m}^2]$.

By rewriting Eq. (18) using Eqs. (19) and (20), we finally have

$$W^{(i,s)} = \left[\frac{\lambda^{(i,s)} D^2 E[{P_m}^2]}{2(1-\lambda^{(i,s)} D E[P_m])} + D\left(E[P_m] - \frac{1}{2}\right) + 1 \right] \cdot t + W_p^{(i,s)}. \tag{21}$$

(B) Extension to Nonuniform Traffic Load with All–Optical Access

In the case of nonuniform traffic load, two or more slots may be assigned within a single superframe for any source/destination pair. The positions of assigned slots must depend on the path accommodation algorithm, and the intervals of slots may be irregular. These make it impossible to derive the packet transmission time in an exact form. Hence, we introduce the assumption that assigned slots are uniformly distributed within the superframe. More specifically, the chance to transmit the minipacket destined for node $(i+s)$ arises at source node i every $D/c^{(i,s)}$ slots. Note that D and $c^{(i,s)}$ mean the number of slots of the superframe and the number of slots assigned to path (i, s) during the superframe, respectively.

Under the above assumption, the mean packet delay can be derived by modifying Eq. (21) as

$$W^{(i,s)} = \left[\frac{\lambda^{(i,s)}(D/c^{(i,s)})^2 E[{P_m}^2]}{2(1-\lambda^{(i,s)}(D/c^{(i,s)})E[P_m])} + \frac{D}{c^{(i,s)}}\left(E[P_m] - \frac{1}{2}\right) + 1\right] \cdot t + W_p^{(i,s)}. \tag{22}$$

(C) Path Splitting Access

If an all–optical path (i, s) is divided into two paths (i, r) and $(i+r, s-r)$, the minipackets on the path splitting path (i, r, s) is electronically stored at the splitting node $i + r$ after OE conversion. Each minipacket must wait for the next time slot allocated for the splitting node $i+r$ for that path. We assume that those minipackets are transmitted on each slot by distinguishing with packets by other all–optical accesses. See Figure 6(b). Then, the packet delay time $W^{(i,s)}$ for path splitting access is represented by

$$\begin{aligned} W^{(i,s)} \quad = \quad & \left[\frac{\lambda^{(i,s)}(\frac{D}{c^{(i,s)}})^2 E[P_m^2]}{2(1-\lambda^{(i,s)}(\frac{D}{c^{(i,s)}})E[P_m])} + \frac{D}{c^{(i,s)}}\left(E[P_m] - \frac{1}{2}\right) + 1\right. \\ & \left. + \sum_{1 \le r < s} \frac{c^{(i,r,s)}}{c^{(i,s)}}\left(\frac{D}{2c^{(i,r,s)}} + e\right)\right] \cdot t + W_p^{(i,s)}, \end{aligned} \tag{23}$$

where $c^{(i,r,s)}$ is the number of splitting paths (i, r, s), and e is the packet relay time at each splitting node, which is assumed to be the superframe length D in the next examples.

4.3.2 Numerical Examples and Discussions

In the following numerical examples, we assume that the distribution of the packet size follows the geometric function

$$f(x) = (1 - 1/P_B)^{x-1} \times 1/P_B. \tag{24}$$

The mean packet size P_B is set to be 500 [byte], and the header and payload sizes of the minipacket, (S_h and S_p) as 2 [byte], and 53 [byte], respectively. The ring capacity, B_R, is fixed at 40 [Gbps].

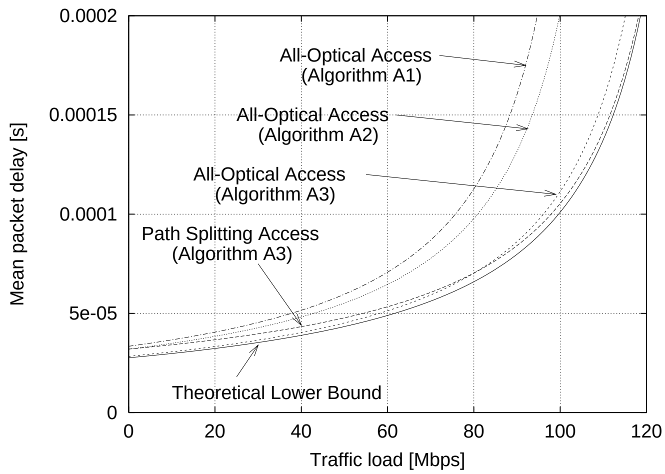


Figure 9: Comparisons of Packet Delay Times

Figure 9 shows the results of the average packet delay time against the traffic load matrix C_2 (Figure 7(b)). Here, the numbers of optical compression/expansion devices are set to be 2 at every node, i.e., $T = R = 2$. The number of time slots per frame is 14 [slot] ($K = 14$). See the corresponding row of Table 1. The superframe lengths of the theoretical lower bound, all–optical access by algorithms A1, A2 and A3, and the path splitting access with A3 are 532, 644, 616, 546 and 532, respectively. In the result, we set the propagation delays, $W_p^{(i,s)}$'s, to be 0 since our primary concern in this subsection is to compare all–optical access by three algorithms (A1, A2 and A3) and the path splitting access.

In Figure 9, both cases of all–optical access (by three algorithms) and path splitting access are shown. The packet delay by the theoretical lower bound is also shown. As shown in the figure, achieving the shorter superframe can lead to shorter packet delay times. This can be confirmed by comparing the results of algorithms A1, A2 and A3. However, path splitting should be carefully treated; when the traffic load is high, splitting the path can decrease the packet transmission time. As the traffic load becomes small, however, path splitting increases the packet transmission delay since it introduces an extra delay at the splitting node.

5 Traffic Accommodation Methods for Optical Compression TDM/WDM Ring

5.1 Theoretical Lower Bound of the Superframe

In this subsection, we show the theoretical lower bound on the length of the superframe that can accommodate the given traffic load C for the OCTDM/WDM ring. It will be used for comparison with our path accommodation method proposed in Subsection 5.2. Since it is difficult to consider all the parameters at the same time, we consider the following three cases separately.

(A) Effects of the number of optical compression devices $\mathcal{T}$ and tuning latency L

We first consider the effects of $\mathcal{T}$ and L, which limits the packet sending rate. The required number of transmission slots at sender node i is $s_p^{(i)} = \sum_{s=1}^{N-1} c^{(i,s)}$ within the superframe. Recall that each optical compression device can at most one minipacket within a frame. Therefore, if the tuning latency of TT can be negligible, the lower bound on the superframe length is given as:

$$h = \max_{0 \le i \le N-1} (\lceil \frac{s_p^{(i)}}{T_i} \rceil) \cdot K. \tag{25}$$

When the tuning latency of TT cannot be negligible, we need to take into account the fact that the more number of wavelengths used at the node does not necessarily lead to the reduction of the superframe length. It is due to the overhead caused by the tuning latency. Let W_u ($1 \le W_u \le W$) be the number of wavelengths that is utilized at the node. If every receiver can tune W_u wavelengths, at least $W_u - 1$ times of tuning operation is required on each optical compression device. That is, at every sender node, at least $L(W_u - 1)$ slots are needed for wavelength tuning. The node with the heaviest load uses $L(W_u - 1) + \max_{0 \le i \le N-1} s_p^{(i)}$ slots for the path accommodation. That is, $LBS(N, \mathcal{T}, -, K, W_u, L, C)$ [slot], the theoretical lower bound by the constraints, $\mathcal{T}$ and L, is derived as:

$$LBS_{\mathcal{T}L}^{(W_u)} \quad = \quad LBS(N, \mathcal{T}, -, K, W_u, L, C)$$

$$= \begin{cases} h, & \\ & \text{if } L(W_u - 1) + \max_{0 \le i \le N-1} s_p^{(i)} \le h \\ & \\ h + \left\lceil \frac{L(W_u-1)+\max_{0\le i\le N-1} s_p^{(i)} - h}{K} \right\rceil \cdot K, & \\ & \text{otherwise.} \end{cases} \tag{26}$$

Note that in finally determining $LBS_{\mathcal{TL}}^{(W_u)}$, W_u should be changed from 1 to W to find out a minimum value of LBS. Then, it is used as an actual lower bound.

(B) Effects of the number of optical expansion device $\mathcal{R}$

We next consider the effect of $\mathcal{R}$ at the receiver node. The number of paths that the receiver node i establishes with other sender nodes is given as $r_p^{(i)} = \sum_{k=0}^{N-1} c^{(k,i-k)}$. Accordingly, $LBS(N, -, \mathcal{R}, K, -, -, C)$ is derived as:

$$\begin{aligned} LBS_{\mathcal{R}} &= LBS(N, -, \mathcal{R}, K, -, -, C) \\ &= \max_{0 \le i \le N-1} \left(\lceil \frac{r_p^{(i)}}{R_i} \rceil \right) \cdot K. \end{aligned} \tag{27}$$

That is, at the receiver node, the number of the optical expansion devices limits the superframe length.

(C) Effects of the frame length K and the number of wavelengths W

We next consider the effects of the frame length K and the number of wavelengths W. If we could have the optimal number of paths which are assigned on link v using wth wavelength denoted as $n^{(v)(w)}$, the lower bound, $LBS(N, -, -, K, W_u, -, C)$ [slot] becomes

$$LBS(N, -, -, K, W_u, -, C) = \max_{0 \le v \le N-1, 0 \le w \le W_u - 1} \left(\lceil \frac{n^{(v)(w)}}{K} \rceil \right) \cdot K. \tag{28}$$

However, we cannot have an explicit formula for $n^{(v)(w)}$. Therefore, we take the following approach.

```
begin
1:  for w = 0 to W_u - 1 do LPT^(v)[w] = 0, P[k] = 0;
2:  i = 0;
3:  repeat
4:     LPT^(v)[k] = min_{0<=w<=W_u-1} (LPT^(v)[w]);
5:     LPT^(v)[k] = LPT^(v)[k] + t_p^{(i)(v)};
6:     P[k] = P[k] + 1;
7:     i = i + 1;
8:  until i > N - 1;
9:  LPT^(v) = max_{0<=w<=W_u-1} (LPT^(v)[w]);
10: P = P[k];
end
```

Figure 10: Largest Processing Time first (LPT) Algorithm

Later, we will incorporate the effect of the frame length K, but for a moment we only consider the effect of the number of wavelengths W solely, i.e., we examine

$$\max_{0 \leq w \leq W_u - 1} (n^{(v)(w)}). \tag{29}$$

By changing W_u from 1 to W, we can find its minimum value S_{LB}. It means that the number of slots which is required to optimally accommodate every path to every wavelength of W_u on the link v. Since the total number of paths of receiver nodes i is $r_p^{(i)} = \sum_{k=0}^{N-1} c^{(k,i-k)}$, we obtain the following equation for the total number of paths for the receiver node i on the link v;

$$r_p^{(i)(v)} = \sum_{k=\min(v,i+1)}^{\max(v,i-1)} c^{(k,i-k)}. \tag{30}$$

For ease of presentation, we sort the order of the above set of $r_p^{(i)(v)}$'s in a descending order, and let $t_p^{(i')(v)}$'s be the results. We then apply the Largest Processing Time first (LPT) algorithm [18, 19] (Figure 10) for obtaining the approximate lower bound S_{LB}; one of the most often used general approximation strategies for list solving scheduling problems. The accuracy of a given list scheduling algorithm depends on the order that the elements appear on the list.

The time complexity of the LPT algorithm (including sorting of the set of $r_p^{(i)(v)}$'s in our case) is also shown in [18, 19]. It is $O(n \log(n))$ since its most complicated task is to sort the set of $r_p^{(i)(v)}$'s. The authors in [19] pointed out that the result obtained by the LPT schedule can be up to

33% larger than the one by an optimal schedule in the worst case. Also, the next relation is given in [20];

$$LPT_{ub}^{(v)} = \left\lceil \left(1 + \frac{1}{P} - \frac{1}{PW_u}\right) LPT_{lb}^{(v)} \right\rceil, \tag{31}$$

where $LPT_{lb}^{(v)}$ and $LPT_{ub}^{(v)}$ are the lower and upper bounds of $LPT^{(v)}$. From Eq. (31), we have

$$\begin{aligned} LPT^{(v)} &\leq \left\lceil \left(1 + \frac{1}{P} - \frac{1}{PW_u}\right) LPT_{lb}^{(v)} \right\rceil, & (32)\\ LPT^{(v)} &\leq \left(1 + \frac{1}{P} - \frac{1}{PW_u}\right) LPT_{lb}^{(v)} + 1, & (33)\\ \frac{LPT^{(v)} - 1}{\left(1 + \frac{1}{P} - \frac{1}{PW_u}\right)} &\leq LPT_{lb}^{(v)}. & (34) \end{aligned}$$

It implies that we cannot decide the lower bound of $LPT^{(v)}$, $LPT_{lb}^{(v)}$, which is a tighter optimal value. Henceforth, we use the following approximate lower bound of $LPT^{(v)}$, $LPT_{lb-approx}^{(v)}$, as;

$$LPT_{lb-approx}^{(v)} = \left\lceil \frac{LPT^{(v)} - 1}{\left(1 + \frac{1}{P} - \frac{1}{PW_u}\right)} \right\rceil \leq LPT_{lb}^{(v)}. \tag{35}$$

Apparently, the accuracy of the above lower bound, $LPT_{lb-approx}^{(v)}$, depends on the result of $LPT^{(v)}$.

Assuming that all of paths on each link are assigned equally to wavelengths, we introduce the total number of paths assigned to the link v as $n^{(v)}$. For given traffic matrix C, $n^{(v)}$ is determined as $n^{(v)} = \sum_{j=v+2}^{v+N} \sum_{s=(v+N+1)-j}^{N-1} c^{(j,s)}$. Then, S_{LB} is given as

$$S_{LB} = \max\left(LPT_{lb-approx}^{(v)}, \lceil \frac{n^{(v)}}{W_u} \rceil\right). \tag{36}$$

We now consider the effect of the frame length K. The link v can accommodate at most KW_u paths in each frame, using all of W_u paths. Therefore, at least $\lceil \frac{n^{(v)}}{KW_u} \rceil$ frames are necessary for accommodating all of paths on link v. Eventually, the lower bound for given K and W is determined as;

$$\begin{aligned} LBS_{KW}^{(W_u)} &= LBS(N, -, -, K, W_u, -, C) \\ &= \max_{0 \leq v \leq N-1} \left(\left\lceil \frac{LPT_{lb-approx}^{(v)}}{K} \right\rceil, \lceil \frac{n^{(v)}}{KW_u} \rceil \right) \cdot K & (37) \end{aligned}$$

From the above three cases, we finally determine $LBS(N, \mathcal{T}, \mathcal{R}, K, W, L, C)$ [slot] from Eqs. (26), (27) and (37) as follows:

$$LBS(N, \mathcal{T}, \mathcal{R}, K, W, L, C) = \min_{1 \leq W_u \leq W} (LBS_{\mathcal{T}L}^{(W_u)}, LBS_{\mathcal{R}}, LBS_{KW}^{(W_u)}) \tag{38}$$

The above bound may not be a tight one because the parameters are considered separately, and it would tend to be smaller than the actual value. On the other hand, the superframe length obtained by our algorithm tends to become larger than the actual one since our proposed algorithm is a heuristic one. Nevertheless, numerical results presented in Subsection 5.2.2 show that the superframe lengths obtained by the lower bound of this section and our proposed algorithm of the next section are very close with each other. It means that both of the theoretical lower bound in this section and our algorithm exhibit good results.

5.2 Path Accommodation Algorithm

We now propose a path accommodation method for the OCTDM/WDM ring. It can be applied to both of uniform and nonuniform traffic load cases. By our heuristic algorithm, it is possible to obtain the near-optimal accommodation results with practical computation time. In Subsection 5.2.1, we propose the algorithm we call APW+APTRS. In Subsection 5.2.2, we show and evaluate the results of the algorithm APW+APTRS.

5.2.1 Algorithm APW+APTRS

Our heuristic algorithm consists of two parts. At first, the APW algorithm assigns each path to a wavelength. That is, it decides the wavelength that a fixed receiver (FR) is tuned. The second part of the algorithm called the APTRS algorithm assigns the path to transmitters, receivers and slots with its actual positions within the superframe. The following two parts of algorithm are executed in turn. See the top part of Figure 11.

```
begin
1:int the length of superframe[W] = {0,···,0}
2:for( W_u =1 ; W_u <= W ; Wu ++){
3:   APW(W_u)
4:   the length of superframe[W_u] = APTRS(W_u)
5:}
6:the length of superframe = min_{1≤W_u≤W}(the length of superframe[W_u])
end
```

```
Procedure APW (W_u){
1:int wave_wait[W_u] = {0,···,0}
2:while( max_{0≤i≤N−1} r_p^(i) > 0 ){
3:  //obtain the node number with heaviest load receiver of all re-
    maining nodes
    i = {i| max_{0≤i≤N−1} r_p^(i)/R_i}
4:  //obtain the wavelength number with the lightest load at this time
    w = {w| min_{0≤w≤W_u−1} wave_wait[w]}
5:  //assign the traffic of the receiver node i to the wavelength w
    C_w += C^i
6:  //update the load of wavelength w
    wave_wait[w] += r_p^(i)
7:  //remove node i from the candidate for the following steps
    r_p^(i) = 0
8:}
}
```

```
Procedure APTRS (W_u){
1: //decide which wavelength each node send packets to at beginning of
this schedule
   for( i =0 ; i < N ; i ++)
2:  first_wave[i] = i%W_u
3: while( remain_setting_paths ){
4:   //obtain the node number with the heaviest load at the transmitter
     i = {i| max_{0≤i≤N−1} s_p^(i)/T_i}
5:   //assign the traffic to node i
     for( w =0 ; w < W_u ; w ++){
6:     w = (w + first_wave[i])%W_u
7:     while(remain_setting_paths_with_sender(i))
8:       set_the_longest_path_with_sender(i)
9:   }
10:  //remove node i as the candidate for the following steps
     s_p^(i) = 0
11:}
12:return the length of the superframe
}
```

Figure 11: Path Accommodation Algorithm for the Optical Compression TDM/WDM Ring

(A) APW Algorithm (Assign each Path to a Wavelength)

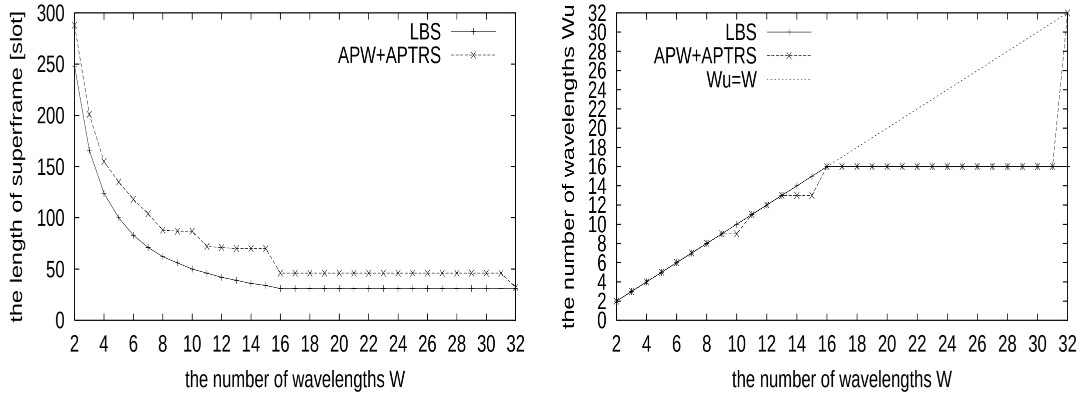
The objective of this part of the algorithm is to divide a traffic matrix C into traffic matrices C_w's for wth wavelength $(0 \leq w \leq W_u - 1)$. The middle part of Figure 11 shows the APW algorithm in detail. Here, C^i is the traffic matrix showing only the paths destined for receiver node i, and other elements are all 0's. During algorithm execution, the array `wave_wait[`W_u`]` is used to decide which wavelength is with the lightest load and which one is the next candidate for assigning paths. Then, the APW algorithm finally puts the number of paths to be included C_w in the array `wave_wait[w]`.

More precisely, the APW algorithm works as follows. First, on line 3, APW obtains the node number i with heaviest load receiver among all remaining nodes, where the load is obtained by $r_p^{(i)}/\mathcal{R}_i$. The paths terminated at node i is assigned the wavelength w (on line 4). The wavelength w is with the lightest load at this time, which can be determined by `wave_wait[w]`. On line 5, the paths terminated at node i is assigned to the wavelength w, and the weight of the traffic, $r_p^{(i)}$, is added to the `wave_wait[w]` on line 6. Finally, node i is removed from the candidate set for the following execution (line 7). The above steps are repeated until every path is assigned a wavelength.

(B) APTRS Algorithm (Assign each Path to Transmitter/Receiver/Slot)

By the APW algorithm, the wavelength that each of receivers is tuned is fixed. (Note that we assume fixed receivers and the receivers is fixed at the tuned wavelength in the OCTDM/WDM ring operation.) Then, we do not have to consider any conflicts among wavelengths at receivers. The APTRS algorithm then chooses one optical compression devices from a set of optical compression devices of T_i's. One optical expansion device and a slot position are also chosen. Then the wavelength is assigned. In doing so, we also have to take account of the allowable number of wavelength tuning, which is limited by the tuning latency,

The key of the algorithm is a selection order of paths, nodes, wavelengths, and transmitters. As shown in the bottom part of Figure 11, the APTRS algorithm first assigns the wavelength for each



(a) The Length of the superframe

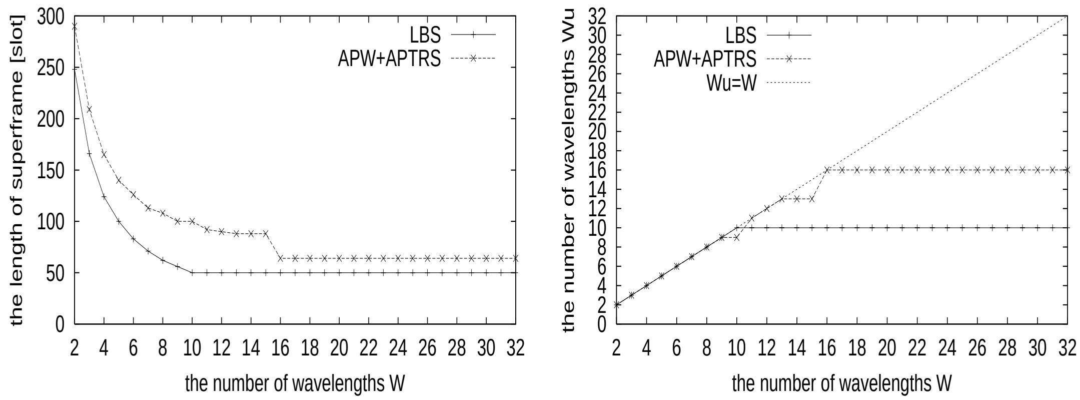
(b) The number of wavelengths for the shortest superframe

Figure 12: The Superframe Length in the Uniform Traffic Load Case with $L = 0$ ($N = 32, K = 1, \mathcal{T} = \{1, 1, .., 1\}$, and $\mathcal{R} = \{1, 1, .., 1\}$)

node (lines 1 and 2). Next, APTRS chooses the node with the heaviest load at the transmitter by using $s_p^{(i)}/\mathcal{T}_i$ (line 4). Then, from lines 5 through 9, slots are continuously assigned to all paths of sender node i, which are assigned the the same wavelength. By doing so, we can avoid wavelength tuning. Then the transmitter of node i is tuned to the next wavelength. The next wavelength is decided on line 6. This operation is iterated until all the wavelengths are examined. Finally, on line 10, node i is removed from the candidate set for the following steps. The iteration of lines 4 to 10 is performed until a set of the transmitter, receiver, and slot is assigned to every path.

5.2.2 Numerical Examples and Discussions

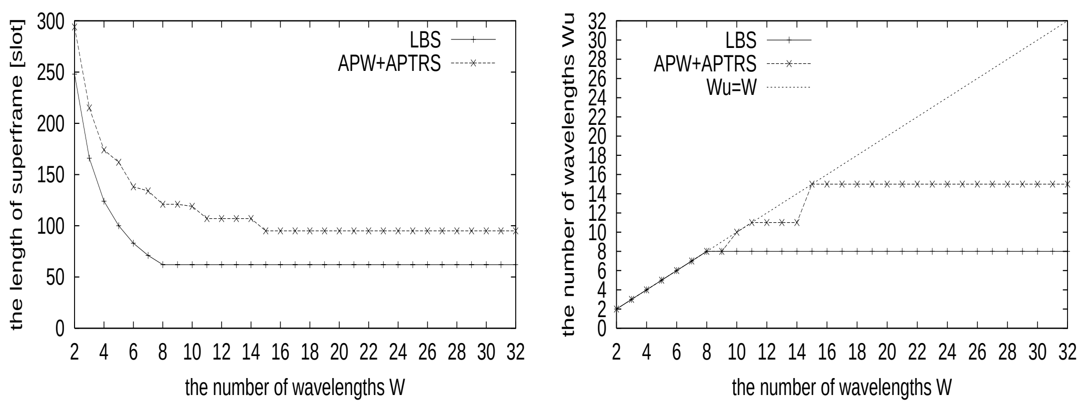
In this subsection, by applying APW+APTRS to uniform and nonuniform traffic load cases, we show the length of the superframe. The theoretical lower bounds are also shown for comparison. Figures 12, 13, and 14 plot the results for the uniform traffic load case. In three figures, the tuning latency L is changed as 0, 2, and 4, respectively. The horizontal axes in the figures are the number of wavelengths W. For other parameters, we set the number of nodes $N = 32$, the frame length $K = 1$, the number of transmitters $\mathcal{T} = \{1, 1, .., 1\}$, and the number of re-



(a) The length of the superframe

(b) The number of wavelengths for the shortest superframe

Figure 13: The Superframe Length in the Uniform Traffic Load Case with $L = 2$ ($N = 32, K = 1, \mathcal{T} = \{1, 1, .., 1\}$, and $\mathcal{R} = \{1, 1, .., 1\}$)

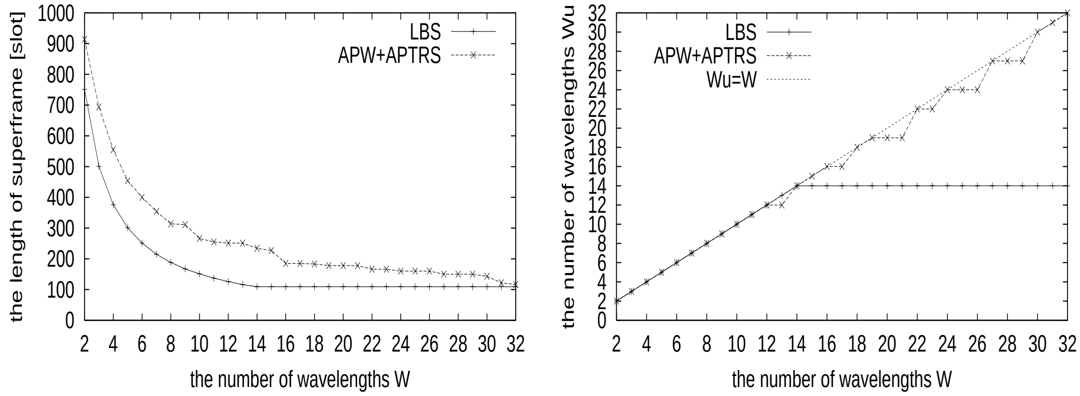


(a) The length of the superframe

(b) The number of wavelengths for the shortest superframe

Figure 14: The Superframe Length in the Uniform Traffic Load Case with $L = 4$ ($N = 32, K = 1, \mathcal{T} = \{1, 1, .., 1\}$, and $\mathcal{R} = \{1, 1, .., 1\}$)

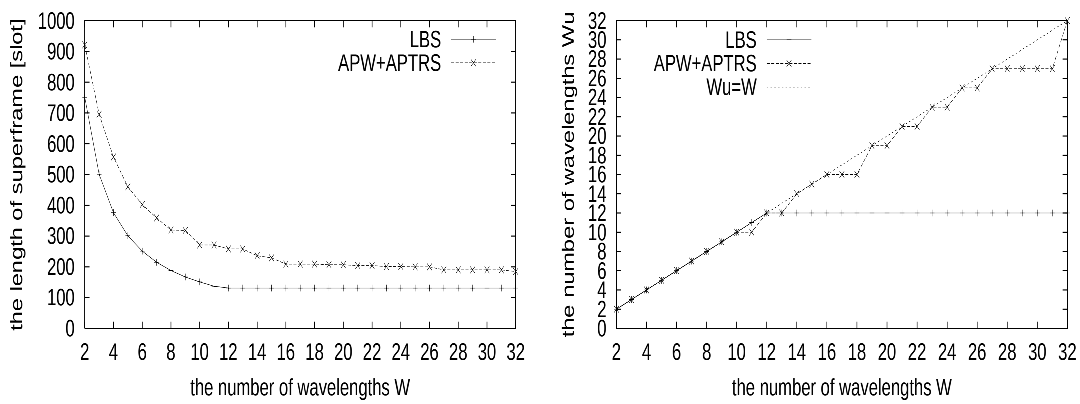
ceivers $\mathcal{R} = \{1, 1, .., 1\}$. The results of APW+APTRS by comparing with the theoretical lower bound, $LBS(N, \mathcal{T}, \mathcal{R}, K, W, L, C)$, derived in Section 5.1 are also shown in figures. Similarly, Figures 15, 16, and 17 show the results for the nonuniform traffic case. Here, the value of each element of the traffic load matrix is chosen randomly between 1 and 5. Other parameters are un-



(a) The length of the superframe

(b) The number of wavelengths for the shortest superframe

Figure 15: The Superframe Length in the Nonniform Traffic Load Case with $L = 0$ ($N = 32, K = 1, \mathcal{T} = \{1, 1, .., 1\}$, and $\mathcal{R} = \{1, 1, .., 1\}$)



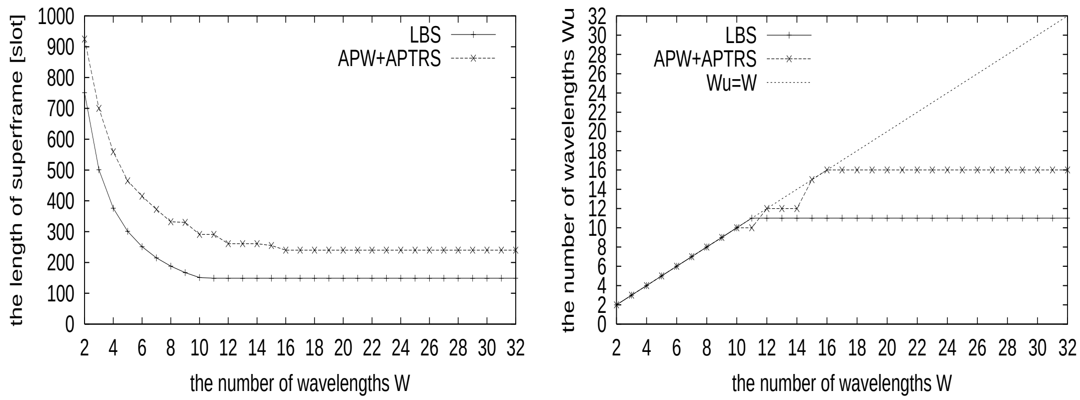
(a) The length of the superframe

(b) The number of wavelengths for the shortest superframe

Figure 16: The Superframe Length in the Nonuniform Traffic Load Case with $L = 2$ ($N = 32, K = 1, \mathcal{T} = \{1, 1, .., 1\}$, and $\mathcal{R} = \{1, 1, .., 1\}$)

changed. From these figures, we can observe that APW+APTRS is effective for both of uniform and nonuniform traffic load cases in almost all parameter regions.

In each figure, the smallest number of wavelengths with which we obtained the smallest length of the superframe is also shown. The horizontal axis in each figure's (b) is the number of wave-



(a) The length of the superframe

(b) The number of wavelengths for the shortest superframe

Figure 17: The Superframe Length in the Nonuniform Traffic Load Case with $L = 4$ ($N = 32, K = 1, \mathcal{T} = \{1, 1, .., 1\}$, and $\mathcal{R} = \{1, 1, .., 1\}$)

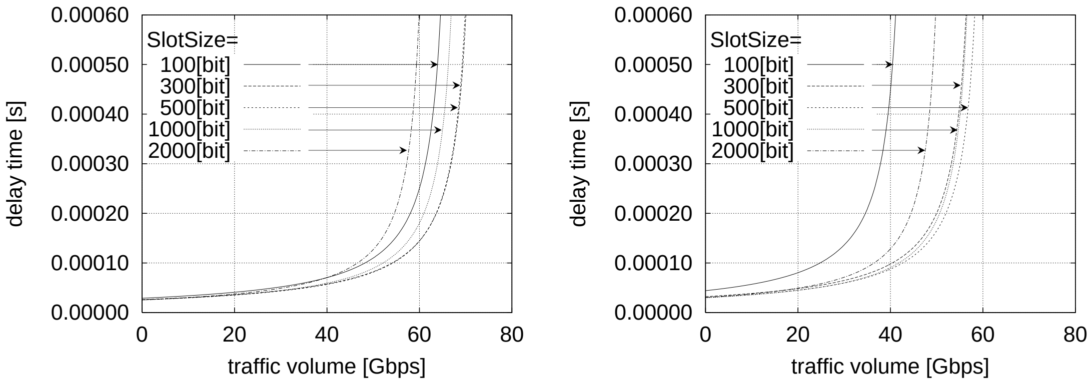
lengths W, and the vertical axis is the number of wavelengths, W_u, with which we obtained the smallest length of the superframe; the value W_u is decided by the analysis of the lower bound shown in Section 5.1 or the results of our accommodation algorithm APW+APTRS. When W_u is equal to W, all of the given W wavelengths are completely used for effective accommodation. When the tuning latency L is small, APW+APTRS comparatively needs more wavelengths to obtain the best results. When it becomes large on the other hand, Such many wavelengths cannot be fully utilized because the total time of tuning latency is roughly proportional to the number of wavelengths.

5.3 Packet Delay Times

When the accomodation algorithm APW+APTRS is applied, the tuning latency of each transmitter is given in the number of slots. However, it is given as the absolute time in an actual situation. That is, the number of slots needed to tune wavelengths is decided by the absolute tuning time and the time–length of one slot on the ring. On the other hand, we have a freedom in determining the slot length, i.e., the minipacket length. Accordingly, when the absolute tuning time is given, the

Table 2: The Superframe Length dependent on the Slot Length

the size of one slot [bit]	the tuning latency [ns]	the tuning latency [slot]	LBS [slot]	APW+APTRS [slot]
100	50	20	248	378
300	50	7	248	304
500	50	4	248	294
1000	50	2	248	290
2000	50	1	248	295



(a) The mean time delay given by the theoretical lower bound

(b) The mean time delay given by the results of the APW+APTRS algorithm

Figure 18: The Mean Delay Times for the Unifrom Traffic Matrix with the Capacity of Each Wavelength 40Gbps, $N = 32$, $K = 1$, $W = 2$, $\mathcal{T} = \{1, 1, .., 1\}$, and $\mathcal{R} = \{1, 1, .., 1\}$

size (in time) of one slot affects the throughput of the network.

Table 2 and Figure 18 show the results of our proposed algorithm APW+APTRS for the mean packet delay times for the uniform traffic load case. It can be derived by the analysis presented in Subsection 4.3 where the $M^x/D/1$ queue is used for each source-destination pair. The service time of this queue corresponds to the superframe length and the batch arrival of minipackets with a general distribution is allowed. In obtaining the results, we set the capacity of each wavelength to be 40Gbps and assume uniform traffic. For other parameters, we set $N = 32$, $\mathcal{T} = \{1, 1, .., 1\}$, $\mathcal{R} = \{1, 1, .., 1\}$, $K = 1$, and $W = 2$. Here, we assume that the distribution of the packet size follows a geometric function. The mean packet size is set to be 500 [byte], and the header size of the minipacket is 2 [byte]. To clearly show the influence of the slot size on the packet delay, we do not include the propagation delay, which depends on the physical length of the ring.

As shown in Table 2, the large size of one slot leads to the small number of slots for the wavelength tuning. However, it is likely to waste the capacity because the possibility that the slot is wasted by the incomplete last minipacket is increased. On the contrary, when the slot size is small, each minipacket is accommodated in slots effectively. However, the tuning latency in slots becomes large in this case. This tradeoff relationship is clearly demonstrated in Figure 18, and about 500[bit] of the slot length leads to the best result in the current parameter settings.

6 Conclusion

In this paper, we have proposed and evaluated the path accommodation methods for the unidirectional OCTDM/WDM rings and analyzed the packet transmission time.

For the unidirectional OCTDM rings consisting of single wavelength, we have first derived the theoretical lower bound for the length of the superframe, in which all paths among nodes are perfectly allocated. Then, three path accommodation algorithms for all–optical access have been proposed to treat the nonuniform traffic load. Next, path splitting access has been treated to decrease the superframe length. We have shown that our algorithm gives good results, but those should be carefully examined since the packet transmission time may be increased by introducing path splitting. This can be checked by our analysis methods.

For the unidirectional OCTDM/WDM rings consisting of multiple wavelengths, we have derived the theoretical lower bound which determines the length of the superframe. For this purpose, we have explicitly considered the tuning latency of the transmitters. It assumes that all paths are perfectly allocated. A path accommodation algorithm for all–optical access is next proposed, which allows both of the uniform/nonuniform traffic cases. Our numerical results have shown that our algorithm can provide reasonable path accommodation in the sense that the superframe lengths obtained by our algorithm are close to the theoretical lower bound. The results of the packet delay times show the importance of deciding the appropriate size of each slot, so that the network throughput can be maximized.

As future research works, the reliability issue for the OCTDM/WDM rings should be investigated.

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