IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received October 14, 2021, accepted November 7, 2021, date of publication November 10, 2021,
date of current version November 22, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3127317

Resource Allocation Scheme Based on Complete Planning Process for Immediate and Advance Reservation in SDM-EONs

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This work was supported in part by the National Natural Science Foundation of China under Grant 61905060, and in part by the Natural Science Foundation of Hebei Province under Grant F2019402240 and Grant F2018402198.

ABSTRACT Immediate reservation (IR) and advanced reservation (AR) become two common traffic models for future space division multiplexing-elastic optical networks (SDM-EONs). However, it is crucial to reduce conflicts between different types of requests and to accommodate more requests with limited resources. In this paper, we propose a resource allocation scheme based on complete planning process (RA-CPP) for IR and AR in SDM-EONs, including request provisioning, resource planning, passive adjustment, and active adjustment. In the request provisioning, the starting time of requests is considered and the earlier transmitted requests have higher resource selection priority. Next, the spectrum blocks with minimal resource spacing between adjacent requests (RS-AR) are planned for requests to maximize the free resources of the network in the resource planning. In addition, for the new request that would be blocked, passive adjustment begins. After planning reserved resources for the new request, conflicting AR requests are re-provisioned. Finally, the active adjustment re-optimizes the resources by increasing the tightness of spectrum resources. Simulation results show that the proposed RA-CPP scheme has greater advantages in blocking probability and spectrum utilization compared with the benchmark schemes.

INDEX TERMS Advanced reservation (AR), blocking probability, complete planning process, elastic optical networks (EONs), immediate reservation (IR), space division multiplexing (SDM).

I. INTRODUCTION

With the rapid development of 5G mobile communications, massive customized high-traffic services proliferate, resulting in the unprecedented growth of network traffic [1]. Traditional wavelength division multiplexing (WDM) networks use a fixed wavelength allocation method for services, which causes the waste of a large number of limited wavelengths [2]. In order to meet more service demands, elastic optical networks (EONs) with finer spectrum granularity and more flexible allocation are proposed [3]. However, the transmission capacity of single-core optical fibers in EONs is approaching its physical limit [4]. In this case, space division multiplexing (SDM) technology based on multi-core fiber has emerged. Then, SDM-EONs are considered as one of the effective ways to solve the problem of network transmission capacity [5].

In SDM-EONs, the routing and spectrum assignment (RSA) problem becomes the more complex routing, core, and spectrum assignment (RCSA) problem. Moreover, future networks need to service more and more different quality-of-service (QoS) requests [6]. Hence, two methods of resource reservation are proposed, namely immediate reservation (IR) and advance reservation (AR). IR services require real-time transmission, that is, resources must be allocated immediately as soon as they arrive at the network. On the contrary, the transmission of AR services has a certain time tolerance, that is, services will request transmission for a certain period of future time [7]. In this paper, AR services with specified starting time, duration, and flexible window (flexible STSD) are considered. For each flexible STSD AR service, it can be transmitted before the latest starting time

The associate editor coordinating the review of this manuscript and approving it for publication was Ehab Elsayed Elattar.

(the sum of the starting time and the flexible window), which improves the flexibility of the transmission [8].

In some researches, the RCSA schemes for IR/AR requests are divided into two phases [9], [10], i.e., request provisioning and resource allocation. First, resources are provisioned for requests when they arrive at the network, and then allocated at the starting time. In the request provisioning, some studies have used a delayed allocation approach [11]–[13] for AR requests, in which resources are not provisioned immediately as soon as the requests arrive, but before the starting time. This approach undoubtedly increases the flexibility of RCSA by exploiting the temporal nature of AR requests. However, these planned resources will be allocated directly, in which the purpose of reserving in advance may not be met. Based on this, this paper considers prioritizing the starting time of all arriving requests, then plans resources for them. By providing higher priorities to earlier transmissions, the resource conflicts between different types of services are avoided to some extent. In addition, due to the limited resources in the network, more efficient resource management is extremely important. In this paper, resource spacing between adjacent requests (RS-AR) is proposed. The smaller the spacing between the requested time slots (TSs) and frequency slots (FSs) and their adjacent occupied resources, the higher the time-domain similarity and frequency-domain tightness of the new and adjacent services, and the higher the resource utilization. Therefore, the spectrum block (SB) with the minimum resource spacing is selected for the service in this paper.

If the available resources cannot be found, AR re-provisioning [9], [14] is adopted to improve the success rate of services. Among them, effective methods are to re-provision AR services with the same link or running time as the new service. In fact, these methods affect a large number of existing AR services in the network, making it difficult to find available resources for these services. Meanwhile, after these services are re-provisioned, the new service may still not be met. Therefore, we first search available resources in the reserved resources for the new service. Then, AR services that occupy these resources as conflicting services are re-provisioned. This re-provisioning is more targeted and more likely to succeed.

In the resource allocation, the provisioned resources are directly allocated to services at starting time. However, these spectrum blocks (SBs) planned in advance may fail to achieve resource optimization due to continuous AR re-provisioning. This paper considers an active adjustment approach to re-optimize the resources by increasing the tightness of spectrum resources. Next, the adjusted resources are allocated to achieve the initial purpose of maximizing free resources.

As mentioned above, to improve the success rate of IR and AR requests, this paper proposes a resource allocation scheme based on complete planning process (RA-CPP) in SDM-EONs. The scheme optimizes resources through the request provisioning, resource planning, request re-provisioning (passive adjustment), and active adjustment. First, the proposed RA-CPP scheme sorts the services that arrive on the network at the same time by the starting time. Then, the available resources with minimal resource spacing are planned. When no resources are found, AR re-provisioning for services conflicted with the new service starts. Next, resources are actively adjusted to ensure maximum free resources and allocated to services. Simulation results show that the proposed RA-CPP scheme can greatly reduce blocking probability and improve spectrum utilization.

This paper is organized as follows. The related works are discussed in Section II. Section III introduces the system model and notations, while Section IV describes the proposed RA-CPP scheme. Section V evaluates and analyses its performance by simulations. Finally, Section VI summarizes the paper.

II. RELATED WORKS

A. IR/AR

For IR, Zhao *et al.* proposed a mixed super-channel (Sp-Ch) oriented RCSA algorithm [15]. And the spectrum allocation issue was solved in dynamic scenario with holding time awareness based on a novel fragmentation metric in [16]. However, to improve QoS, AR requests were concerned. They were proposed in WDM networks [17] and investigated in EONs for the first time in [18]. Next, a farsighted spectrum resource allocation algorithm was proposed to reduce AR blocking in EONs [19]. Chen *et al.* introduced the available time-spectrum consecutiveness and then three effective time-aware RSA algorithms were proposed for AR [20]. In addition, in [21], the proposed RSA algorithms relieved IR/AR conflicts in a two-dimensional time/frequency domain. However, there were few studies on hybrid IR/AR requests [22].

B. RESOURCE ALLOCATION SCHEMES IN DIFFERENT NETWORKS

The resource allocation of IR/AR requests in both WDM networks and EONs has been studied [2]. In WDM networks, References [23] and [24] solved static routing and wavelength assignment (RWA) for multicast advance reservation by integer linear programming, and then the dynamic RWA was solved in [25] and [26]. In EONs, Lu *et al.* proposed revenue-driven AR provisioning and resource allocation schemes for deadline-driven AR [27]. In addition, to reduce spectrum fragmentation, Zhu *et al.* defined a new spectrum-time-cut metric and proposed several fragmentation-aware RSA algorithms, in which resources with the minimum spectrum-time cut were assigned to requests [28], [29].

In SDM-EONs, Sugihara *et al.* proposed a spectrum partitioning method that divided the spectrum resources into prioritized zones, and each was used to accommodate the requests that required the same FSs [31]. To further reduce blocking probability, an RCSA algorithm for dynamic IR/AR with holding time was proposed [30]. And the time-spectrum partition was divided into AR-prior and IR-prior zones to address the fairness resource assignment of hybrid AR and IR scenarios. Still, few works on resource allocation schemes for hybrid IR/AR requests in SDM-EONs were found.

C. OPTIMIZED RESOURCE ALLOCATION SCHEMES FOR AR

In recent years, optimized resource allocation schemes for AR have emerged. Firstly, the resource allocation based on delayed spectrum allocation (DSA) effectively improves the flexibility of transmission. The concept of delayed allocation for WDM-enabled networks was proposed in [10]. Afsharlar *et al.* studied some DSA algorithms in EONs [9], [11], [12]. These algorithms were also divided into two phases, namely request provisioning and resource allocation. The spectrum resources were pre-planned according to certain criteria before the starting time and then allocated to requests. Based on it, a novel DSA (N-DSA) algorithm was investigated [13], in which the resource allocation of AR requests was delayed until just before transmission. In this way, spectrum resources were planned better. However, the purpose of resource reservation might not be achieved, and the conflicts of the requested resources at the same time would increase. Therefore, the starting time of requests is considered in this paper. Earlier transmitted requests have higher resource selection priority.

Secondly, AR re-provisioning is also an important method to further reduce blocking probability. In [14], Wang *et al.* defined a metric called frequency-slot consumption ratio (FCR) and designed a re-provisioning optimization algorithm based on FCR to accommodate more requests. In addition, Afsharlar *et al.* not only proposed DSA but also large-window (LW), small-window (SW), and limited-link (LL) re-provisioning methods when no available resources were found for the new request [9]. The LW method re-provisioned AR services between the arrival time and end time of the new service, while between the starting time and end time in the SW method. And LL method re-provisioned AR services requesting the same link as the new service. These methods reduced the service congestion to a certain extent. However, lots of services were re-provisioned, which made it difficult to find available resources for them. And after AR re-provisioning, the resources might still not accommodate the new service. Based on it, the available resources in the reserved resources are first searched for the new service. AR services that occupy these resources will be re-provisioned.

Therefore, in this paper, we focus on the problem of resource allocation for IR and AR in SDM-EONs. Through resource optimization in the request provisioning, resource planning, passive adjustment, and active adjustment, the RA-CPP scheme is proposed. In the request provisioning, arriving requests are sorted according to the starting time. Then, the spectrum block with minimal resource spacing is selected for them in turn. Next, for the new service that would be blocked, the available resources in the reserved resources are searched, and AR services occupying these resources are re-provisioned. Finally, the resource allocation with active adjustment is adopted to ensure the optimization of the planned resources.

III. SYSTEM MODEL AND NOTATIONS

In this section, the network model and related notations are first given. Then, the resource model is established in SDM-EONs. Finally, we propose the resource spacing between adjacent requests to describe the resources occupation better. They lay a foundation for the proposed RA-CPP scheme.

A. NETWORK MODEL

We model the SDM-EONs as a graph $G(V, E, C)$, where V is the set of nodes, E represents the set of bi-direction links between nodes, and C is the set of cores on each fiber link. The spectrum on each core of the link is divided into many FSs and frequency granularity is denoted as BC. In the resource allocation, the constraints of spectrum continuity, contiguity, and non-conflicts need to be satisfied. Moreover, we assume the lightpaths have assigned cores that do not change in their routing paths, i.e., the spatial continuity constraint is also imposed. As discussed in [32], these assumptions are often adopted.

TABLE 1. Request parameters and assumptions.

Parameters	Values
BC, Bandwidth of each frequency slot	12.5 Gbps
b, Range of bandwidth requirement	12.5–200 Gbps
N, Number of slots for guard bands per request	2
Maximum transmission distance of BPSK (M=1)	4000
Maximum transmission distance of QPSK (M=2)	2000
Maximum transmission distance of 8-QAM (M=3)	1000
Maximum transmission distance of 16-QAM (M=4)	500
Average request duration slots [9]	20
Book-ahead time slots [33]	Uniform (1,100)
Time slots of flexible windows [21]	Uniform (1,9)

In the model, we consider two types of requests: IR and AR. The connection request with arriving time t_a, starting time t_s, holding time t_h, bandwidth requirement b Gigabit per second, and flexible window l from source node s to destination node d is denoted as $R(s, d, b, t_a, t_s, t_h, l)$. For IR requests, the arrival time is the same as the starting time, and the flexible window size is zero. When a request R arrives at the network, a lightpath P from node s to d is planned, and the available SB is searched. The size of the SB is calculated by:

$$f = \lceil b/(BC \cdot M) \rceil + N \tag{1}$$

where b is bandwidth requirement, M is modulation level, and N is guard bands among requests. Four modulation formats are considered in this paper. The assumed values for the requests are listed in Table 1.

In addition, the inter-core crosstalk is considered and calculated by (2) [34], where h is the mean increase in crosstalk per unit length, n is the number of the adjacent cores, and L [km] is the length of the fiber. In (3), k, r, β, and Λ are the coupling coefficient, bend radius, propagation constant, and core pitch, respectively. Their values are set as 1.27×10^5, 50 [mm], 4×10^6, and 40 [μm] [35]. The crosstalk thresholds of BPSK, QPSK, 8-QAM, and 16-QAM are -14, -18.5, -21, and -25 [dB] [36]. In this paper, resources that meet the crosstalk thresholds are allocated. If no resources are found, the request will be blocked.

$$XT = \frac{n - ne^{-(n+1)2.h.L}}{1 + ne^{-(n+1)2.h.L}} \tag{2}$$

$$h(k, \Lambda) = \frac{2k^2 r}{\beta \Lambda} \tag{3}$$

B. RESOURCE MODEL

A large number of services enter the network, requesting transmission between certain nodes for a period of time. Then, we allocate free resources to the requests for the time. After the transmission is complete, these resources are released and returned to the free state.

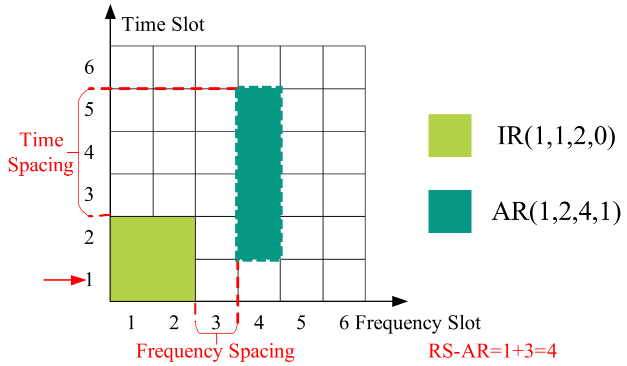

FIGURE 1. Resource model and resource usage on a link.

In hybrid IR/AR, the requests are more time-sensitive. AR demand arrives in advance and requests resource reservation for the following period. In addition, AR demand has a flexible transmission time, that is, it can be transmitted before the latest starting time. Therefore, in order to allocate resources within the appropriate time better for demands, this paper establishes the resource model. In the model, spectrum and time are abstracted into finer granularity frequency slot (FS) and time slot (TS) respectively, which makes that limited resources are planned for requests in a finer way. As shown in Fig.1, the resource model on a link is established, where the horizontal axis is FS and the vertical axis is TS. Services requesting the link occupy continuous FSs and TSs, that is, a rectangular resource block. It can be seen that at TS 1, two requests arrive at the network. IR service starts to be transmitted after allocating resources, while AR service planned resources is not transmitted until the starting time TS 2.

C. RESOURCE SPACING BETWEEN ADJACENT REQUESTS

In this subsection, to maximize resource utilization, we propose resource spacing between adjacent requests (RS-AR). In the established resource model, the request occupancy is visually represented. As it can be seen from Fig.1, different resource blocks composed of continuous TSs and FSs meet corresponding requests. The larger the contiguous free resource block, the more requests it can satisfy. Therefore, it is extremely necessary to maximize free resource blocks.

First, as the spectrum resources are limited in the network, the smaller the gap between the resources occupied by adjacent requests, the higher the frequency-domain tightness. Thus, the continuity of remaining free spectrum resources is higher. These continuous resources will have a greater chance to accommodate subsequent requests. Second, the resources requested by lightpaths are released after the transmission ends. The smaller the end time interval between them and their neighbors, the higher the time-domain similarity. Thus, they can make more room for larger requests at the same time in the future.

Based on this, the RS-AR is proposed to find the resource with the smallest spacing maximizing the free resources in the network. It consists of two parts, frequency spacing and time spacing, which are calculated, as follows:

$$RS - AR = (f_{rs} - f_{as}) + |t_{ae} - t_{re}| \tag{4}$$

where f_{ae}, t_{ae}, f_{rs}, and t_{re} indicates the end FS, end TS of adjacent request, starting FS, and end TS of new requests respectively. Taking Fig. 1 as an example, we mark the resource spacing between two requests. The smaller the value is, the larger the resource utilization is in the network.

IV. RESOURCE ALLOCATION SCHEME BASED ON COMPLETE PLANNING PROCESS

For IR and AR requests, a resource allocation scheme based on complete planning process is given and implemented by three algorithms in this section. Among them, the complete planning process includes four optimization phases: request provisioning, resource planning, passive adjustment, and active adjustment, which really maximizes the resource utilization in SDM-EONs.

A. REQUEST PROVISIONING ALGORITHM

The request provisioning for IR and AR works as Algorithm 1, including the resource planning and passive adjustment. The input of the algorithm is the arriving connection requests $R\,(s,\ d, b, t_a,\ t_s, t_h, l)$, and the outputs are the provisioned requests $R_{\text{provision}}$, present time t, and planned SBs PSB. In the request provisioning, we use the starting time-first approach for connection requests. The earlier the requests' starting time, the higher the priority for resource planning. Then, resources are planned based on RS-AR for them in Algorithm 2. Next, if the available resources have not yet been found at the final starting time, the passive adjustment is performed for AR requests conflicted with the new request, which is also called AR re-provisioning.

When new connection requests (R) arrive, we first store them in the unplanned requests ($R_{\text{unplanned}}$) and record the present time t (step 1). The requests in $R_{\text{unplanned}}$ are sorted by the starting time (step 2). Then, for each connection request (R^i), the flag for successful provisioning is set to 0 and resources are planned based on Algorithm 2 (steps 3-5).

When the SB is found, it is stored in *PSB* and the flag is 1 (steps 6-8). R^i is removed from $R_{\text{unplanned}}$ to $R_{\text{provision}}$ (step 9). If the resources are not planned at the latest starting time, AR re-provisioning begins (steps 10-11). The available SBs (*SB*) that meet the crosstalk thresholds are searched in the reserved resources (*RR*) and requests transmitted on left FS are recorded (step 12). If *SB* are found, their RS-AR are calculated using (4) (steps 13-14). Next, we sort *SB* according toRS-AR in ascending order (step 15). AR requests occupying each SB^i are re-provisioned as conflicting requests (R_{conflict}) (steps 16-17). The resources are planned for each conflicting AR request (R^j) based on Algorithm 2 (steps 18-19). Once there are no available resources for R^j, the next SB^i is selected (steps 20-22). The *PSB*, $R_{\text{unprovision}}$, $R_{\text{provision}}$, and flag are updated when all AR requests find available resources (steps 23-32). Finally, if the flag is 0, R^i is blocked (steps 33-36).

The resource planning based on RS-AR for IR and AR requests works as Algorithm 2. For each connection request (R^i), we plan the shortest paths (P^i) based on Dijkstra algorithm (step 1). Then, we search the first available SBs (*B*) that meet the crosstalk thresholds on each core (*c*) and record request that reserve or transmit on left FS (steps 2-4). Then, the RS-AR (RS^i) of *B* are calculated using (4) (step 5). The SB (PSB^i) with the minimum of RS^i for R^i is selected and returned (step 6).

B. RESOURCE ALLOCATION ALGORITHM WITH ACTIVE ADJUSTMENT

The resource allocation with active adjustment is proposed in this paper. In hybrid IR/AR, we first use some optimization methods to reserve resources for requests arriving at the network. However, these resources planned in advance may lose the advantage of optimization due to the occupancy and release of adjacent resources before the requests' starting time. Specifically, we adopt resource planning based on RS-AR. By comparing with the TSs and FSs occupied by left request, we select the SB with the smallest resource spacing for the request, maximizing the free resources for more future requests. Due to AR re-provisioning, the surrounding lightpaths leave, and the SB to be allocated may not satisfy the minimization of resource spacing, but also crack the continuity of free resources. Therefore, we use the active adjustment to re-optimize the resources by increasing the tightness of spectrum resources in the frequency domain.

The resource allocation procedure in our proposed scheme is given in Algorithm 3. When the present time (t) is between the starting time and the latest starting time, it is time for resources to be allocated to provisioned request (R^i). For each R^i, the selected SB (B^i) is found (steps 1-3). Then, we search the first left occupied FS of B^i and record its number (f_L^i) on each link (L^i) in the path (P^i) of R^i (steps 4-6). Next, the minimum value (f^i) of f_L^i is decided (step 7). Finally, to minimize frequency spacing, the SB of beginning FS (f^i+1) is allocated to R^i (steps 8-10).

Algorithm 1 Request Provisioning

Input: $R(s, d, b, t_a, t_s, t_h, l)$.
Output: $R_{\text{provision}}$, t, and *PSB*.
1 Store R in $R_{\text{unprovision}}$ and record the present time t.
2 Sort $R_{\text{unprovision}}$ according to the starting time.
3 **for** each R^i of $R_{\text{unprovision}}$ **do**
4 success = 0.
5 Plan resource for R^i as PSB^i based on **Algorithm 2**.
6 **if** $PSB^i \neq None$ **then**
7 Store PSB^i in *PSB*.
8 success = 1.
9 Remove R^i from $R_{\text{unprovision}}$ and add it to $R_{\text{provision}}$.
10 **else**
11 **if** $t == ti\ a + l^i$ **then// AR re-provisioning (Passive adjustment)**.
12 Search the available SBs that meet the crosstalk thresholds as *SB* in the reserved resources *RR*(*e, c, f*) and record the requests that transmit on left FS.
13 **if** $SB \neq None$ **then**
14 Compute their RS-AR using (4).
15 Sort *SB* according to the RS-AR.
16 **for** each SB^i of *SB* **do**
17 Find the conflicting AR requests occupying SB^i as R_{conflict}.
18 **for** each R^j of R_{conflict} **do**
19 Plan resources for R^j as PSB^j based on **Algorithm 2**.
20 **if** $PSB^j == None$ **then**
21 Break.//Select the next SB^i.
22 **end if**
23 **end for**
24 **if** $PSB^j \neq None$ **then**
25 success = 1.
26 Update the *PSB* for R_{conflict}.
27 Remove R^i from $R_{\text{unprovision}}$ and add it to $R_{\text{provision}}$.
28 **end if**
29 **end for**
30 **end if**
31 **end if**
32 **end if**
33 **if** success == 0 **then**
34 Block the request R^i.
35 **end if**
36 **end for**

To sum up, the RA-CPP scheme is proposed in this paper to maximize resource utilization. Firstly, in the request provisioning, the requests with earlier starting time have higher priority for resource allocation. Then, resource planning based on RS-AR maximizes the free resources in the network by narrowing the spacing of the spectrum occupied by requests and their departure time. When no available resources are found at the latest starting time, the passive adjustment is adopted. The available block is searched in the reservation resources occupied by AR requests that have not been transmitted. Next, conflicting requests on the SB are re-provisioned to improve the success rate of requests. However, due to the establishment and removal of lightpaths in the network, the planned resources in advance may not achieve resource optimization. We propose the active

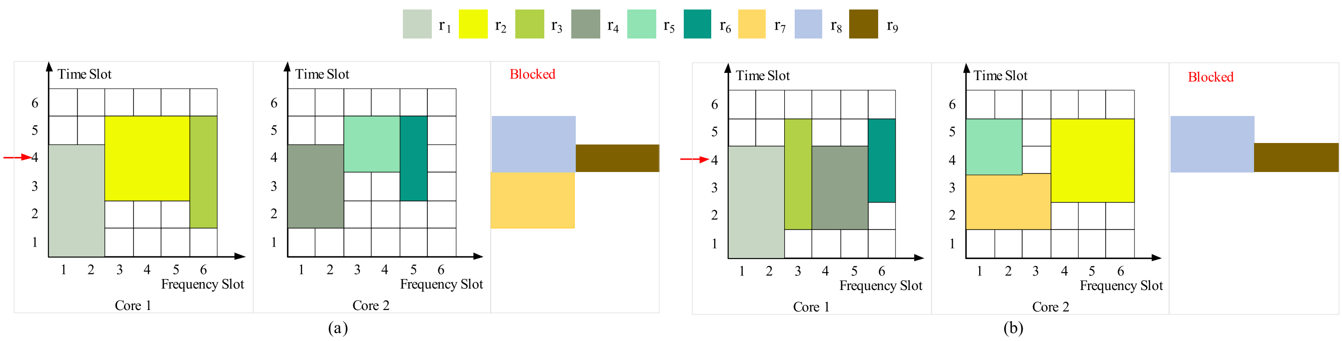

FIGURE 2. Comparison of resource allocation using (a) FF and (b) N-DSA schemes when the current system time slot is 4.

Algorithm 2 Resource Planning Based on RS-AR

Input: $R^i(s, d, b, t_a, t_s, t_h, l)$.
Output: Planned SBs PSB^i.

Plan the shortest path as P^i based on Dijkstra algorithm.
for each core c of P^i **do**
  Search the first available SBs that meet the crosstalk thresholds as B and record request that reserve or transmit on left FS.
end for
Compute the RS-AR of B as RS^i using (4).
Select the SB with the minimum of RS^i as PSB^i for R^i.

Algorithm 3 Resource Allocation With Active Adjustment

Input: $R_{\text{provision}}$, t, and PSB.
Output: Spectrum allocation.

for each R^i of $R_{\text{provision}}$ **do**
  if $t == tis$ or ($t > tis$ and $t <= tis + l^i$) **then**
    Find the selected SB B^i from PSB.
    for each link L^i in P^i of R^i **do**
      Search the first left occupied FS of B^i and record its number as fiL.
    end for
    Decide the minimum value f^i of fiL.
    Allocate the SB of beginning FS f^i+1 for R^i.
  end if
end for

adjustment method, that is, the planned resources are adjusted to increase the tightness of spectrum resources. Through resource optimization of the four phases, more requests are satisfied.

The proposed RA-CPP scheme is compared with three benchmark schemes:

Immediate spectrum allocation scheme (i.e., First-Fit, FF): each request is planned resources as soon as it arrives at the network, and these resources are allocated when the transmission begins.

Novel delayed spectrum allocation scheme (N-DSA) [13]: it delays the selection and allocation of spectrum resources for the arriving requests until the transmission begins.

Delayed spectrum allocation with limited link scheme (DSA-LL) [9]: the spectrum allocation is similar to FF. The difference is that when a new request cannot find the available resources at the latest starting time, the re-provisioning of AR requests that traverse the same links as it is triggered. These requests are sorted according to their starting time, and the spectrum resources are re-selected for them in turn. If the available resources can be planned for all requests, the re-provisioning is successful. Otherwise, the request is blocked.

Here's a simple example to show the results of several spectrum allocation schemes. For the sake of expression, nine lightpaths requesting a link are assumed, and their demands are summarized in Table 2. The two types of bandwidth requests (IR/AR) are considered, and the flexible window size for each AR is set to 1. It is assumed that there are two cores on the link, each with six FSs. Therefore, resource allocations using FF and N-DSA schemes on the link are shown in Fig. 2; horizontal and vertical directions present the frequency slot and time slot, respectively. Meanwhile, the procedures and results of resource allocations in the DSA-LL and proposed RA-CPP are shown in Fig. 3 and Fig. 4. Resource blocks in different colors represent that they are occupied by different requests. Dashed line blocks indicate that the service has been provisioned but not yet transmitted. The red arrow represents the present time slot.

TABLE 2. Summary of request demands.

Request	r_1	r_2	r_3	r_4	r_5	r_6	r_7	r_8	r_9
IR/AR	IR	AR	IR	IR	AR	AR	IR	AR	AR
Arriving TSs	1	1	2	2	2	2	2	3	3
Starting TSs	1	3	2	2	4	3	2	4	4
Holding TSs	4	3	4	3	2	3	2	2	1
Number of required FSs	2	3	1	2	2	1	3	3	3

In the FF scheme, resources are allocated to requests based on their arrival order, as shown in Fig. 2(a). However, when requests r_7, r_8, and r_9 arrive, they will be blocked due to the shortage of free resources. The N-DSA scheme plans and allocates resources to requests at their starting time. As can be seen from Fig. 2(b), request r_7 is assigned at FSs 1, 2, and 3 of core 2. Requests r_8 and r_9 will be still blocked. Furthermore, the resource assignment of the DSA-LL scheme when the time slot is 2 and 3 is presented in Fig. 3. At TS 2, since no available resources for request r_7, all planned lightpaths between the starting time and the end time of request r_7 will be handled. Here, FSs 3, 4, and 5 of core 1

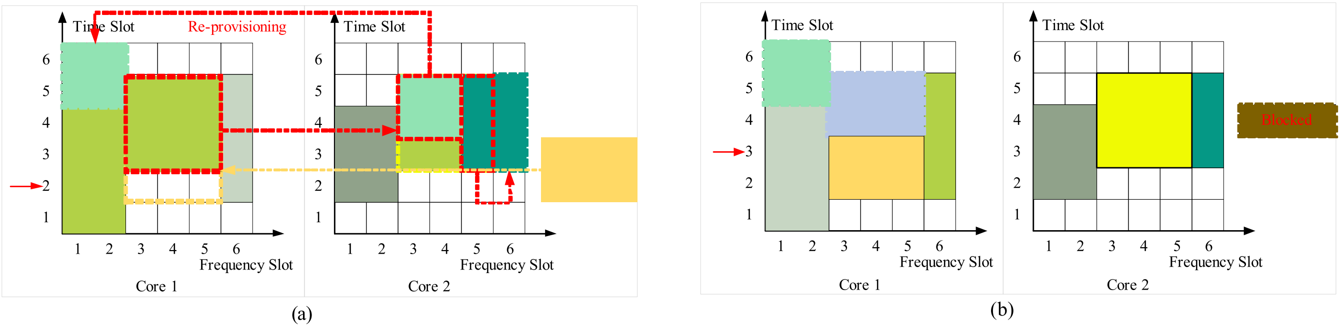

FIGURE 3. Resource allocation using DSA-LL scheme when the current system time slot is (a) 2 and (b) 3.

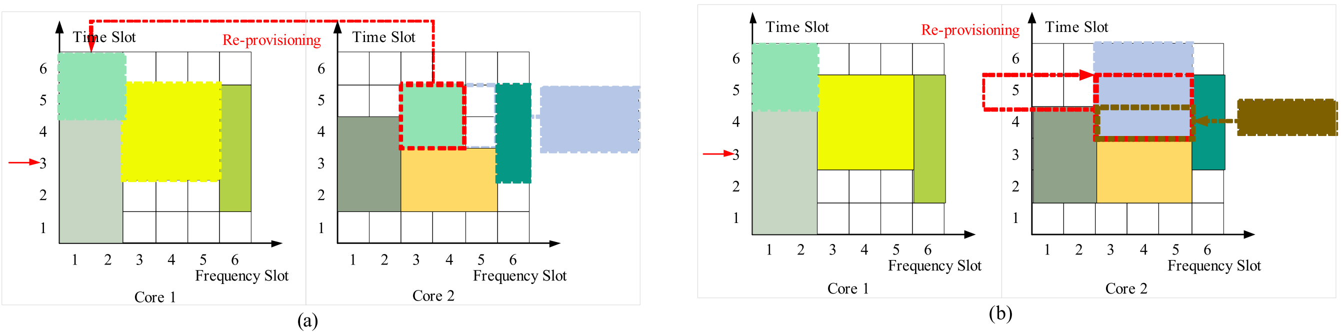

FIGURE 4. Resource allocation using proposed RA-CPP scheme when (a) request r_8 and (b) request r_9 arrive at the network.

at TSs 2 and 5 are provisioned for request r_7. The requests r_2, r_5, and r_6 that have not been transmitted are re-provisioned according to their starting time. Thus, request r_2 occupies FSs 3, 4, and 5, request r_6 occupies FS 6 on core 2, and request r_5 occupies FSs 1 and 2 of core 1. At TS 3, FSs 3, 4, and 5 of core 1 at TSs 4 and 5 are provisioned for request r_8, as shown in Fig. 3(b). However, when request r_9 arrives, the re-provisioning of overlapping AR lightpaths cannot still meet the requirements of available resources, so request r_9 is blocked.

In the proposed RA-CPP scheme, the starting time of requests is considered. If the service that would be blocked can be planned in the reserved resources, conflicting AR services are re-provisioned. When request r_8 arrives at the network, FSs 3, 4, and 5 of core 2 are planned, and request r_5 is re-provisioned in Fig. 4(a). Then, request r_8 is re-provisioned to free up FSs 3, 4, and 5 of core 2 at TS 4 for request r_9. Through two re-provisioning procedures, all requests are transmitted. As shown in Fig. 4(b), the resources are successfully allocated for nine lightpath requests, which is significantly better than other schemes.

V. SIMULATION ANALYSIS

In this section, we evaluate and compare the performance of FF, N-DSA, DSA-LL, and proposed RA-CPP schemes through using the 11-node, 26-link COST239 network [19], [37], and the 14-node, 21-link NSFNET network [38], [39], as shown in Fig. 5.

We assume that there are seven cores in each link [40]. Both IR requests and AR requests are generated in the same proportion, and their information is shown in Table 1. The lightpath

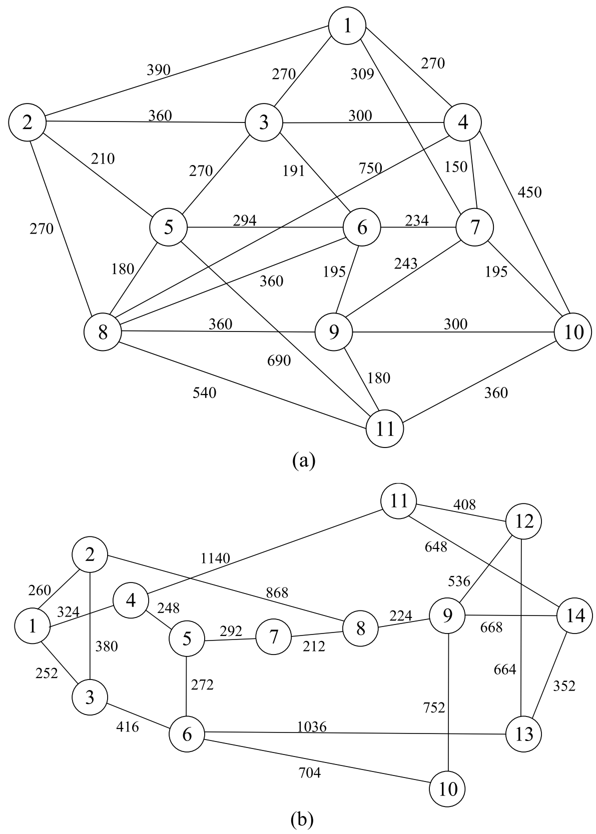

FIGURE 5. The networks of (a) 11-node, 26-link COST239, and (b) 14-node, 21-link NSFNET.

requests are randomly generated between the node pairs of each test network in the simulation. The arrival of lightpaths follows Poisson distribution and holding time follows

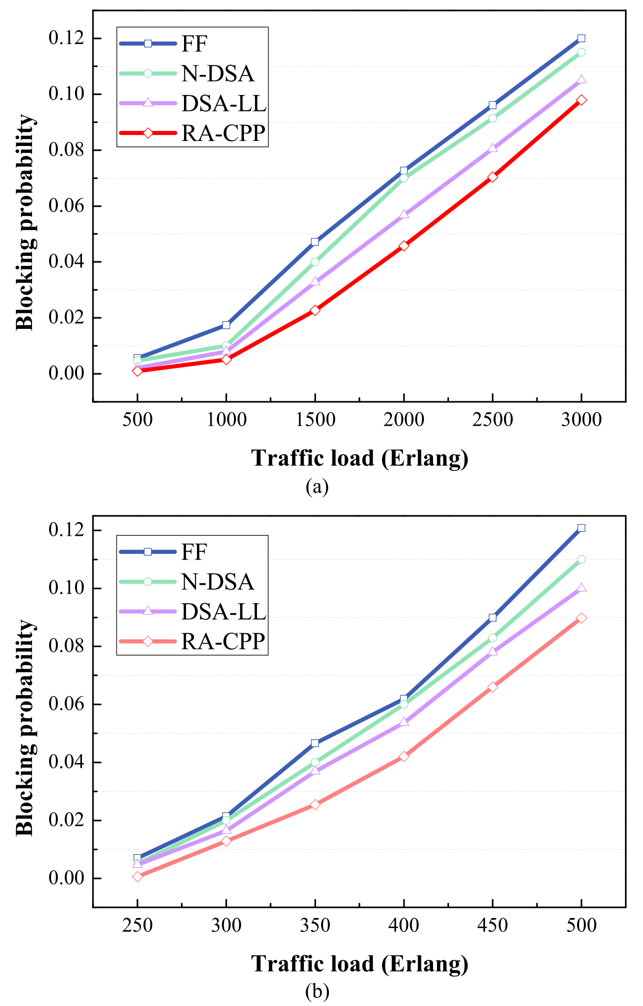

FIGURE 6. Blocking probability performance comparison on the four schemes evaluated in (a) COST239 and (b) NSFNET networks.

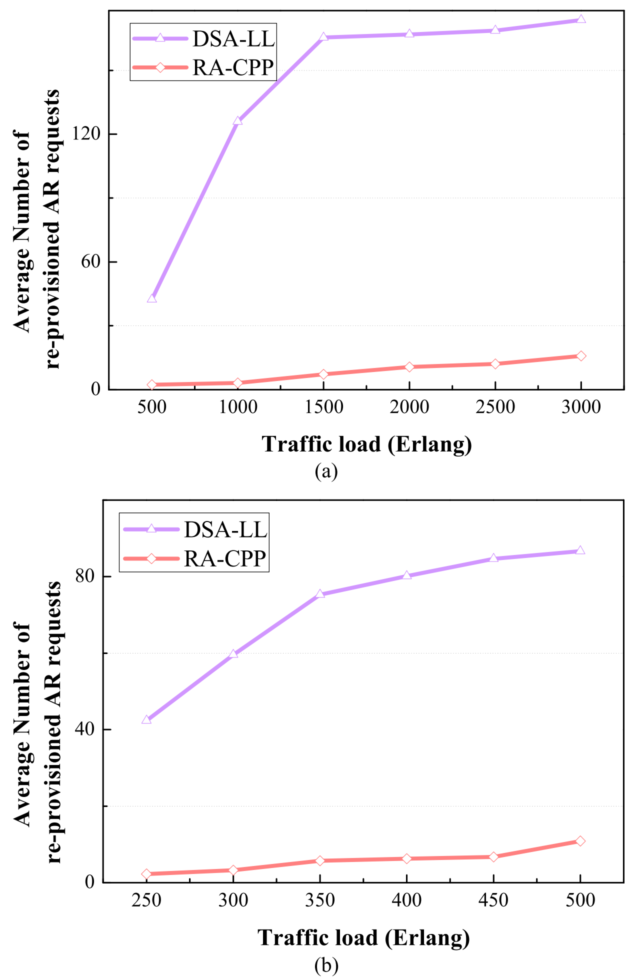

FIGURE 7. Average number of re-provisioned AR request comparison on the four schemes evaluated in (a) COST239 and (b) NSFNET networks.

negative exponential distribution. Each point in the following diagrams is simulated 10 times for 100,000 requested lightpaths. The evaluation results are presented with 95% confidence intervals.

A. BLOCKING PROBABILITY AND AVERAGE NUMBER OF RE-PROVISIONED AR REQUESTS

The blocking probability of the proposed RA-CPP scheme is first compared with the other benchmark schemes. Fig. 6 describes the results of blocking probability obtained by applying these schemes for different networks. It can be seen that the blocking probability is the lowest in the proposed RA-CPP scheme and DSA-LL, N-DSA, and FF schemes in decreasing order. Meanwhile, the RA-CPP scheme increases the acceptable loads by about 35%, 26%, and 14% compared with FF, N-DSA, and DSA-LL schemes when the blocking probability is 5% in COST239 network.

The FF scheme serves as an immediate allocation scheme, reserving resources for services once they arrive at the network. These resources will not be changed and used by other services until the transmission ends. It ignores the consideration of service starting time, which may result in the blocking of IR services due to numerous available resources being reserved in advance. Based on it, the N-DSA scheme delays the selection and allocation of resources to the start of service transmission. This scheme alleviates the blocking of IR services to a certain extent. However, it also degrades the temporal flexibility of resources requested by AR services, resulting in more blocking. Therefore, in the request provisioning of RA-CPP, the arriving requests are sorted by the starting time. Services that are transmitted earlier have a higher priority for resource selection, ensuring their successful transmissions. For other services, they have more time and chance to find available resources. The proposed RA-CPP scheme also alleviates the conflict of resources requested by services at the same time and reduces blocking probability.

On the other hand, if available resources cannot be found, the DSA-LL scheme re-provisions AR services on the same link requested by the new service and sorts them by starting time. In Fig. 7, the average number of re-provisioned AR requests is displayed in two networks. It is observed that a large number of AR services are re-provisioned in the DSA-LL scheme. For these services, the available resources are hard to be found, which reduces the advantages of the DSA-LL scheme. Compared with the DSA-LL scheme,

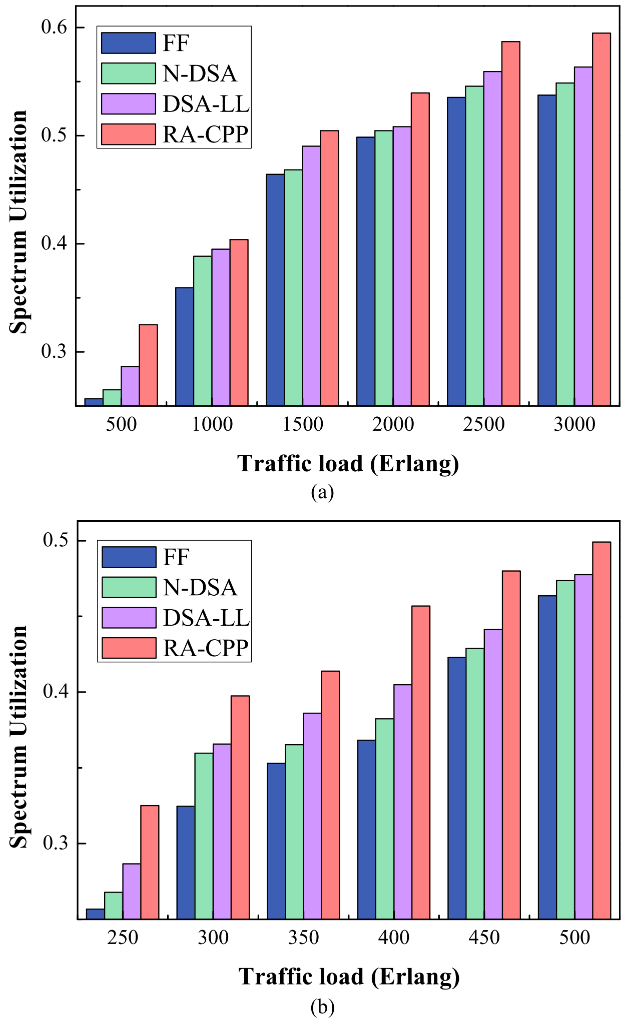

FIGURE 8. Spectrum utilization comparison on the four schemes evaluated in (a) COST239 and (b) NSFNET networks.

our re-provisioning is more targeted and fewer requests are re-provisioned. Specifically, we first search the available resources in the reserved resources for the new service. Then, conflicting requests occupying the resources are re-provisioned, which improving the success rate of requests.

In addition, we choose SBs with minimal resource spacing for requests in resource planning and use the active adjustment before resource allocation, freeing up more resources from the limited resources for subsequent requests. Therefore, the proposed scheme can accommodate more requests through the complete planning process and effectively reduce blocking probability.

B. SPECTRUM UTILIZATION AND FRAGMENTATION RATIO

Figs. 8(a) and 8(b) compare the spectrum utilization using four schemes in COST239 and NSFNET networks, respectively. It is observed that the proposed scheme provides the highest spectrum utilization in two networks. This is because the spectrum resources with minimal resource spacing are selected for sorted services. By optimizing the sequence and location of reserved resources, the free resources in the network are maximized. Moreover, resource allocation with active adjustment once again ensures the efficient use of limited resources.

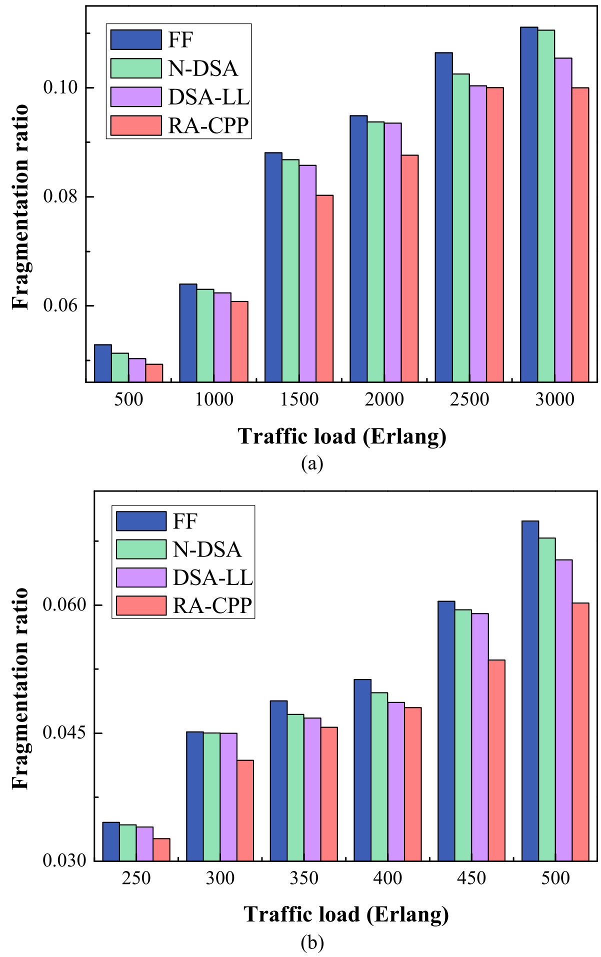

FIGURE 9. Fragmentation ratio comparison on the four schemes evaluated in (a) COST239 and (b) NSFNET networks.

There is the lowest spectrum utilization for the FF scheme. This is because as long as the service arrives at the network, the spectrum resources with the lowest frequency slot index are planned for it. For AR services, the time and flexibility of transmission are ignored, making the planned resources unable to accommodate the requests that need to be transmitted earlier. The spectrum utilization is reduced. In the N-DSA scheme, the transmission time is taken into account, and resources are planned before transmission. It avoids resource provisioning in advance and improves spectrum utilization to a certain extent. However, the volume of services requesting free resources at the same time increases, putting pressure on the limited resources. In the DSA-LL scheme with AR re-provisioning, the spectrum utilization is improved. In fact, the transmission time is taken into account only in the re-provisioning. In order to make full use of the service nature and further improve the resource utilization, the earlier the service is transmitted, the higher the priority will be in our scheme. For each sorted service request, the available resources are planned before the latest starting time.

Moreover, we also present the fragmentation ratio in two networks as shown in Fig. 9. The fragmentation ratio is the ratio of the number of unoccupied SBs to FSs. In the resource allocation of benchmark schemes, the service duration is not considered. With the continuous setup and release of lightpath, lots of small free spectrum blocks appear in the network, and the fragmentation ratio increases. It is seen that the proposed RA-CPP scheme shows the lowest fragmentation ratio for each network. This is because we realize the maximization of continuous free spectrum resources. Specifically, in the frequency domain, the continuity of the free spectrum resources is improved by minimizing spacing between SBs occupied by adjacent requests. Then, the interval between the end time of the new requests and surrounding requests is minimized in the time domain. After a period of time, the resources occupied by requests are released, resulting in larger available resources. Therefore, the minimization of RS-AR increases the number of continuous resources in the link not only from the perspective of the current frequency domain but also the future time domain. The fragmentation ratio is significantly reduced.

VI. CONCLUSION

In this paper, we solved the problem of resource allocation for hybrid IR/AR services in SDM-EONs. Then, a resource allocation scheme based on complete planning process was proposed. By dividing the complex resource allocation process into different phases, resource optimization was truly achieved.

First, the services were prioritized according to the starting time to alleviate the conflicts of requested resources. The earlier the services were transmitted, the higher priority was given for the resource selection. Second, resource planning based on the resource spacing between adjacent requests maximized the free resources in the network. Third, we used passive adjustment for the new incoming request that would be blocked. In this phase, conflicting AR requests were re-provisioned after planning reserved resources for the new request. Fourth, when transmission began, the planned resources in advance may not achieve the purpose of resource optimization due to AR re-provisioning. Therefore, the resource allocation with active adjustment was used to leave more available resources for the following requests by increasing the frequency-domain tightness. The simulation verified the effectiveness of the proposed RA-CPP scheme on COST239 and NSFNET networks. Results showed that the RA-CPP scheme outperformed the benchmark schemes in blocking probability and spectrum utilization. Meanwhile, the fragmentation ratio and the average number of re-provisioned AR requests could be decreased.

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