Scheduling Algorithm for Uniform/Nonuniform Traffic in Unidirectional Optical Compression TDM/WDM Rings with Tuning Latency

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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). 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 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.

Keywords: Optical Compression TDM, Path Accommodation Method, Optical Unidirectional Ring Network, WDM, Tuning Latency

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 transmitters (and receivers), since it employs the optical pulse compression/expansion for ring access [6]. We showed the path accommodation methods suitable to the bidirectional OCTDM rings consisting of 2 fibers (clockwise and anti-clockwise) in [7], and proposed the methods for unidirectional rings in [8].

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

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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 [9–11]. The path accommodation method for the TDM/WDM star-based networks is shown in [10], and the medium access control protocol for the TDM/WDM ring networks is proposed in [12]. 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 the path accommodation method suitable for the OCTDM/WDM ring networks. Following [10], 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.

Note that in this paper, we consider an all–optical access at each node. In [8], we proposed the path–splitting access methods where the performance of OCTDM (without WDM) rings can be actually improved by carefully splitting the path into several ones at intermediate nodes when an OE/EO conversion is not a bottleneck. In this paper, we do not consider it for simplicity, but the extension to such a case can also be treated.

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 derive theoretical lower bounds on the number of slots, which is the required number of slots for accommodating all the paths. The bound is represented by several network parameters, which include numbers of optical compression/expansion devices, tuning latency, and the number of slots within a frame. In Section 5, our path accommodation method is proposed. The effectiveness of our algorithm is evaluated in Section 6 by comparing with the theoretical lower bounds derived in Section 4. In Section 6, we also evaluate the packet delay time to investigate the influence of the tuning latency. Conclusions and future works are summarized in Section 7.

2. TECHNOLOGIES AND STRUCTURE OF THE OCTDM/WDM RING

This section briefly introduces optical compression/expansion techniques and a structure of each node in the OCTDM/WDM ring. An access method to the ring for packet emission is also described.

2.1. Optical 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 (Fig. 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 the multiple optical compression/expansion devices are necessary at each access point if consecutive packets are compressed/expanded at the node.

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].

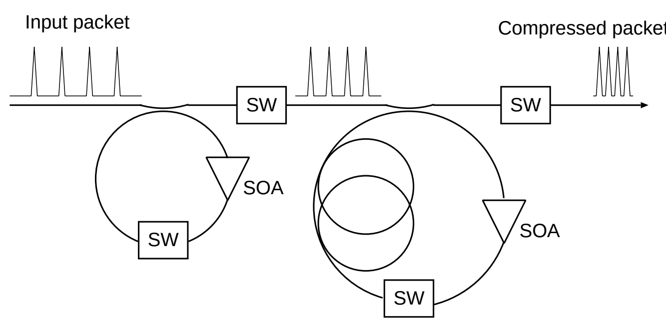


Figure 1. Bit Compression Device

2.2. Tuning Transmitter and Fixed Receiver

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 [10] 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 1Gbps to 10Gbps, 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.

2.3. Access Method to the OCTDM/WDM Ring

We consider the unidirectional OCTDM/WDM ring network. It is assumed that that a wavelength is time-slotted, and every slots are synchronized over wavelengths.

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 some fixed length data sets, called '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 introduce a frame which is a set of slots, and we assume that each optical compression device (and expansion device) can access only one slot during the frame due to a limitation of optical compression/expansion. Since all paths cannot be always accommodated within one frame, we also introduce the set of frames which can accommodate all requested paths. It is called as 'superframe'. Figure 2 shows the relationship among the slot, frame, and superframe.

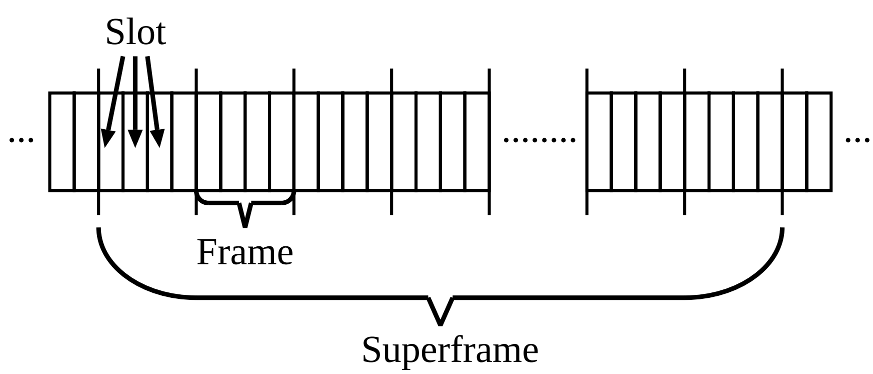


Figure 2. the relation of slots, frames, and superframes

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

In this section, we introduce our network model of the optical compression OCTDM/WDM ring. See Figure 3 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 Fig. 3, the link n connects nodes n and $n+1$. On the link, there are the number W of wavelengths. A length of one frame

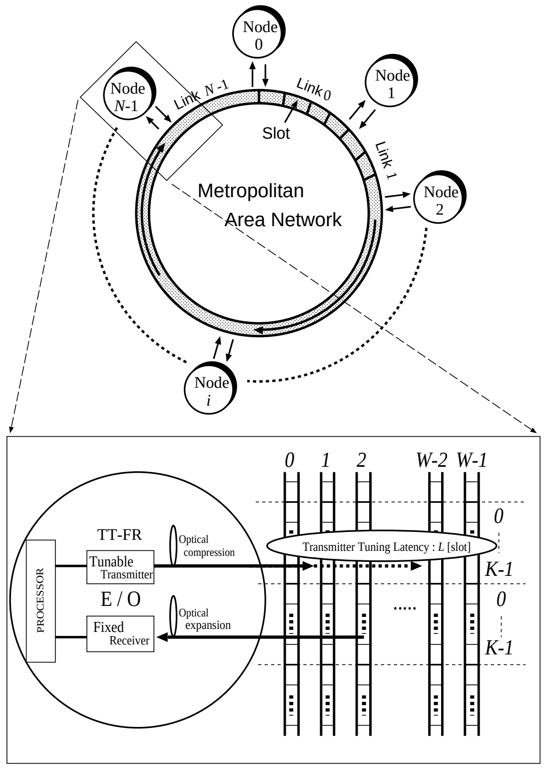


Figure 3. Structure of the OCTDM/WDM Ring and Each Node

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 $mod(k, N)$. Also, we assume that the traffic load is expressed in integer values, i.e., the required number of slots for path (i, s) takes an integer value $c^{(i,s)}$. A N by N matrix $C = \{c^{(i,s)}\}$ is given as the traffic load matrix. Hereafter, we implicitly assume that the total sum of the traffic load does not exceed the ring capacity, so that it is always possible to accommodate all of paths.

4. THEORETICAL LOWER BOUND OF THE SUPERFRAME

In this section, we show the theoretical lower bound on the length of the superframe that can accommodate the given traffic load C. It will be used for comparison with our path accommodation method proposed in the next section. We define the lower bound as $LBS(N, \mathcal{T}, \mathcal{R}, K, W, L, C)$ [slot] dependent on the following parameters; the number of nodes N, the number of optical compression devices and expansion devices at each node $\mathcal{T}, \mathcal{R}$, the frame length K, the number of wavelengths W, the tuning latency L, and the traffic matrix C. 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:

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

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:

$$LBS_{\mathcal{T}L}^{(W_u)} = LBS(N, \mathcal{T}, -, K, W_u, L, C) = \begin{cases} h, & \text{if } L(W_u - 1) + \max_{0 \le i \le N-1} s_p^{(i)} \le h \\ h + \left\lceil \frac{L(W_u-1) + \max_{0 \le i \le N-1} s_p^{(i)} - h}{K} \right\rceil \cdot K, & \text{otherwise.} \end{cases} \tag{2}$$

Note that in finally determining $LBS_{\mathcal{T}L}^{(W_u)}$, 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:

$$LBS_{\mathcal{R}} = LBS(N, -, \mathcal{R}, K, -, -, C) = \max_{0 \le i \le N-1} \left(\lceil \frac{r_p^{(i)}}{R_i} \rceil \right) \cdot K. \tag{3}$$

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

$$LBS(N, -, -, K, W_u, -, C) = \max_{0 \le v \le N-1, 0 \le w \le W_u - 1} \left(\lceil \frac{n^{(v)(w)}}{K} \rceil \right) \cdot K. \tag{4}$$

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

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

$$\max_{0 \le w \le W_u - 1} (n^{(v)(w)}). \tag{5}$$

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;

$$r_p^{(i)(v)} = \sum_{k=\min(v, i+1)}^{\max(v, i-1)} c^{(k,i-k)}. \tag{6}$$

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 [13,14] 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.

LPT Algorithm

```
begin
    for w = 0 to W_u - 1 do LPT^(v)[w] = 0, P[k] = 0;
    i = 0;
    repeat
        LPT^(v)[k] = min_{0<=w<=W_u-1} (LPT^(v)[w]);
        LPT^(v)[k] = LPT^(v)[k] + t_p^(i)(v);
        P[k] = P[k] + 1;
        i = i + 1;
    until i > N - 1;
    LPT^(v) = max_{0<=w<=W_u-1} (LPT^(v)[w]);
    P = P[k];
end
```

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 [13,14]. 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 [14] 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 [15];

$$LPT_{ub}^{(v)} = \left\lceil \left(1+\frac{1}{P}-\frac{1}{PW_u}\right) LPT_{lb}^{(v)} \right\rceil, \tag{7}$$

where $LPT_{lb}^{(v)}$ and $LPT_{ub}^{(v)}$ are the lower and upper bounds of $LPT^{(v)}$. From Eq. (7), we have

$$LPT^{(v)} \leq \left\lceil \left(1+\frac{1}{P}-\frac{1}{PW_u}\right) LPT_{lb}^{(v)} \right\rceil, \tag{8}$$

$$LPT^{(v)} \leq \left(1+\frac{1}{P}-\frac{1}{PW_u}\right) LPT_{lb}^{(v)} + 1, \tag{9}$$

$$\frac{LPT^{(v)}-1}{\left(1+\frac{1}{P}-\frac{1}{PW_u}\right)} \leq LPT_{lb}^{(v)}. \tag{10}$$

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;

$$LPT_{lb-approx}^{(v)} = \left\lceil \frac{LPT^{(v)}-1}{\left(1+\frac{1}{P}-\frac{1}{PW_u}\right)} \right\rceil \leq LPT_{lb}^{(v)}. \tag{11}$$

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

$$S_{LB} = \max\left(LPT_{lb-approx}^{(v)}, \lceil \frac{n^{(v)}}{W_u} \rceil\right). \tag{12}$$

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;

$$LBS_{KW}^{(W_u)} = LBS(N,-,-,K,W_u,-,C) = \max_{0\leq v\leq N-1}\left(\left\lceil \frac{LPT_{lb-approx}^{(v)}}{K} \right\rceil, \lceil \frac{n^{(v)}}{KW_u} \rceil\right)\cdot K \tag{13}$$

From the above three cases, we finally determine $LBS(N, \mathcal{T}, \mathcal{R}, K, W, L, C)$ [slot] from Eqs. (2), (3) and (13) as follows:

$$LBS(N, \mathcal{T}, \mathcal{R}, K, W, L, C) = \min_{1 \leq W_u \leq W} (LBS_{\mathcal{T}L}^{(W_u)}, LBS_{\mathcal{R}}, LBS_{KW}^{(W_u)}) \quad (14)$$

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 Section 6 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. PATH SCHEDULING 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, which will be shown in the next section. 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 algorithms are executed in turn. See the top part of Fig. 4.

5.1. 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 4 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.

5.2. 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 Fig. 4, the APTRS algorithm first assigns the wavelength for each 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.

6. EVALUATION OF OUR PROPOSED PATH SCHEDULING ALGORITHM

In this section, we first evaluate our scheduling algorithm APW+APTRS proposed in Section 5. We first compare the results of APW+APTRS with the theoretical lower bound, $LBS(N, \mathcal{T}, \mathcal{R}, K, W, L, C)$, derived in Section 4, and discuss the characteristics of the OCTDM/WDM ring. The average packet delay time from sender to receiver is next investigated in Subsection 6.2.

```
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
```

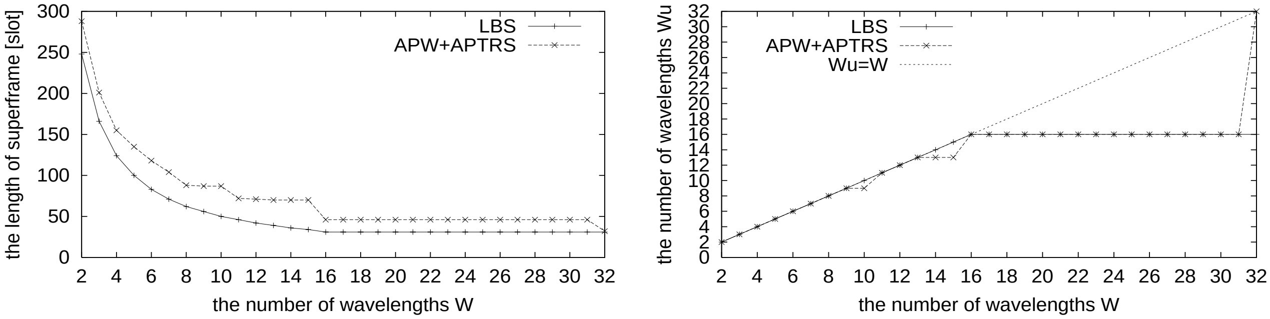
```
Procedure APW (W_u){
1:int wave_wait[W_u] = {0,···,0}
2:while( max_{0≤i≤N−1} r_p^(i) > 0 ){
3:  //obtain the node number with heaviest load receiver of all remaining nodes
    i = {i| max_{0≤i≤N−1} r_p^(i)/R_i}
4:  //obtain the wavelength number with the lightest load at this time
    w = {w| min_{0≤w≤W_u−1} 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 4. Path Scheduling Algorithm for the OCTDM/WDM Rings

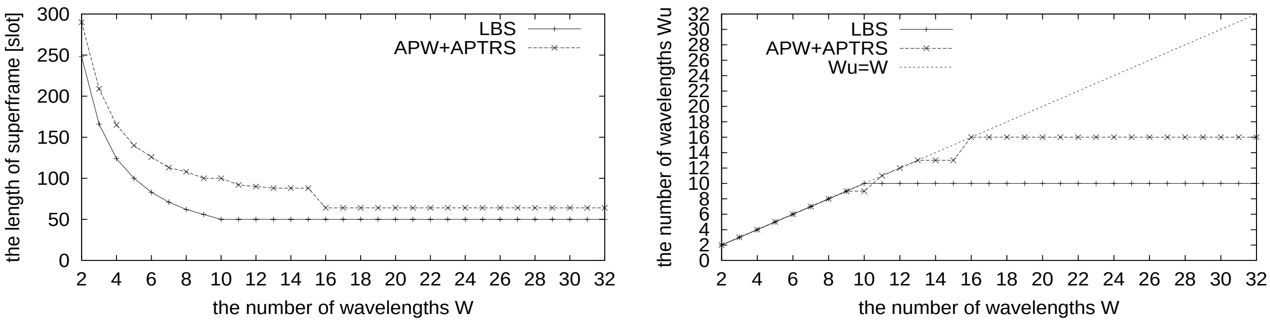
6.1. The Length of Superframe

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 5, 6, and 7 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 receivers $\mathcal{R} = \{1, 1, .., 1\}$. 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 4 are also shown in figures. Similarly, Figs. 8, 9, and 10 show the results for the nonuniform traffic case. Here, the value of each element of the traffic load matrix is chosen



(a) The length of the superframe (b) The number of wavelengths for the shortest superframe

Figure 5. The superframe length in the uniform traffic load case with $L = 0$ ($N = 32, K = 1, \mathcal{T} = \{1, 1, .., 1\}, and \mathcal{R} = \{1, 1, .., 1\},$)

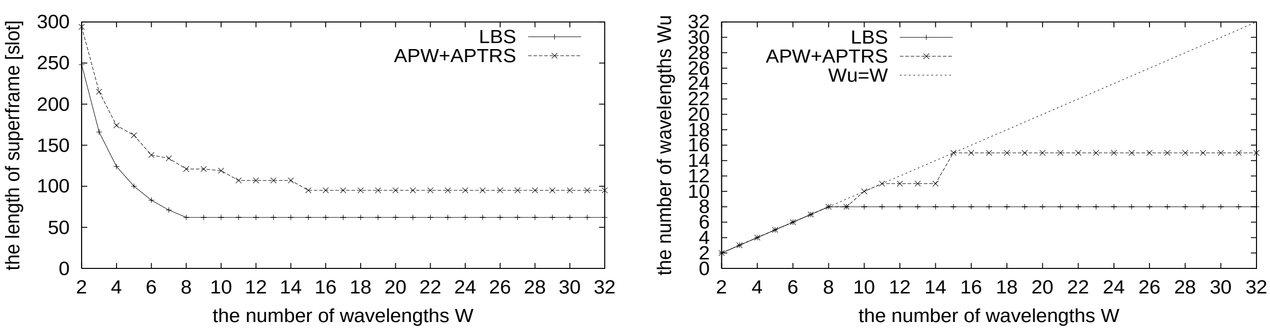


(a) The length of the superframe (b) The number of wavelengths for the shortest superframe

Figure 6. The superframe length in the uniform traffic load case with $L = 2$ ($N = 32, K = 1, \mathcal{T} = \{1, 1, .., 1\}, and \mathcal{R} = \{1, 1, .., 1\},$)

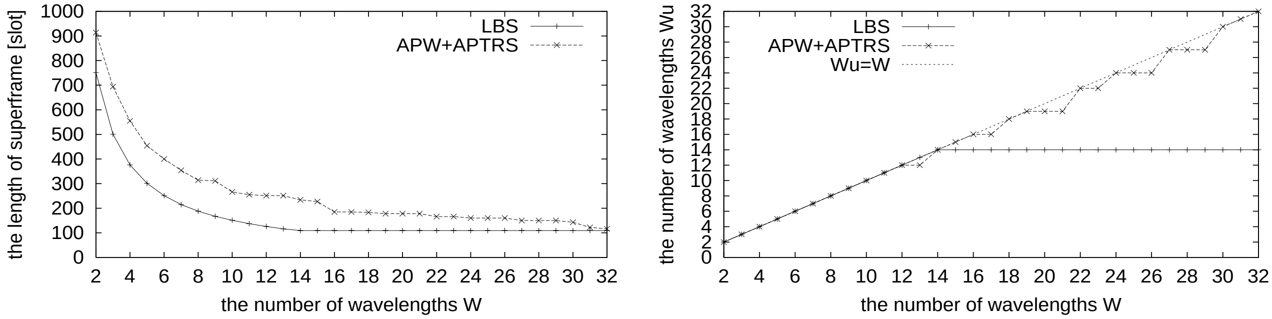
randomly between 1 and 5. Other parameters are unchanged. From these figures, we can observe that APW+APTRS is effective for both of uniform and nonuniform traffic load cases in almost all parameter regions.

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 wavelengths 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 4 or the results of our scheduling 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.



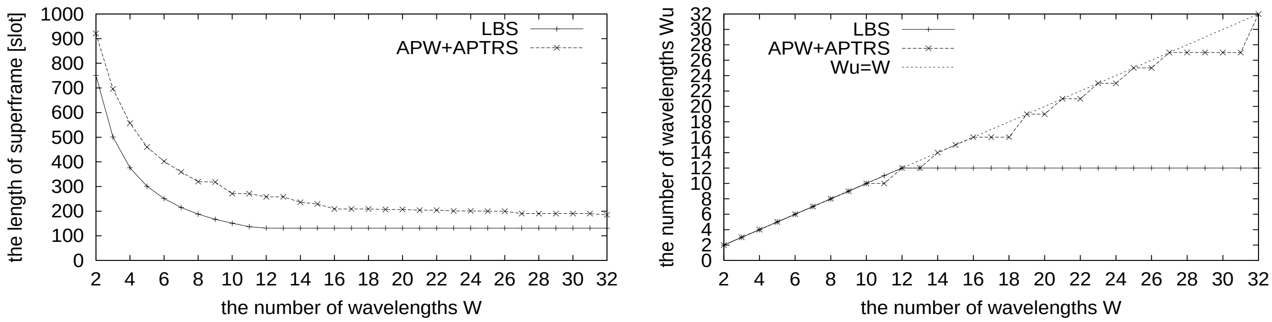
(a) The length of the superframe (b) The number of wavelengths for the shortest superframe

Figure 7. The superframe length in the uniform traffic load case with $L = 4$ ($N = 32, K = 1, \mathcal{T} = \{1, 1, .., 1\}, and \mathcal{R} = \{1, 1, .., 1\},$)



(a) The length of the superframe (b) The number of wavelengths for the shortest superframe

Figure 8. The superframe length in the nonuniform traffic load case with $L = 0$ ($N = 32, K = 1, \mathcal{T} = \{1, 1, .., 1\}, and \mathcal{R} = \{1, 1, .., 1\}$,)



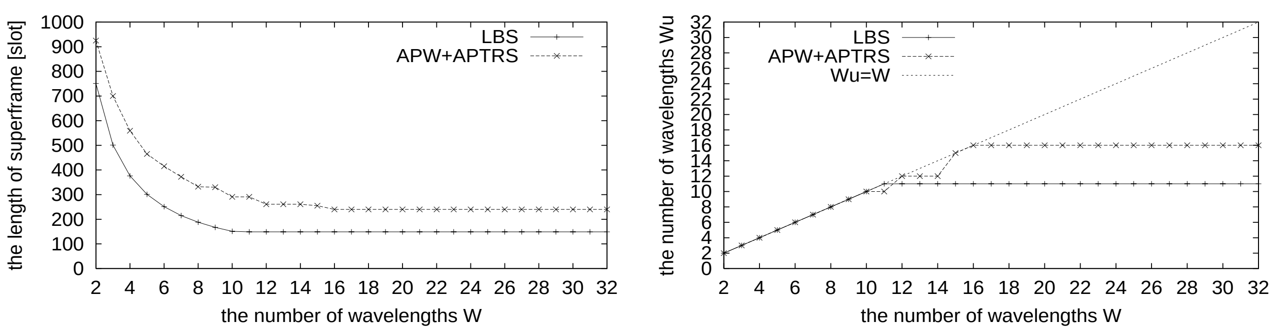
(a) The length of the superframe (b) The number of wavelengths for the shortest superframe

Figure 9. The superframe length in the nonuniform traffic load case with $L = 2$ ($N = 32, K = 1, \mathcal{T} = \{1, 1, .., 1\}, and \mathcal{R} = \{1, 1, .., 1\}$,)

6.2. Packet Delay Time

In the previous subsection, 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 size (in time) of one slot affects the throughput of the network.

Table 1 and Fig. 11 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 [16] 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

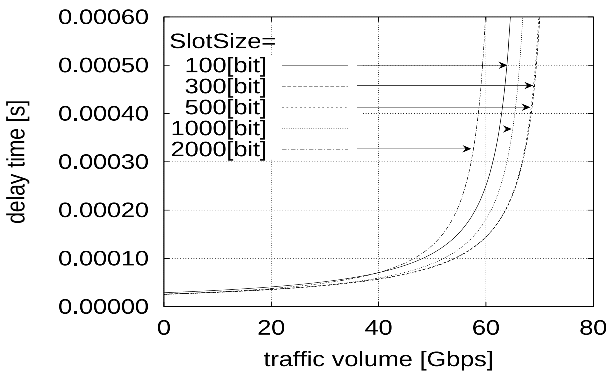


(a) The length of the superframe (b) The number of wavelengths for the shortest superframe

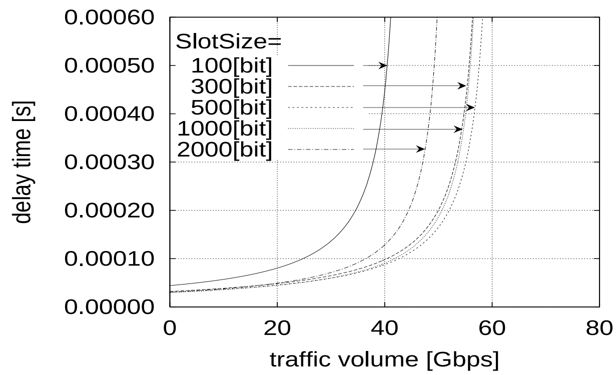
Figure 10. The superframe length in the nonuniform traffic load case with $L = 4$ ($N = 32, K = 1, \mathcal{T} = \{1, 1, .., 1\}, and \mathcal{R} = \{1, 1, .., 1\}$,)

Table 1. The superframe length dependent on the slot length

the size of one slot	the tuning latency		LBS	APW+APTRS
[bit]	[ns]	[slot]	[slot]	[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 11. 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 $\mathcal{R} = \{1, 1, .., 1\}$

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 1, 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 Fig. 11, and about 500[bit] of the slot length leads to the best result in the current parameter settings.

7. CONCLUDING REMARKS AND FUTURE WORKS

In this paper, we have proposed and evaluated the path accommodation methods for the unidirectional OCTDM/TDM rings. We have first derived the theoretical lower bound which determines the length of the superframe. 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 show 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. As future research works, the reliability issue for the OCTDM/WDM rings should be investigated.

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