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Proposal of Rip-up & Re-allocate Algorithm for Optical Layer-2 Switch Network

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Abstract: We are developing an optical layer-2 switch network that uses both wavelength-division multiplexing and time-division multiplexing technologies for efficient traffic aggregation in metro networks. For efficient traffic aggregation, path bandwidth control is key because it strongly affects bandwidth efficiency. For this paper, we propose a dynamic time-slot allocation method that uses periodic information of difference values of traffic variation. This method can derive near-optimal allocation with lower computational cost, which enlarges the maximum available network size compared with conventional time-slot allocation methods. Numerical results show that the proposed method enables dynamic path control in 1K-node-scale optical layer-2 switch network, which leads to cost-effective metro networks.

Key words: WDM/TDM ring networks; Dynamic time-slot allocation; Difference value of traffic; Time-slot schedule; Operation sequencing algorithm; Time-slot selection algorithm
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0 Introduction

Network (NW) traffic is increasing exponentially; therefore, it is becoming increasingly necessary to create cost-effective NWs in terms of equipment expense and/or power consumption. To respond to this world-wide trend, we are developing an optical layer-2 switch network (OL2SW-NW) that can efficiently accommodate traffic in a large-scale NW[1-2]. In the OL2SW-NW, each WDM channel is divided into fixed time intervals known as Time Slots (TSs). At every fixed time period T, some TSs are then allocated to each path according to the volume of traffic on the corresponding node pair so as to follow the traffic fluctuation. The OL2SW-NW is a viable NW system, especially in a wide-area metro NW, for cost-effectively coping with future increases in traffic. A unified transport NW that can effectively accommodate multiple services will be possible with our NW system, which differs from the typical NW system where the quasi-static BandWidth (BW) is dedicated to every individual service. Hence, the OL2SW-NW may potentially replace ROADM systems[3], which have been widely deployed, in the near future.

In the OL2SW-NW, traffic information on all paths is collected at a central server for centralized path control. Thus, TS-allocation processing will produce a bottleneck in large-scale NWs. We propose a fast TS allocation method that uses periodic traffic information and weighting algorithms for operation sequencing and TS selection. We also report on our evaluation of its effectiveness.

1 Optical layer-2 switch network

1.1 Architecture of OL2SW-NW

The OL2SW-NW is a ring-formed aggregation NW that has several hundreds to a thousand nodes and connects core and access NWs. Fig. 1 shows the outline of the OL2SW-NW connected to 10 IP routers and 1000 access switches (SWs). We assume that IP routers at the edge of future core NWs will achieve load balancing between the ten routers by applying virtualization technology[4]. We also assume that next generation access systems, such as WDM/TDM-PON[5] and LTE-Advanced[6], will be introduced into future access NWs. Therefore, each access SW communicates with ten routers and the traffic on each SW-router pair fluctuates dynamically (larger volume and more bursty). Based on the above assumption, traffic in the future metro NW defined in this paper is assumed to have the following characteristics; even if the total amount of NW traffic does not change, each flow on each SW-router pair dynamically fluctuates; the fluctuation is at a rate of 100 Mbps per 1 s to 1 min[7]; and the volume of each flow can vary from tens of Mbps to Gbps. In the conventional WDM-based wavelength-routed metro NW architecture, the paths are generally managed on longer timescales and most

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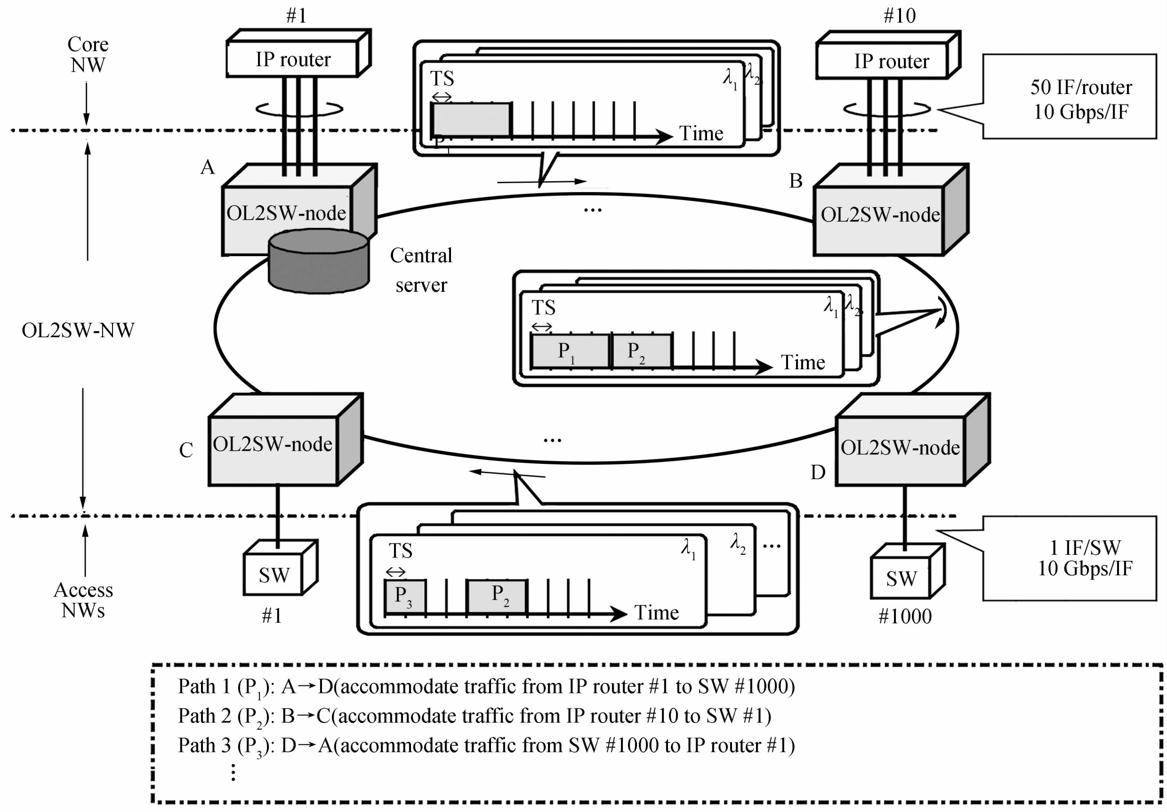
operations are executed according to predetermined plans. Hence, the conventional metro NW cannot adapt to a shorter-timescale fluctuation and tends to statically allocate wavelength-granularity BW to paths for tolerating the peak load, which wastes NW resources and requires a large amount of redundant resources. In the OL2SW-NW, however, the wavelength BW is partitioned into TSs and the BW of each path is dynamically controlled in TS-granularity on the same time scale as traffic fluctuation. This means that T in our NW depends on the target traffic model and each path BW is controlled in more than or comparable to fluctuation granularity. For specifically accommodating the above-described traffic model, T should be set to less than 1 s and the path BW should be controlled in less than 100 Mbps. Otherwise (i. e., T is larger or TS-size is larger), it will be impossible to follow the traffic fluctuation, which wastes BW or causes large latency due to the lack of BW.

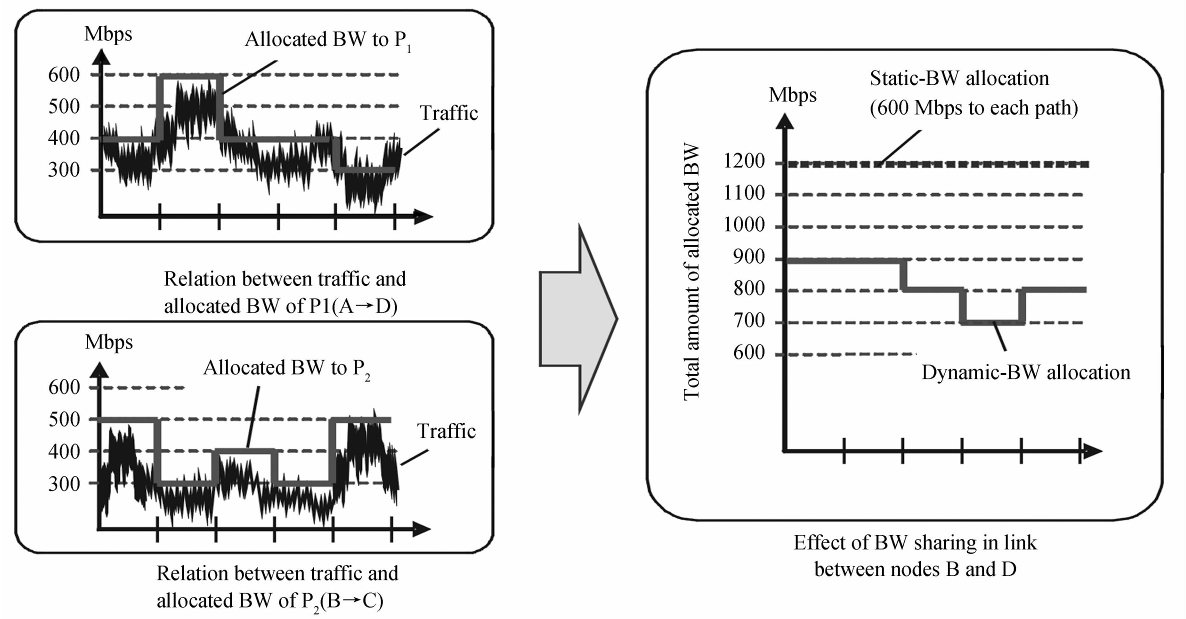
The path-BW allocation and data transmission scheme on the WDM-ring in the OL2SW-NW is depicted in Fig. 1(a). On the (1-channel, some TSs are allocated to paths 1 (P_1), 2 (P_2), and 3 (P_3). The data accommodated in P_1 are dropped at OL2SW-node D, data accommodated in P_3 are added to TSs that had been occupied by P1, which leads to beneficial use of WDM-ring resources. Fig. 1(b) simply illustrates the relation between the traffic fluctuation and allocated BW on the (1-channel of the link between nodes B and D. Please note that the timescale is not in hours but in seconds. The dynamic-BW allocation scheme wastes less BW compared with the static-BW allocation scheme. Therefore, by achieving maximum throughput with limited resources, such as in PON systems[8], WDM channels can be efficiently shared by many paths. Thus, the OL2SW-NW can be designed with fewer WDM channels than static-BW-assigned NWs. This reduces the amount of NW equipment required such as fibers, transponders, and SW-ports.

1.2 Dynamic path control operation

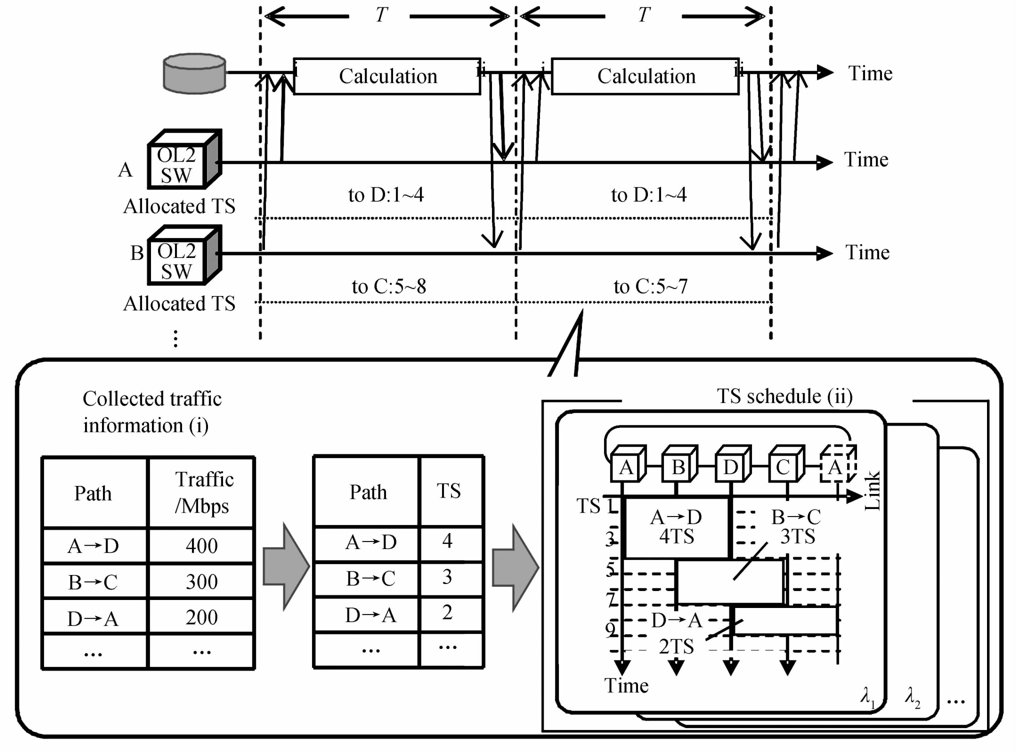
In the OL2SW-NW, all nodes regularly advertise the traffic information to the central server as shown in Fig. 1(c). The central server determines the number of TSs to be allocated to each path according to traffic and executes Time Slot Allocation (TSA). A TS schedule, which is a 3-dimensional (links, wavelengths, and time-slots) table that represents the condition of TSA, i. e., a data sequence in each wavelength in each link, is then



(a) Path setup and data transmission in OL2SW-NW



(b) Relation between traffic and allocated BW in link between nodes B and D



Path	Traffic /Mbps
A→D	400
B→C	300
D→A	200
...	...

Path	TS
A→D	4
B→C	3
D→A	2
...	...

(C) Operation of dynamic path control in OL2SW-NW

Fig. 1 Outline of OL2SW-NW architecture

derived. Then each node functions according to the TS schedule produced by the central server. Please note that for simplicity the link propagation delays are not depicted in Fig. 1(c); however, the delays result in a shifted time-slot allocation. The effect of delays in control signal exchange is also negligible since advertising delays in metro NWs are assumed to be much smaller than T. Time slot allocation, i. e., resource-allocation processing in the OL2SW-NW differs from that for PON systems, which is called DBA[8]. Time slot allocation in the OL2SW-NW is not tree based but ring based, so multipoint-to-multipoint resource allocation on the ring, where upstream and downstream traffic are multiplexed, is necessary, which has higher computational complexity. Current TSA methods (e. g. Ref. [9,10]) generally require excessive computation time in 1K-node-scale NWs and seem to be inappropriate; hence, a much faster TSA method needs to be developed.

2 Proposed method: rip-up & re-allocate

A central server must allocate some TSs on wavelength channel(s) to each path at T intervals to derive the TS schedule. In this allocation processing, creating a TS schedule from scratch with each cycle requires much time complexity. In response, we propose a dynamic TSA method called "Rip-up & Re-allocate (R&R)." This method focuses only on the difference value of traffic change and applies this change to the TS schedule; it allocates additional TS(s) to some paths and releases the TS(s) already allocated to paths. This results in reducing computation time because some paths whose traffic volume had not changed much in the previous interval are omitted from TSA calculation. This method is suitable to accommodate metro-traffic whose fluctuation is not as drastic as access-traffic.

The proposed method consists of the following three steps; derivation of the difference value of traffic changes, releasing TS(s) allocated to paths whose traffic volume had decreased, and allocating TS(s) to paths whose traffic volume had increased. In this method, the server partially changes the TS schedule according to traffic fluctuation in the previous interval and reproduces the schedule in the next TSA calculation. Thus, NW performance, in terms of throughput and latency, strongly depends on the algorithm used. Therefore, better algorithms that suppress the deviation from the optimal solution are important. Periodic optimization on a short timescale in limited resources, in order to follow traffic fluctuation, can reduce redundant resources, so our method is expected to suppress the required NW resources.

2.1 Difference value derivation of traffic change

Let $R_{\mathrm{s,d}}(\tau_k)$ be the traffic information (e. g. volume) at (τ_k of a path whose source and destination are s and d respectively, where k is a natural number and (τ_k satisfies ($\tau_{k+1} - \tau_k = T$. In this step, the difference value of traffic variation is derived by comparing $R_{\mathrm{s,d}}(\tau_k)$ and $R_{\mathrm{s,d}}(\tau_{k-1})$. The difference value is translated into the number of TSs, $D_{\mathrm{s,d}}$ (e. g. the value is rounded down to 100 Mbps, and 100 Mbps = 1 TS in this paper). This step determines not only the paths to be changed BW but also how many TSs should be released or added.

2.2 Rip-up

The TS(s) already allocated to paths that satisfy $D_{\mathrm{s,d}}<0$ is(are) ripped up, i. e., released from the TS schedule. Naturally, the number of TSs that should be ripped up is $|D_{\mathrm{s,d}}|$. In this step, there are two essential points; "which path should be started with?" and "which TS should be released?" This means, rip-up operation sequencing and TS selection algorithms are quite important. We now give more details about these algorithms and their features.

2.2.1 *Operation sequencing algorithms for Rip-up*

First-fit Path Selection (FPS): All paths in a NW are numbered and this algorithm executes rip-up operation in ascending sequence of the number of paths that satisfies $D_{\mathrm{s,d}} < 0$. This algorithm has a low computation cost since no arithmetic processing is required.

Random Path Selection (RPS): This algorithm finds all paths that satisfy $D_{\mathrm{s,d}}<0$ and executes rip-up operation in a random order. This algorithm changes the order every T and attains the fairness between paths.

Largest-fluctuating-Longest Path First (LLPF): This algorithm uses a weighting function $w_{\mathrm{s,d}}$ defined in Eq. (1) which takes into account traffic fluctuation and the path length. Paths are executed rip-up operation in descending sequence of $w_{\mathrm{s,d}}$ and the tie is broken in a random manner. This algorithm preferentially handles large variation, so higher convergence speed to the optimal solution is expected.

$$w_{\mathrm{s,d}} = \alpha|D_{\mathrm{s,d}}| + \beta L_{\mathrm{s,d}} \qquad (1)$$

where $L_{s,d}$ denotes the path length in terms of hop number of a path whose source and destination are s and d, respectively. In addition, α and β are coefficients that satisfy $\alpha \gg \beta$.

2.2.2 *Time-slot selection algorithms for Rip-up*

First-Fit Time-slot (FFT) Rip-up: This algorithm searches the TSs allocated to the intended path from lower-numbered slots to higher ones, and the first TS(s) is(are) selected and released. FFT has a low computation cost since global information is not required.

Random-Fit Time-slot (RFT) Rip-up: This algorithm finds all TSs allocated to the intended path and randomly selects TS(s) to be released.

Rip-up Considering Cost Function (CCF Rip-up): This algorithm finds the already allocated TS(s) and slot(s), to the intended path, which maximizes the cost function RR_Cost(slot) defined in Eq. (2) and releases it(them). The cost function in Eq. (2) is aimed at creating large successive vacant TSs by rip-up operation. Successive vacant TSs means that the TSs of adjacent links are vacant.

$$\mathrm{RR\_Cost}(\mathrm{slot}) = \mu H(\mathrm{slot}) + \upsilon V(\mathrm{slot}) + \mathrm{slot} \qquad (2)$$

where μ and υ are coefficients that are beneficial in making the successive vacant TSs longer and wider for high tolerance to large traffic fluctuation. We set $\mu > \upsilon$ (to give increased priority to long paths in large-scale NWs. The term H(slot) is the sum of the number of links that satisfy any of the following requirements; (i) terminal node is s and the slot-th TS is vacant, (ii) initial node is d and the slot-th TS is vacant. The term V(slot) is the sum of the number of links that satisfy any of the following requirements; (i) the link where the intended path goes through and the (slot−1)-th TS is vacant, (ii) the link where the intended path goes through and the (slot+1)-th TS is vacant.

In addition, we define the estimative index of the size of successive vacant TSs. First, we define the size per slot as SVTS(slot) in Eq. (3), then, we define the size across the TS schedule as Average SVTS in Eq. (4).

$$\mathrm{SVTS(slot)} = \mathrm{VTS(slot)} \,/\, \mathrm{VAN(slot)} \tag{3}$$

where VTS(slot) and VAN(slot) represent the total vacant TSs in slot and the number of continuous stretches of vacant TSs in slot on the ring, respectively.

$$\text{Average SVTS} = \sum\{\mathrm{SVTS(slot)}\}/\mathrm{VTN} \tag{4}$$

where $\sum\{\mathrm{SVTS(slot)}\}$ and VTN represent the sum of SVTS(slot) in all slot and the number of slot that has no less than 1 vacant TS, respectively. Fig. 2 is an illustration of successive vacant TSs. When Average SVTS is larger, long paths are easier to setup, as shown in Fig. 2.

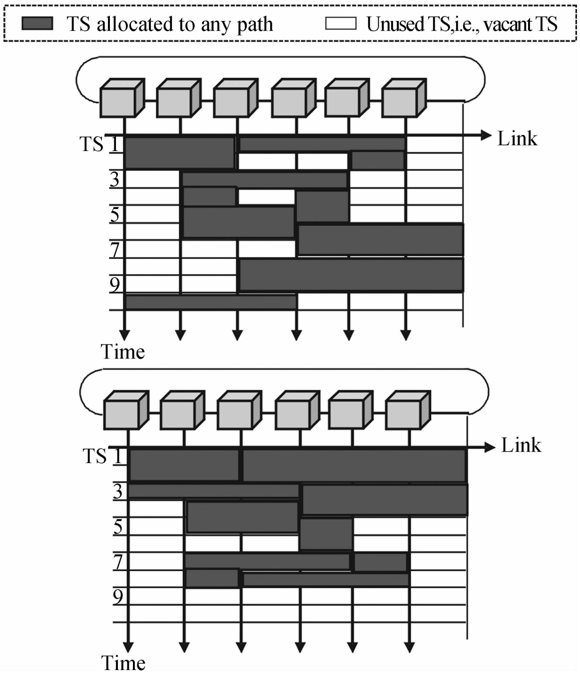


Fig. 2 Concept of successive vacant TSs

2.3 Re-allocate

Additional TS(s) is (are) re-allocated, i. e., reserved on the TS schedule, to paths that satisfy $D_{s,d}>0$. Naturally, the number of TSs that should be re-allocated is $|D_{s,d}|$. As with the rip-up operation described in Sec. II B, re-allocate operation sequencing and TS selection algorithms are quite important. We discuss the details of these algorithms and their features.

2.3.1 *Operation sequencing algorithms for Re-allocate*

There are three kinds of algorithms (FPS, RPS, and LLPF) similar to Rip-up.

2.3.2 *Time-slot selection algorithms for Re-allocate*

First-Fit Time-slot (FFT) Re-allocate: This algorithm searches the vacant TSs from lower-numbered slots to higher ones, and the first TS(s) is (are) selected and reserved. The basic idea for this algorithm is to pack the additional TS(s) towards the start of the TS schedule. This algorithm has a low computation cost since global information is not required.

Random-Fit Time-slot (RFT) Re-allocate: This algorithm finds all vacant TSs allocatable to the intended path and randomly selects TS(s) to be reserved. This algorithm has a low computation cost and is expected to exhibit convergence to the optimal allocation as well as mutation in well known genetic algorithms.

Re-allocate Considering Cost Function (CCF Re-allocate): This algorithm finds the vacant TS(s) and slot(s), allocatable to the intended path, which minimizes the cost function RR_Cost(slot) defined in Eq. (2) and reserves it(them). The basic idea for CCF Re-allocate is to avoid as much disjuncture of successive vacant TSs as possible.

2.4 Strategy for adoption of algorithms

As previously described, algorithms to be applied affect the characteristics of the dynamic path control such as attainable NW size and throughput. We now present the criteria for algorithm adoption.

First, when the short calculation time and high throughput must be balanced, LLPF should be applied as the operation sequencing algorithm for both rip-up and re-allocate to attain higher convergence speed to the optimal allocation. Next, FFT Rip-up should be applied as the time-slot selection algorithm when calculation time is emphasized; however, CCF Rip-up should be applied when high throughput is needed. We apply CCF Rip-up to reduce the required NW resources. When throughput is emphasized, CCF Re-allocate should then be applied as the time-slot selection algorithm; however, the number of TSs to be searched in re-allocate operation is generally much larger than that in rip-up operation, so we apply FFT Re-allocate to reduce calculation time. FFT Re-allocate can achieve high allocation efficiency when CCF Rip-up creates large successive vacant TSs on the TS schedule.

The general outline of R&R is depicted in Fig. 3. The TS schedule at τ_k is derived from the TS schedule at τ_{k-1}, $R_{s,d}(\tau_{k-1})$ and $R_{s,d}(\tau_k)$. First, the difference value of traffic change is derived, as shown in Fig. 3 (a). Then, with respect to each path satisfying $D_{s,d}<0$, rip-up using LLPF and CCF is executed, as shown in Fig. 3(c). Finally, with respect to each path satisfying $D_{s,d}>0$, re-allocate using LLPF and FFT is executed, as shown in Fig. 3(d).

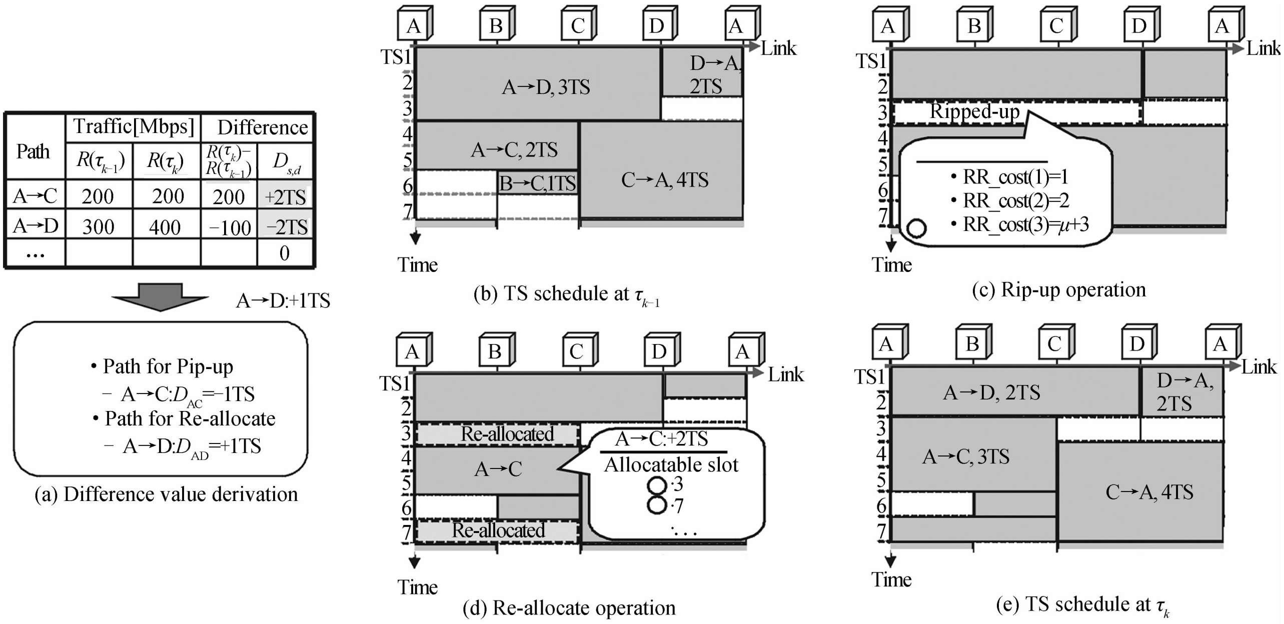


Fig. 3 Schematic of proposed time-slot allocation method.

3 Performance evaluation

We conducted several experiments to investigate the effectiveness of our method. We assumed the OL2SW-NW model described in Section One. The tested physical topology was single-ring with ten connected IP routers and N connected access SWs. Logical paths were setup between each pair of OL2SW-node connected to a router and OL2SW-node connected to access SW. For traffic flowing into each path, we assumed that traffic from multiple users in multiple access NWs are multiplexed and the average volume was set to 400 Mbps (=4 TS). The average value of the total amount of both upstream and downstream traffic was $N\times10\times400$ Mbps $=4N$ Gbps. We also assumed that the total amount of traffic throughout the NW does not change on a short timescale; however, traffic on each path dynamically changes, so traffic on one path increases, whereas traffic on another path decreases simultaneously. The maximum traffic volume on one path was set to 4 Gbps on the second timescale. The magnitude of traffic fluctuation on each path was set from 0.02 TS to 1 TS. This means the absolute value of traffic fluctuation per T interval, and we call the average value of this index per path Average Traffic Fluctuation (ATF).

Other assumptions were as follows. Time synchronization was completed across the NW. The capacity of each WDM-channel was 10 Gbps. Full wavelength-conversion function was equipped at each node, so all wavelengths on all ingress fibers can be converted to any wavelength on any egress fiber. The TSA computation was programmed in C language and was executed on a commercial PC with a Core2 Duo E8400 3-GHz CPU. Initial allocation at τ_0 was derived using a conventional TSA method[9] that can compute near-optimal allocation.

3.1 Performance comparisons of algorithm combinations

We investigated the effect of each algorithm. The proposed method, R&R, deviates from the optimal allocation over time because the previous allocation on the TS schedule is taken over. Thus, we evaluated allocation efficiency variation in terms of required NW resources over time, as shown in Fig. 4 and Fig. 5, when N was 1000 and ATF was set to 0.5 TS. We define the required wavelengths as $W_{\min}$. This means the required minimum number of wavelengths for accommodating the traffic without considering protection nor BW for the control-plane. If allocation-efficiency degradation occurs due to time-slot continuity constraint[11], $W_{\min}$ increases, so the effect of reduction in NW resources is lowered. Fig. 4 plots the $W_{\min}$ at each τ_k during 200 T when CCF Rip-up & FFT Re-allocate were applied. The three kinds of operation sequencing algorithms are compared in Fig. 4. Please note that the $W_{\min}$ of the conventional approach, i. e., static-BW allocation to fit the maximum amount of traffic, is 4000 (not explicitly shown in Fig. 4 and Fig. 5). Also, please note that the ideal lower bound of $W_{\min}$ is 400. The results reveal that degradations of allocation converge regardless of the applied operation sequencing algorithm. They also reveal that the $W_{\min}$ of R&R is much less than that of the conventional approach; therefore, our OL2SW-NW, which uses R&R, can be created with much fewer resources.

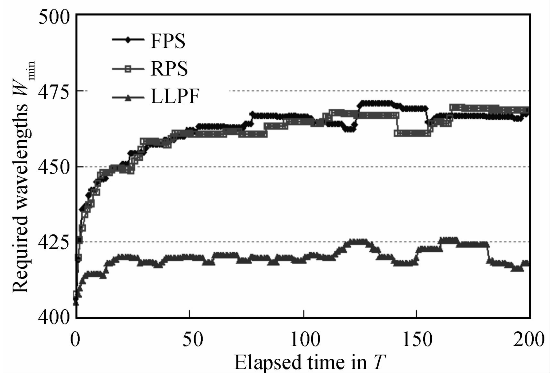


Fig. 4 Comparison of operation sequencing algorithms

The required wavelengths when applying FPS or RPS increase from the ideal lower bound by around 15%; however, LLPF can suppress the deviation to around 5%. That is, the upper bound of increase in required wavelengths resulting from a different operation sequencing algorithm is 15%. Fig. 5 similarly plots $W_{\min}$ when LLPF was applied as the operation sequencing algorithm and time-slot selection algorithms were compared. The results show that applying either CCF Rip-up or CCF Re-allocate enables suppression of the required-resource increase from the ideal lower bound within 8%. The results also reveal the time-slot selection for rip-up is more important than that for re-allocate, FFT Rip-up & FFT Re-allocate tends to worsen because it is not an intelligent method, and the performance of CCF Rip-up & FFT Re-allocate falls between CCF Rip-up & CCF Re-allocate and FFT Rip-up & CCF Re-allocate. The lower bound of CCF Rip-up & FFT Re-allocate performance seems to be that same as that of FFT Rip-up & CCF Re-allocate and the upper bound seems to be that of CCF Rip-up & CCF Re-allocate.

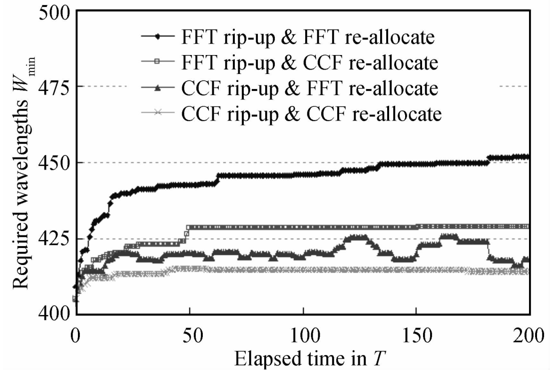


Fig. 5 Comparison of time-slot selection algorithms

Further comparison experiments were conducted to verify the effect of each algorithm. The obtained Average SVTS values after rip-up operation are shown in Fig. 6 when CCF Rip-up and FFT Rip-up were applied. Fig. 6 plots the Average SVTS normalized by that when N was set to 250 and FFT Rip-up was applied. This graph shows that CCF Rip-up effectively creates large successive vacant TSs on the TS schedule. Re-allocate operation uses this large vacant area; therefore, CCF Rip-up & FFT Re-allocate performed better, as shown in Fig. 5. In addition, the time required for R&R when N was set to 1 000 are shown in Fig. 7. This figure plots the calculation time normalized by that when ATF was 0.25 TS and FFT Re-allocate was applied (actual value is about 300 ms). This graph shows that CCF Re-allocate requires excessive computational time compared to FFT Re-allocate. This is because CCF Re-allocate must search many more allocatable TSs. The calculation time of CCF Re-allocate increases sharply with increase in ATF and/or NW size; therefore, CCF Re-allocate seems to be unsuitable for large-scale NWs. Therefore, CCF Rip-up & FFT Re-allocate can achieve better allocation to suppress the required NW resources with lower computational cost.

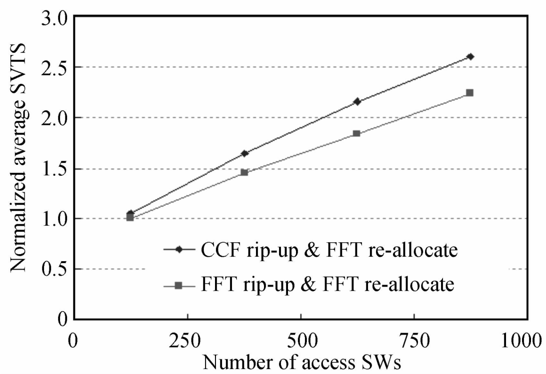


Fig. 6 Impact of time-slot selection algorithm on increase in SVTS size for rip-up

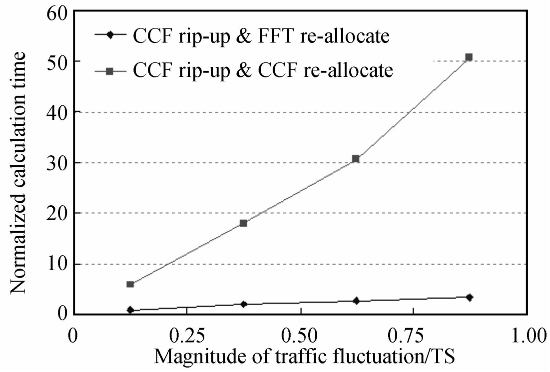


Fig. 7 Impact of time-slot selection algorithm on reduction of calculation time for re-allocate

3.2 Impact of Proposed Method on Reduction of Calculation Time

We then evaluated the relationship between the NW size and TSA calculation time of R&R to estimate the maximum feasible NW size in terms of the number of nodes. The calculation times required for deriving the allocation when applying LLPF and CCF Rip-up &

FFT Re-allocate is shown in Fig. 8. The results show that R&R can drastically reduce the calculation time compared with the conventional method[9]. In general, there is a trade-off between performance and computation time, so the conventional method attains near-optimal allocation at the cost of longer calculation time, as can be seen in Fig. 5 and Fig. 8. The conventional method can nearly achieve the lower bound for the required wavelengths; however, large computation time makes it impossible to set adequate T in large-scale NWs. Whereas, our algorithms can reduce computation time while suppressing performance degradation to be marginal in the assumed model. The proposed method enables us to set T as a short time period; hence, fine-granularity BW control on the same timescale as traffic fluctuation can be achieved. We clarified that R&R allowed the maximum NW size to be increased by four times or more when the admissible calculation time was 1 s in the assumed model. As a result, the 1000-node-scale OL2SW-NW can be centrally controlled at 1-s intervals with high allocation efficiency (suppressing the increase in required NW resources). The proposed method enables flexible path control and efficient BW sharing by many paths in the 1000-node-scale OL2SW-NW, which leads to cost-effective NWs.

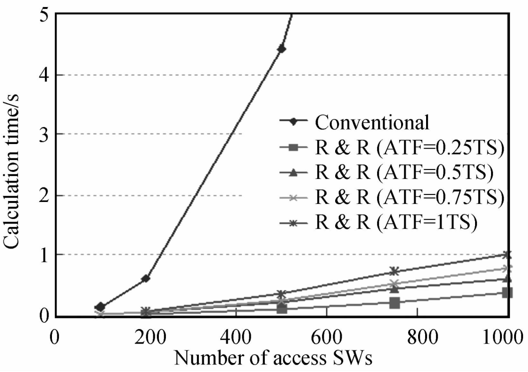


Fig. 8 Impact of proposed method on reduction of calculation time

4 Conclusion

We proposed a TSA method for an OL2SW-NW that has 1 000 nodes. This method uses periodic information of difference values of traffic fluctuation. By dynamically omitting paths whose volume of accommodating traffic changed less than the TS-unit BW during the control interval from TSA calculation, TSA-computation scale can be reduced. By applying a weighting function considering the difference value and path length, deviation from the optimal allocation can be suppressed. By clustering vacant TSs, flexible BW allocation, which enables efficient traffic aggregation, is possible. Thus, the proposed method can reduce calculation time to achieve high throughput in large-scale metro NWs, which leads to dynamic BW control on the same timescale as traffic fluctuation in the OL2SW-NW. Therefore, the OL2SW-NW that uses R&R makes significant reduction in required NW resources possible compared with conventional network systems. Our method will be cost-effective in creating future metro NWs.

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