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Path Accommodation Methods for Unidirectional Rings with Optical Compression TDM

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SUMMARY
In this paper, we propose path accommodation methods for unidirectional rings based on an optical compression time-division multiplexing (OCTDM) technology. We first 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. 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.

key words: *Optical Compression TDM, Path Accommodation Method, Optical Unidirectional Ring Network, Theoretical Lower Bound*

1. Introduction

A packet–switched ring with all–optical access can be realized by optical wavelength multiplexing (WDM) or optical time–division multiplexing (OTDM) techniques. In the last few years, it has become evident that an optical pulse compression/expansion technology [1], [2] is useful for the OTDM rings, which is called OCTDM (Optical Compression TDM). OCTDM can provide high–speed backbone networks with 1 to 100 Gbps [3], [4]. As described in [3], since the optical node of the OCTDM ring receives the packet from LAN, bit intervals are shortened to fit the time slot length of the backbone ring. When receiving the packet at the destination node, it is lengthened to fit the LAN speed.

In OCTDM, we need a routing policy to decide how each slot within a frame is used by every node pair. In conventional TDM, it is easy to accommodate the traffic on the ring in the following manner. 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 can retrieve the packet by observing the destination address in the header. This 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 should be limited by the number of transceivers since each node employs optical pulse compression/expansion for ring access [5]. The path accommodation methods suitable for OCTDM with bidirectional rings is shown in [6].

In this paper, we first propose the path accommodation methods for unidirectional rings with OCTDM. 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 (see Section 5.4). In this paper, we first describe the path accommodation methods for all–optical access, by which we try to obtain the theoretical lower bound in the number of slots/frames. 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 [7] for WDM rings.

As a related work, the path allocation method for the WDM ring is shown in [8], [9]. Zhang and Qiao proposed a cost-effective design method for accommodating a *wavelength path* for every node pair [8]. In their method, the number of wavelengths is a limited resource. In their subsequent work [10], the time needed to accommodate all paths for a given number of wavelengths was also obtained. They considered the fixed packet length, and therefore, the time was slotted in the WDM system. Thus, their system is similar to our OCTDM ring. However, they did not obtain the packet transmission time, which will be presented in the current paper. Also, path splitting was not considered in [8]–[10].

This paper is organized as follows. In Section 2, we first describe an OCTDM ring structure and our model. In Section 3, we derive the theoretical lower bound for the number of frames necessary to accommodate all paths for given parameters (the numbers of transmitters/receivers and time slots). In Section 4, three path accommodation algorithms are considered, and we propose a traffic–splitting access method suitable for the OCTDM ring. The effectiveness of those algorithms is then compared based on the theoretical lower bounds shown in Section 3. In Section 5, we analytically obtain and evaluate the packet delay time. Conclusions and future work are summarized in Section 6.

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2. Optical Pulse Compression/Expansion Technique and the Structures of the OCTDM Ring

2.1 Optical Pulse Compression/Expansion Technique

Optical pulse compression/expansion technology is promising for realizing a very high-speed backbone ring [5]. When the packet is input to the optical line, the bit interval is compressed by the fiber delay loop (Fig. 1). Since the compression rate with one loop is limited, a high compression rate can be achieved by using several steps if it cannot be realized directly. Also, the compression/expansion frequency at each compression/expansion device is limited; consecutive packet compression/expansion requires optical compression/expansion devices at each access point. A semiconductor optical amplifier (SOA) and switch (SW) are inserted into the loop to compensate the loss on the fiber delay loop. Then, the packet is transmitted onto the ring. When the packet is received in the LAN from the optical line, bit expansion is performed as a reverse procedure of bit compression. More details of the optical pulse compression technique are described in [1], [2], and [11].

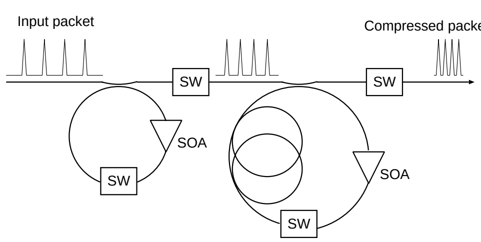


Fig. 1 Bit Compression Device

2.2 Structure and Access Method of the OCTDM Ring

To explain the structure of the OCTDM ring, we first introduce some notations. We consider a unidirectional ring with capacity B_R $[\mathrm{bps}]$. It has N nodes on the ring, being time slotted. Each frame is of a fixed–time length with K slots. The nodes are numbered clockwise from 0 to $N-1$. Node i and Node $i+1$ are connected by link i. See also Fig. 2.

Figure 3 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.

The transmission speed of the minipacket is identical to that of the backbone OCTDM ring. However, there is a limit to the number of minipackets that the transmitter can put into the slot, due to speed mismatch between the backbone ring and LANs. More precisely, we consider that each

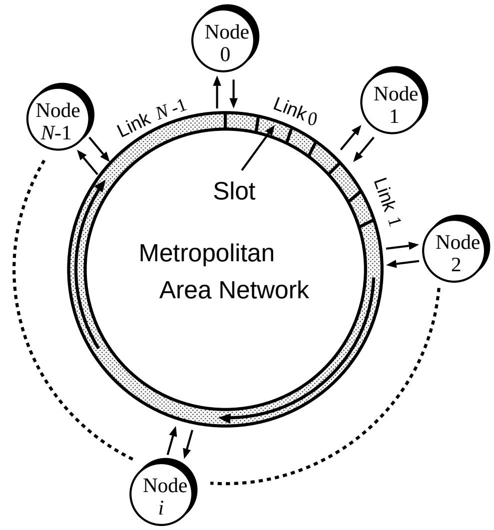


Fig. 2 Unidirectional Ring with Optical Compression TDM

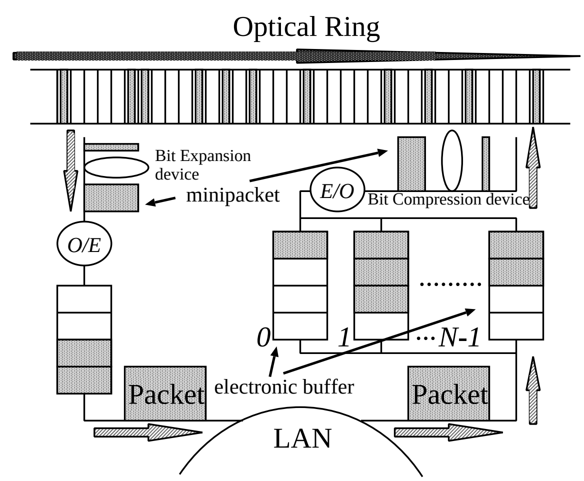


Fig. 3 Node Structure and Access Method

transmitter can place only one minipacket during the fixed time duration, which is referred to as the *frame* (Fig. 4) 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* (Fig. 4). The superframe may consist of several frames. On the ring, the superframe is cyclically carried.

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

In this paper, we first focus on the optimal path accommodation method to minimize the number of frames/slots in the next section.

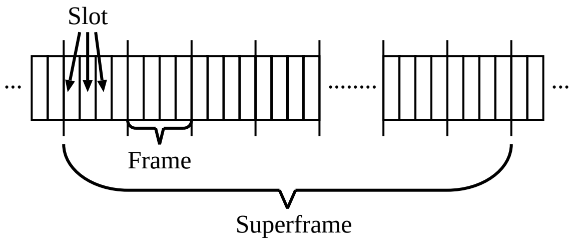


Fig. 4 Relations among Slot, Frame, Superframe

3. Lower Bounds of Superframe Length

3.1 Introduction of Notations

We assume that node i is equipped with T_i transmitters and R_i receivers. 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 transmitters and receivers, respectively. We use the notation $T = j$ if every node on the ring has an identical number j of transmitters; i.e., $\mathcal{T} = \{j, j, \cdots, j\}$. Similarly, $R = k$ shows that every node can receive k minipackets within a frame.

The path from source node i to destination node $(i+s)$ is represented by (i, s), where s is clockwise distance between two nodes in hop counts. To simplify the representation in the following presentation, we will use k $(\geqq N)$ to represent the node number. In that case, k should be read as $mod(k, N)$.

3.2 Traffic Demands

Our main purpose in this section 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 $F = \{f^{(i,s)}[\text{bps}]\}$ is given, where $f^{(i,s)}[\text{bps}]$ 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.

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

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

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

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

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

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

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

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

$$(\forall i \forall s) \qquad \frac{B_R}{LB(N, \mathcal{T}, \mathcal{R}, K, C) \cdot K} \cdot c^{(i,s)} \geqq f^{(i,s)}, \qquad (5)$$

where $LB(N, \mathcal{T}, \mathcal{R}, K, C)$ is the theoretical lower bound (see Subsection 3.3) 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.

3.3 Theoretical Lower Bounds

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 transmitters), $\mathcal{R}$ (set of the numbers of receivers), K (number of time slots within the frame), and C (traffic load matrix). We define it as $LB(N, \mathcal{T}, \mathcal{R}, K, C)$. Note that the theoretical lower bound in WDM rings was investigated in [10] 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 [6]. 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 transmitters/receivers 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

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

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, $LB(N, \infty, \infty, K, C)$, is thus given as

$$LB(N, \infty, \infty, K, C) = \max_{0 \leqq i \leqq N-1} \left\lceil \frac{n^{(i)}}{K} \right\rceil. \qquad (7)$$

(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 transmitters (T_i) and receivers (R_i). That is, $LB(N, \mathcal{T}, \infty, \infty, C)$ and $LB(N, \infty, \mathcal{R}, \infty, C)$ are derived as

$$LB(N, \mathcal{T}, \infty, \infty, C) = \max_{0 \leqq i \leqq N-1} \left\lceil \frac{s_p^{(i)}}{T_i} \right\rceil, \tag{10}$$

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

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

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

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 transmitters/receivers and the number of time slots in the frame. Then we achieve a ring with higher throughput.

4. Path Accommodation Algorithms

In this section, we propose three 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 transmitters and receivers are effectively used. In what follows, we will first present the path accommodation method in the case of all–optical access in Subsection 4.1. The case with path splitting access is then treated in Subsection 4.2, where some paths are split at some node between source/destination nodes, in order to achieve the shorter superframe. Subsection 4.3 is devoted to the presentation of the numerical examples.

4.1 All–Optical Access

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 transceivers are taken into account. Algorithm A3 reflects the accommodation balance for the effective use of the slots.

4.1.1 Algorithm A1

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 transmitter for the source node and the receiver 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 below. The attempt to set up the path first checks to see if transmitters, receivers, and slots are available on path (i, s) when $c^{(i,s)} \geqq 1$ (see Line 7). If it is true, path (i, s) is actually set. Then, $c^{(i,s)}$ is reduced by one.

Algorithm A1

```
1:  Init:  the_superframe_length = 1
2:  while (every path cannot be set up)
3:     if (a path cannot be set up at all)
4:        the_superframe_length++
5:     for (s= N-1; s >= 1; s--)
6:        for (i=0; i <= N-1; i++)
7:           Attempt to set the path (i, s)
8:  the_superframe_length is finally obtained
```

4.1.2 Algorithm A2

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, transmitters, and receivers. Here, the 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 below.

Algorithm A2

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++`
`the_superframe_length` is finally obtained

4.1.3 Algorithm A3

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 below.

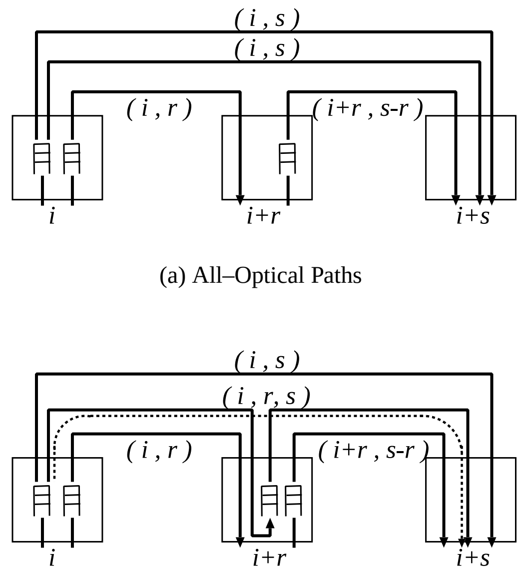
Algorithm A3

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 <=` $\lfloor \frac{N}{2} \rfloor - 1$`; i++)`
    attempt to set each path $(i, \frac{N}{2})$ and $(i+\frac{N}{2}, \frac{N}{2})$
  `for (s=1; s <=` $\lfloor \frac{N}{2} \rfloor - 1$`; s++)`
    `for (i=0 ; i <= N-1 ; i++)`
      set each path (i, s) and $(i+s, N-s)$
finally obtain `the_superframe_length`

4.2 Path Splitting Access

In the previous subsection, we proposed three 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 Fig. 5. Suppose that in the case of all–optical access (Fig. 5(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 $(i+r, s-r)$ into two paths, as shown in Fig. 5(b). Then, we still need only three slots within the frame. We refer to such a path (i,r) 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.



(b) Path Splitting

Fig. 5 Difference between All–Optical and Path Splitting Accesses

The purpose of this subsection is to propose the path splitting algorithm; numerical results will be presented in the next subsection. The packet delay including possible path splitting will be provided in the next section.

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 transmitters/receivers having the lowest weight along the path is selected as its splitting point. Consequently, the splitting node $i+r$ is chosen if

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

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

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

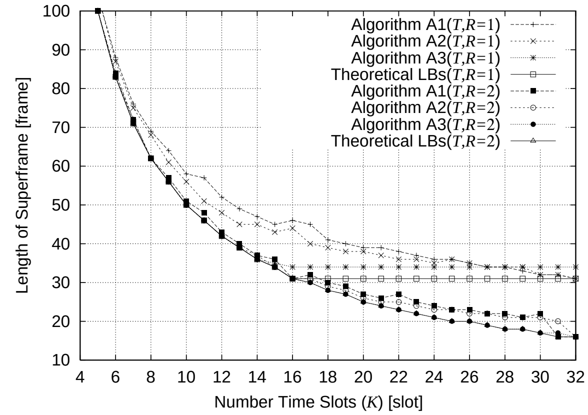
(c) C_3

Fig. 6 Traffic Matrices for Numerical Examples

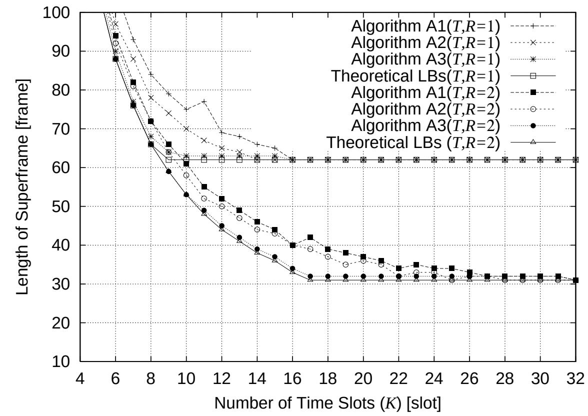
4.3 Numerical Examples of Algorithms and Access Methods

In this subsection, we first compare the three algorithms A1, A2 and A3 presented in the previous subsection. The number of nodes, N, is fixed at 32. For the traffic load matrices, we will consider C_1 (Fig. 6(a)), C_2 (Fig. 6(b)) and C_3 (Fig. 6(c)). The characteristics of those traffic matrices are summarized below.

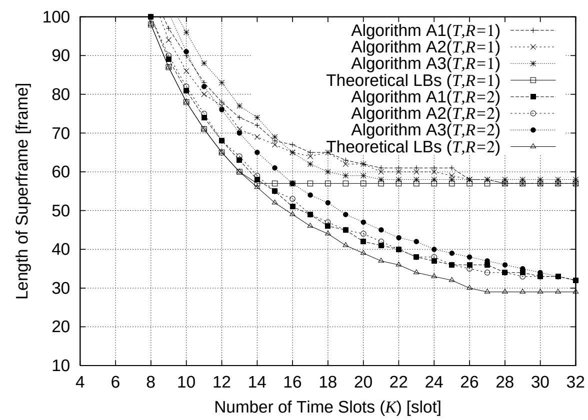
- C_1: a uniform traffic load.
- C_2: all paths except the ones with destination node 31 are uniform. The load of paths from any source node to destination node 31 is twice as large as that of others.



(a) Traffic matrix C_1



(b) Traffic matrix C_2



(c) Traffic matrix C_3

Fig. 7 Comparisons of Lower Bounds and Superframe Lengths obtained by applying algorithms A1, A2 and A3

- C_3: the load of each path is randomly decided between 0 and 3.

We assume that the numbers of transmitters/receivers per node are identically set; i.e., $T = R$.

Figs. 7(a), 7(b) and 7(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 transceivers are considered: $T = R = 1$ and $T = R = 2$. The horizontal axis ($4 \leqq K \leqq 32$) 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 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 section.

5. Analysis of Packet Delay Times

In this section, 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 in Subsection 5.1. The result is then modified to derive the approximate packet delay time for the nonuniform traffic load in Subsection 5.2. The packet delay time for path splitting access is next considered in Subsection 5.3. 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 5.4.

5.1 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:

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

Table 1 Results by Path Splitting for Traffic Load Matrix C_2

# of $T_{ransmitters}$, $R_{eceivers}$	# of slots (K)	Theoretical LB	All-Optical Access			Path Splitting Access					
			A1	A2	A3	A1	# of split	A2	# of split	A3	# of split
1	11	62	77	67	63	64	13	66	1	62	1
1	12	62	69	65	63	65	4	63	2	62	1
1	13	62	68	64	63	63	5	62	2	62	1
2	11	48	55	52	49	51	13	50	5	48	1
2	12	44	52	50	45	47	10	48	5	44	1
2	13	41	49	47	42	45	11	44	6	41	1
2	14	38	46	44	39	41	12	41	7	38	(14,1,17) 1
2	15	36	44	43	37	39	13	39	10	36	1
2	16	33	40	40	34	37	5	38	4	33	1
2	26	31	33	32	32	32	1	31	3	31	2

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

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

5.2 Extension to Nonuniform Traffic Load in 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

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

5.3 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 Fig. 5(b). Then, the packet delay time $W^{(i,s)}$ for path splitting access is represented by

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

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.

5.4 Numerical Examples and Discussions

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

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

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 8 shows the results of the average packet delay time against the traffic load matrix C_2 (Fig. 6(b)). Here, the numbers of transceivers 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

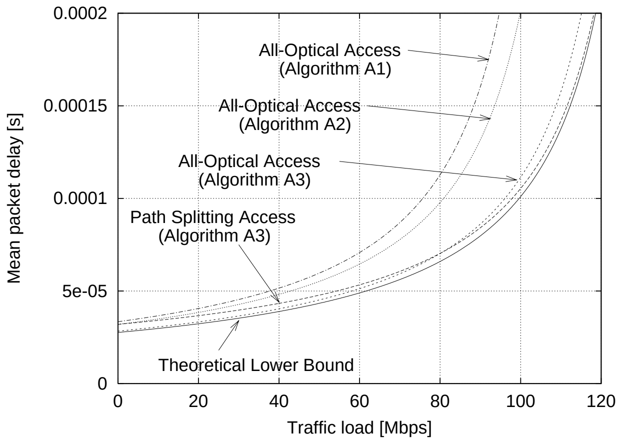


Fig. 8 Comparisons of Packet Delay Times

access by algorithms A1, A2 and A3, and the path splitting access are 38, 46, 44, 39 and 38, 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 Fig. 8, 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.

6. Concluding Remarks and Future Work

In this paper, we have proposed and evaluated path accommodation methods for the unidirectional OCTDM ring, and analyzed the packet transmission time. We first derived the theoretical lower bound for the length of the superframe, in which all paths among nodes are perfectly allocated. Three path accommodation algorithms for all–optical access were then proposed to treat the nonuniform traffic load. Path splitting access was then treated to decrease the superframe length. Our algorithm was successful, but the result should be carefully examined since the packet transmission time may be increased by introducing path splitting. This can be checked by our analysis methods.

As future research work, the reliability of OCTDM rings should be investigated. We should also study the effectiveness of the optical compression TDM/WDM where the optical compression is applied to each of multiple wavelengths in WDM.

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