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Re-Provisioning of Advance Reservation Applications in Elastic Optical Networks

WEI WANG[1], YONGLI ZHAO[1], (Senior Member, IEEE), HAORAN CHEN[1], JIE ZHANG[1], HAOMIAN ZHENG[2], YI LIN[2], AND YOUNG LEE[2]
[1]Institute of Information Photonics and Optical Communications, Beijing University of Posts and Telecommunications, Beijing 100876, China
[2]Network Research Department, Huawei Technologies Co., Ltd., Shenzhen 518129, China

Corresponding author: Yongli Zhao (yonglizhao@bupt.edu.cn)

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ABSTRACT Driven by the development of cloud computing and mobile Internet, network-based applications have become diverse. Besides the usual immediate reservation (IR) applications, which need to be served immediately, advance reservation (AR) applications have been introduced to support initial-delay-tolerance services, such as grid computing, virtual machine backup, and so on. The provisioning mechanism of AR applications is different from that of IR applications, because AR requests don't require to be served immediately, and the network operator must decide the exact serving time in the AR service provisioning process. Based on the scheduling features of AR requests, this paper formulates a resource model and sets up a control framework for elastic optical networks to support AR services. We propose an optimization algorithm with three reprovisioning policies to dynamically reprovision the AR applications, which have already been scheduled. Both the proposed control framework and algorithm are developed on the basis of an open network operating system, which is an open-source software-defined networking controller. Also, the performance of the proposed algorithm is evaluated via software simulation. Demonstration results show the benefits of reprovisioning, and simulation results show that the reprovisioning optimization algorithm can improve the efficiency of network spectrum resource.

INDEX TERMS Optical fiber communication, advanced reservation, software-defined networking.

I. INTRODUCTION

Driven by the development of cloud computing and mobile Internet, network applications become to be diverse. As supplements for usual immediate reservation (IR) requests, advance reservation (AR) has been introduced into Internet as a novel kind of service request, which is essential to support initial-delay-tolerance applications (e.g., data backup, grid computing, etc.) [1]. Compared with IR requests, the unique feature of AR requests is that they don't require to be served immediately. AR requests are typically classified into two types, namely, 1) time-fixed, which means the start and end service time are fixed, and 2) time-flexible, which means the start and end service time are not specific time points, but loose time windows [2].

The calendaring features of AR requests make networks more predictable, and they also endow network operators with the ability to plan their networks via optimization-oriented scheduling. However, such features also make the provisioning procedures of AR applications more complicated, since two basic issues should be considered simultaneously to accommodate each AR request. One is scheduling problem, which can decide the exact service time window, and the other one is the resource allocation problem in advance [3], [4]. The problem of AR provisioning has been investigated with various optimization objectives (e.g., time-spectrum fragmentation), which all attempted to accommodate each AR request with an optimal solution. For instance, fixed and adaptive bandwidth-allocation policies were studied and compared in wavelength division multiplex (WDM) networks, and it was verified that dynamic bandwidth adjustment can improve the network resource utilization [5]. The problem of routing and bandwidth scheduling was discussed in the context of variable bandwidth advance reservation, and several heuristic algorithms were proposed to minimize the data transfer time by allocating time-varying bandwidth [6], [7]. From a comprehensive view, several algorithms combining scheduling with routing, modulation and spectrum assignment were proposed and evaluated for dynamic AR provisioning in EON [8]. Furthermore, aiming at the problem of two-dimensional fragmentation, several approaches (e.g., data oriented malleable reservation, time-spectrum fragmentation aware RSA and scheduling) were studied to improve spectrum efficiency [9]–[13]. Our previous work has studied cross-stratum resource reservation schemes in optical data-center networks to achieve joint load balance between computing and network stratums [14]. In general, the above works focused on the provisioning problem and their common general objective was to accommodate each arrived request with an optimal solution. However, this kind of optimization is only meaningful for the time point, when AR requests arrive, because AR requests are provisioned one by one in order of their arrival.

One of the most important features of AR is that the reserved resource for each scheduled AR request would not be activated until the scheduled start time arrives. Hence, network operators still have opportunities to re-provision (e.g., re-schedule/re-allocate resource) scheduled requests during their initial-delay periods. Based on this consideration, reference [15] and our previous work [16] have discussed the concept and implementation of re-provisioning for AR applications in WDM networks. This paper mainly focuses on the re-provisioning optimization algorithm for AR applications and performance evaluation in elastic optical networks (EON).

On the basis of the proposed control framework in our previous work, this paper formulates an EON resource model to support the provisioning of AR applications, and proposes a re-provisioning optimization (RPO) algorithm with three policies to re-provision AR applications and to improve the spectrum efficiency in EON. We have built a testbed based on open network operating system (ONOS) to demonstrate the benefit of re-provisioning in EON. Also, software simulations are conducted to evaluate the performance of proposed re-provisioning policies.

II. AR RE-PROVISIONING ENABLED CONTROL FRAMEWORK

In order to endow network operator with the ability of re-provisioning AR applications, an AR re-provisioning enabled control framework is designed based on SDN, which can provide centralized control ability. As shown in Fig. 1, the proposed control architecture is composed of three planes, i.e., application plane, control plane and data plane.

The application plane includes a set of northbound applications, which can provide service management interfaces for network customers and operators. In AR scenario, two kinds of applications are designed for customer and provider respectively. AR client (AR-C) is the one for customers to issue AR requests by specifying the required time and bandwidth parameters. Service scheduling expert (SSE) is designed for transport network provider to optimize reserved spectrum resources via re-provisioning.

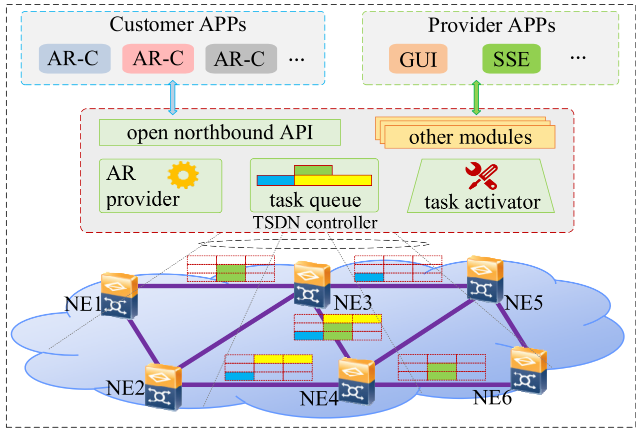

FIGURE 1. AR re-provisioning enabled control framework.

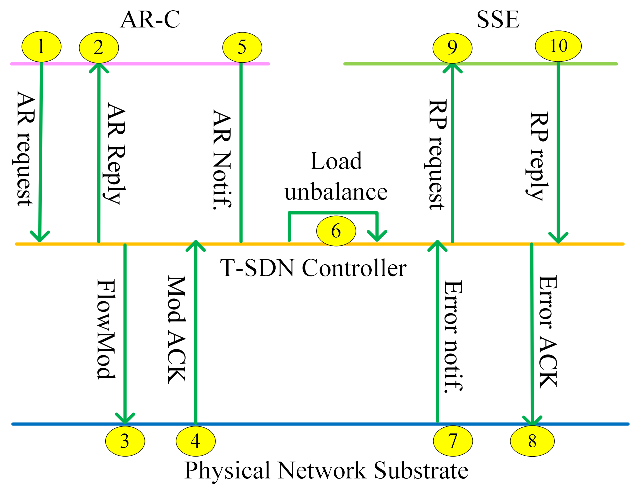

FIGURE 2. Work flows of AR re-provisioning.

The control plane refers to the transport SDN (TSDN) controller, which plays as the hypervisor of underlying physical network elements (NEs). Besides usual modules (e.g., path computation element (PCE), connection control module, etc.), three modules are introduced particularly to manage AR requests, and they are AR provider, task queue, and task activator. AR provider is an enhanced connection manager, and it can accommodate AR requests with scheduling and resource reservation algorithms. Task queue stores the information of each scheduled AR service in order of their scheduled start time. Task activator monitors the task queue, and would activate the scheduled services when their scheduled start time is due.

The data plane is composed of a set of programmable transport network elements. Note that this plane is un-aware of the scheduled AR applications, and it is just responsible for carrying users' traffic via spectrum channels as indicated by TSDN controller.

The workflows of the proposed architecture are illustrated as Fig. 2. The provisioning procedures of AR request are illustrated by step 1-5. To apply for an AR connection from transport networks, AR-C initially sends an AR request to TSDN controller. After processing the request, TSDN controller sends an AR reply back to AR-C to report the provisioning status (in step 1-2). Once the scheduled start time of a scheduled AR request arrives, TSDN controller sends Flow Mod messages to corresponding NEs. After finishing configuration, NEs send back the configuration results to TSDN controller via Mod ACK, and TSDN controller sends AR notification as response for Mod ACK (step 3-5). Besides the procedures above, AR re-provisioning related procedures are also designed in this framework for two scenarios. 1) Once resource occupation load is high or request blocking detected, TSDN controller sends RP request to SSE to report un-optimal status, and SSE sends RP reply to TSDN controller after finishing the re-provisioning optimization (step 6 and 9-10). 2) Once error occurs in physical networks, corresponding NE sends Error notification to TSDN controller, which will sends Error ACK message (step 9-10) back. TSDN controller calculates the affected scheduled requests and sends RP request to SSE. SSE starts to execute re-provisioning optimization and then sends RP reply to TSDN controller (step 7-10).

III. RE-PROVISIONING OPTIMIZATION ALGORITHM FOR AR APPLICATIONS IN EON

In this paper, the problem of AR re-provisioning is addressed in EON, and the spectrum resource in EON is simplified as frequency slots (FSs) without converting them to bitrates. In general, each scheduled AR request is expressed as $r^{p,f}_{t_s,t_e,t_d}$, in which t_s and t_e are the scheduled start and end service time, t_d is the tolerated deadline time, p is the selected path from source to destination, and f is a set of allocated FSs.

A. TIME-AWARE RESOURCE MODEL OF EON

In AR scenario, spectrum resource is labeled not only in link and spectrum dimensions, but also in time dimension. In order to describe such 3-dimensional resource clearly, we formulate a spectrum resource model, which can also be measured in time dimension. Network topology is modeled as a graph $G(V, E)$, where V and E are the sets of nodes and fiber links respectively. In spectrum dimension, the available spectrum of each fiber link is segmented into multiple FSs, and in time dimension, the FSs in each fiber link are dispersed into different time slots. We define an auxiliary matrix M^l_{F*T} as formulation (1), to denote the occupation status of F FSs at T time slots in each fiber link l, where $l \in E$. The matrix element $O^{id}_{i,j}$ is a binary key, which denotes the occupation status of FS i at time j, and id here refers to the request index who is scheduled to occupy this FS block. For example, $O^8_{1,2} = 1$ means that the 1st FS at time slot 2 is occupied by service 8, while $O^{-1}_{3,2} = 0$ represents that the 3rd FS at time slot 2 is not reserved by any service.

Based on this matrix, the work load of each fiber link can be measured jointly in spectrum-time dimensions. For each time slot t $(0 < t < T)$ before the end of predictable time T, we define FCR^t_l as the FS consumption ratio in fiber link l. FCR^t_l is expressed as formulation (2), where F is the total number of FSs on link l, and $\sum_{i=0}^{F} O^{id}_{i,t}$ is the number of reserved FSs on link l at time t. All the (l, t) pairs whose FCR^t_l are higher than a predetermined threshold FCR_{hv} are taken as heavy load block and are denoted by a set B_{hv}, which is illustrated in formulation (3). According to the wavelength consistent constraint on one lightpath in EON, the FS occupation status of a lightpath p, which is usually composed of a set of fiber links, is calculated as formulation (4). Note that the operator $\coprod$ in (4) refers to the binary OR operation of all the matrix elements which sit at the same location in operated matrixes.

$$M^l_{F*T} = \begin{pmatrix} O^{-1}_{0,0} & O^{-1}_{0,1} & \cdots & O^{-1}_{0,T} \\ O^{-1}_{1,0} & O^{-1}_{1,1} & \cdots & O^{-1}_{1,T} \\ \vdots & \vdots & \ddots & \vdots \\ O^{-1}_{F,0} & O^{-1}_{F,1} & \cdots & O^{-1}_{F,T} \end{pmatrix} \tag{1}$$

$$FCR^t_l = \sum_{i=0}^{F} O^{id}_{i,t}/F \tag{2}$$

$$B_{hv} = \{(l, t) | FCR^t_l > FCR_{hv}\} \tag{3}$$

$$M^p_{F*T} = \coprod_{l \in p} M^l_{F*T} \tag{4}$$

B. RE-PROVISIONING OPTIMIZATION (RPO) ALGORITHM

As AR requests arrive and leave dynamically in networks, spectrum resource might not be optimally reserved for lacking of knowledge about future requests. Take Fig. 3 as an example, where service #1 and #2 have already been scheduled, the coming of service #3, which requires FSs between time 3 to 5, will cause 4FSs (FCR=2/3) being reserved at time slot #4. Consequently, it is necessary to re-provision certain scheduled requests to achieve optimization. One of the metrics, which can measure un-optimal conditions, is FS consumption ratio FCR^t_l. On the basis of this metric, one RPO algorithm is designed to optimize the reserved spectrum condition via the following procedures: 1) find out the link-time pairs whose FS consumption ratio is higher than a predetermined threshold; 2) find out the AR requests who result in the heavy load described above; 3) release the reserved spectrum of some AR requests and re-provision them to balance the overall load.

The procedures of RPO are described in Algorithm 1. Firstly, the spectrum occupation matrix of each link $l \in E$ can be updated periodically according to all scheduled AR connections. Based on the latest resource matrix, the work load FCR^t_l of each link $l \in E$ at each time slot t $(0 < t < T)$ can be calculated as formulation (2), and the heavy load spectrum block set B_{hv} can be got from formulation (3). Secondly, we can find out the AR requests which have been scheduled to occupy the spectrum at heavy load block, according to the reservation information (routing, scheduling, spectrum assignment). The requests heavy load of spectrum block $(l, t) \in B_{hv}$ are denoted by a candidate request set R^t_l, as illustrated in formulation (5). Since one AR request

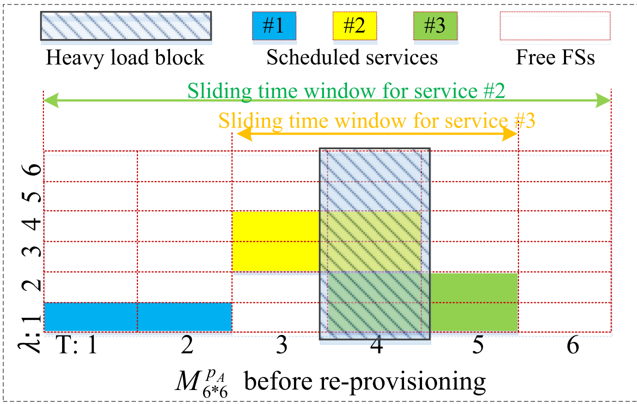

FIGURE 3. Illustrative scheduling condition without re-provisioning.

may cross multiple time-link spectrum blocks, and thus cause heavy load to multiple blocks, it is necessary to remove the overlapping requests (who are found to occupy multiple heavy load blocks) via getting the union set R of all the R_l^t as formulation (6), so that one candidate request would not be re-provisioned multiple times. To measure the contribution of each request $r_{t_s,t_e,t_d}^{p,f} \in R$ to the un-optimal condition, an auxiliary set $A(r_{t_s,t_e,t_d}^{p,f})$ is defined as formulation (7) to denote all the heavy load blocks it caused. For a candidate request, the more elements are in its auxiliary set, the more blocks are heavy loaded because of it. Hence, the number of the elements in the auxiliary set of each AR request is used to measure its weight of causing heavy load, namely, $H(r_{t_s,t_e,t_d}^{p,f})$. In order to eliminate heavy load blocks more efficiently, the proposed RPO algorithm are designed to re-provision the candidate requests in the decreasing order of their heavy-load weight. The procedures of re-provisioning can be seen in section 3.C.

$$R_l^t = \{(t_s, t_e, t_d, p, w) | t_s \leq t \leq t_e, l \in p\} \quad (5)$$

$$R = \cup R_l^t, \quad \forall (l, t) \in B_{hv} \quad (6)$$

$$A(r_{t_s,t_e,t_d}^{p,f}) = \{(l, t) | l \in p, t_s \leq t \leq t_e, (l, t) \in B_{hv}\} \quad (7)$$

The time complexity of RPO algorithm is O($|E|$*T) + O($|BS_{hv}|$)+O($|R_l^t|$)+O($|R_l^t|$)*O(RP), where $|E|$ is the number of the edges in G(V,E), T is the number of the time slots we predict for future, $|BS_{hv}|$ is the number of the heavy load blocks, $|R_l^t|$ is the number of the candidate requests for re-provisioning, and O(RP) is the time complexity to re-provision one AR request. In the worst case, the maximum value of $|BS_{hv}|$ is $|E|$*T, which means that all the FS-time blocks are heavy loaded. The maximum value of $|R_l^t|$ is |E|*T*F, where F refers to the number of the FSs on one fiber link. The worst case of $|R_l^t|$ means that each predictable FS-time block of each link is scheduled for one single request. O(RP) is analyzed in section 3.3 according to specific procedures of different re-provisioning policies. In general, the overall time complexity of RPO algorithm can be expressed as O($|E|^*T$) + O($|E|^*T$) + O($|E|^*T^*F$) + O($|E|^*T^*F$)*O(RP).

Algorithm 1 Re-Provisioning Optimization Algorithm

input: network $G(V, E)$ and AR requests set R $= \{r_{t_s,t_e,t_d}^{p,f}\}$;
output: re-provisioned requests $R' = \{r_{t_s',t_e',t_d}^{p',f'}\}$;
for each fiber link $l \in E$, **do**
  for each predictable time slot $t (0 < t < T)$, **do**
    calculate FCR_l^t of link l at time t per (1);
    if FCR_l^t is higher than threshold FCR_{hv}, **then**
      put pair (l, t) into heavy-loaded block set BS_{hv};
    end if
  end for
end for
for each heavy-loaded block $(l, t) \in BS_{hv}$, **do**
  find out all requests who occupy (l, t), as set $\mathcal{R}_l^t$;
end for
get union set R of all R_l^t to remove overlapped requests;
for each candidate request $r_{t_s,t_e,t_d}^{p,f} \in R$, **do**
  calculate its heavy load weight $H(r_{t_s,t_e,t_d}^{p,f})$ per (8);
end for
sort candidate requests in decreasing order of their heavy load weight;
for each candidate request $r_{t_s,t_e,t_d}^{p,f} \in R$, **do**
  re-provision it as re-provisioning policies in section 3.3;
end for

C. RE-PROVISIONING POLICIES

Since scheduled requests have already been provisioned once, some of provisioning parameters (e.g., scheduled start and end time, routing path and allocated FSs) can be reused in the re-provisioning procedures. Reusing different kinds of parameters may result in different re-provisioning results and spectrum efficiency. To find a better one, here we provide three re-provisioning strategies to re-provision the scheduled AR applications by reusing different parts of existing parameters.

Before allocating new resource for a candidate request $r_{t_s,t_e,t_d}^{p,f}$, the reserved resource should be released firstly to avoid its effects on re-provisioning. Based on the latest resource matrix of each link, the resource occupation status M_{F*T}^p of a candidate path p can be calculated as formulation (4) according to the consistent constraint in spectrum dimension. In order to express the spectrum occupation status at each time slot more clearly, we divide resource matrix M_{F*T}^p into several vectors as formulation (8), where vector c_t^p is the t^{th} column of M_{F*T}^p as formulation (9). Without considering the case of discontinuous transmission, the allocated FSs for one request should be continuous in time dimension. Consequently, the FS occupation status of path p during time t_1 to t_2, are calculated as formulation (10), where the $\coprod$ operator is logical OR of each element at same position. The FS consumption ratio FCR_{t_1,t_2}^p of path p during time t_1 to t_2, is calculated per

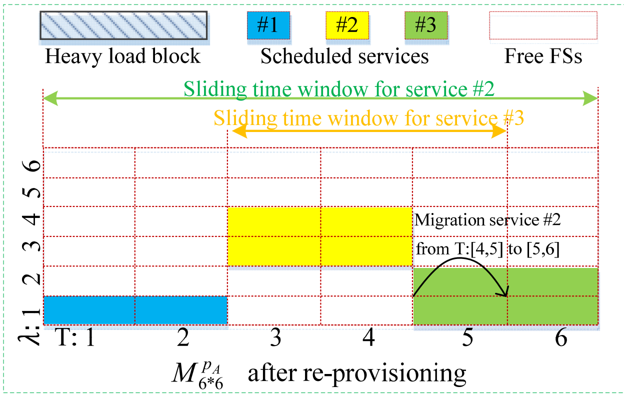

FIGURE 4. Illustrative re-provisioning condition with RS-AF-EP.

formulation (2).

$$M^{p}_{F*T} = (c^{p}_{0}, c^{p}_{1}, \cdots c^{p}_{t} \cdots c^{p}_{T}) \tag{8}$$

$$c^{p}_{t} = (O^{id}_{0,t}, O^{id}_{1,t}, \cdots O^{id}_{f,t} \cdots O^{id}_{F,t})^{T} \tag{9}$$

$$c^{p}_{t_1,t_2} = \coprod_{t_1 \le t < t_2} c^{p}_{t} = (O_0, O_1 \cdots O_f \cdots O_F)^{T} \tag{10}$$

$$PM^{p}_{t_1,t_2} = \left(1 + \frac{t_{std} - t_1}{t_{std} - t_p}\right) * (1 - FCR^{p}_{t_1,t_2}) \tag{11}$$

To re-accommodate a scheduled request with optimal time-spectrum resources, we need an effective metric to measure the priority of each candidate resource block. Besides the spectrum consumption ratio, which is important for load balancing, the serving time should also be considered. On the one hand, earlier start time is preferred in customers' perspective, because it means shorter initial delay, On the other hand, the spectrum resources in earlier time slots should be reserved preferentially because they are nearer to the present time, which means the spectrum would become invalid. The priority metric $PM^{p}_{t_1,t_2}$ is proposed as formulation (11) to measure the resource block during time t_1 to t_2, on path p. In formulation (11), t_p is present time, and t_{std} is an adjustment factor for the candidate start-time's impact on the priority metric, which is always set as the old start time of a scheduled AR request during re-provisioning optimization. In addition, if (11) is used for AR provisioning instead of re-provisioning, t_{std} could be set as $t_{std} = t_p + t_{fix}$, where t_{fix} is a fixed time duration. Based on the definitions above, three re-provisioning policies are designed.

1) RE-SCHEDULE THE ALLOCATED FSs ON EXISTING PATH

For a request $r^{p,f}_{t_s,t_e,t_d}$, this policy keeps the existing path and the allocated FSs unchanged, and just adjusts the start and end time. To achieve optimization only in time dimension, RS-AF-EP finds the optimal time duration, which has the highest priority metric, as the new serving period to re-accommodate the candidate request. Note that the new serving time duration should not exceed the tolerated deadline time. The procedures of RS-AF-EP are described in Algorithm 3. As illustrated by the example in Fig. 4, the maximum time ranges for service #2 and #3 are [1, 6] and [3, 5] respectively, and RS-AF-EP migrates service 2 from time [4, 5] to [5, 6] to avoid heavy load at time slot 4.

Algorithm 2 Re-Schedule the Allocated FSs on Existing Path (RS-AF-EP)

input: scheduled AR request $r^{p,f}_{t_s,t_e,t_d}$;
output: re-provisioned AR request $r^{p',f'}_{t'_s,t'_e,t_d}$;
release the reserved FSs for $r^{p,f}_{t_s,t_e,t_d}$, and update $M^{l}_{F*T} (l \in p)$;
initialize a temporary lowest priority metric as $PM_{low} = 0$;
for each $t (t_{pres} \le t < t_d - (t_e - t_s))$, **do**
  get $c^{p}_{t,t+(t_e-t_s)}$ of p during $[t, t + (t_e - t_s)]$ per (11);
  if $O_f = 0, \forall f \in w, (O_f \in c^{p}_{t,t+(t_e-t_s)})$, **then**
    get $FCR^{p}_{t,t+(t_e-t_s)}$ of p during $[t, t+(t_e-t_s)]$ per (2);
    get $PM^{p}_{t,t+(t_e-t_s)}$ of p during $[t, t+(t_e-t_s)]$ per (12);
    if $PM^{p}_{t,t+(t_e-t_s)} > PM_{low}$, **then**
      set t_{opt} as t, PM_{low} as $PM^{p}_{t,t+(t_e-t_s)}$;
    end if
  end if
end for
set $r^{p',f'}_{t'_s,t'_e,t_d}$ as $t'_s = t_{opt}$ and $t'_e = t_{opt} + (t_e - t_s)$.

The time complexity of RS-AF-EP is O($t_d - (t_e - t_s) - t_{pres}$), where t_d is the deadline time, t_s and t_e are the scheduled start and end time respectively, and t_{pres} is the present time. In the worst case, the max value of $t_d - (t_e - t_s) - t_{pres}$ is T, which is the number of predictable time slots. Hence, the time complexity of RS-AF-EP is O(T). With this policy, the overall time complexity of RPO algorithm can be expressed as O(|E|*T)+O(|E|*T)+O(|E|*T*F)+O(|E|*T*F)*O(T), and it can be concluded as O(|E|*T^2*F). Hence, RPO is guaranteed to run in polynomial time.

2) RE-SCHEDULE AND RE-ALLOCATE FSs ON EXISTING PATH

For a candidate request $r^{p,f}_{t_s,t_e,t_d}$, this policy just reuses the existing path, and tries to adjust the service time duration and FSs simultaneously. To achieve joint optimization in both time and spectrum dimension, RS-RF-EP firstly finds the optimal time duration, which has the highest priority metric, as the new serving time duration to re-accommodate the candidate request. From the optimal time duration, RS-RF-EP should also allocate required FSs for the candidate request according to contiguous constraint for sub-carriers in EON. Note that the new service time duration should not exceed the tolerated deadline time. The procedures of RS-RF-EP are described in Algorithm 3. Taking Fig. 5 as an example, the maximum time ranges for service #2 and #3 are [1, 6] and [3, 5] respectively, and RS-RF-RR reallocates serving time and FSs for both service 2 and 3 during the sliding time window.

The time complexity of RS-RF-EP is O($t_d - (t_e - t_s) - t_{pres}$), where t_d is the deadline time, t_s and t_e are the scheduled

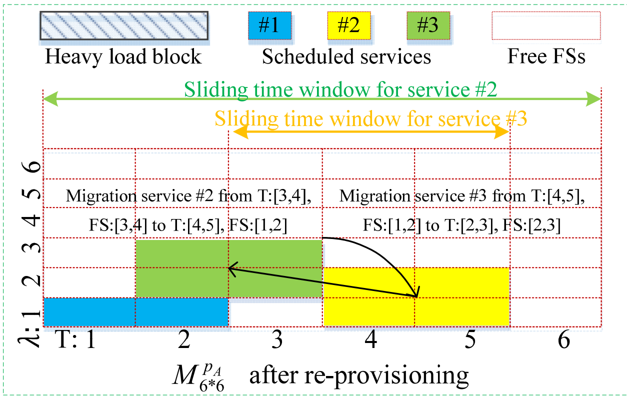

FIGURE 5. Illustrative re-provisioning condition with RS-RF-EP.

Algorithm 3 Re-Schedule and Re-Allocate FSs on Existing Path (RS-RF-EP)

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input: scheduled AR request $r^{p,f}_{t_s,t_e,t_d}$;
output: re-provisioned AR request $r^{p',f'}_{t'_s,t'_e,t_d}$;
release the reserved FSs for $r^{p,f}_{t_s,t_e,t_d}$, and update $M^l_{F*T}(l \in p)$;
initialize a temporary lowest priority metric as $PM_{low} = 0$;
for each $t(t_{pres} \leq t < t_d - (t_e - t_s))$, **do**
    get $c^p_{t,t+(t_e-t_s)}$ of p during $[t, t+(t_e-t_s)]$ per (11);
    get $FCR^p_{t,t+(t_e-t_s)}$ of p during $[t, t+(t_e-t_s)]$ as (2);
    get $PM^p_{t,t+(t_e-t_s)}$ according to (12);
  if $PM^p_{t,t+(t_e-t_s)} > PM_{low}$, **then**
        set t_{opt} as t, PM_{low} as $PM^p_{t,t+(t_e-t_s)}$;
  end if
end for
assign required FSs from $c^p_{t_{opt},t_{opt}+(t_e-t_s)}$ as f_{opt}.
set $r^{p',f'}_{t'_s,t'_e,t_d}$ as $t'_s = t_{opt}$, $t'_e = t_{opt}+(t_e-t_s)$, and $f' = f_{opt}$.

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start and end time respectively, and t_{pres} is the present time. In the worst case, the maximum value of $t_d - (t_e - t_s) - t_{pres}$ is T, which is the number of predictable time slots. Hence, the final complexity of RS-RF-EP is O(T). Based on this policy, the overall time complexity of RPO algorithm can be expressed as O($|E|$*T) + O($|E|$*T) + O($|E|$*T*F) + O($|E|$*T*F)*O(T), and it can be concluded as O($|E|$*T^2*F). Hence, RPO is guaranteed to run in polynomial time.

3) RE-SCHEDULING, RE-ALLOCATING FSs AND RE-ROUTING

Re-using none of the existing parameters, this policy tries to adjust the serving time duration, FSs and path simultaneously. To achieve such three-dimensional optimization, RS-RF-RR firstly calculates k shortest paths from source to destination node. Among all the candidate paths, RS-RF-RR finds out the optimal time duration, which has the highest priority metric, as the new service time duration to re-accommodate the candidate request. The path, on which the optimal time duration is found, would be taken as the target path for re-provisioning. During the optimal time duration on the candidate path, RS-RF-RR allocates the required FSs for candidate request according to contiguous constraint for sub-carriers in EON. Note that the new service time duration should not exceed the tolerated deadline time.

Algorithm 4 Re-Schedule, Re-Allocate FSs and Re-Route (RS-RF-RR)

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input: scheduled AR request $r^{p,f}_{t_s,t_e,t_d}$;
output: re-provisioned AR request $r^{p',f'}_{t'_s,t'_e,t_d}$;
release the reserved FSs for $r^{p,f}_{t_s,t_e,t_d}$, and update $M^l_{F*T}(l \in p)$;
initialize a temporary lowest priority metric as $PM_{low} = 0$;
get k shortest paths from source to destination as a set P_k using KSP algorithm;
for each candidate path $cp \in P_k$, **do**
  for each $t(t_{pres} \leq t < t_d - (t_e - t_s))$, **do**
get $c^{cp}_{t,t+(t_e-t_s)}$ of p during $[t, t+(t_e-t_s)]$ per (11);
get $FCR^{cp}_{t,t+(t_e-t_s)}$ of cp during $[t, t+(t_e-t_s)]$ as (2);
  get $PM^{cp}_{t,t+(t_e-t_s)}$ per(12);
  if $PM^{cp}_{t,t+(t_e-t_s)} > PM_{low}$, **then**
set t_{opt} as t, p_{opt} as cp, and PM_{low} as $PM^{cp}_{t,t+(t_e-t_s)}$;
  end if
  end for
end for
assign required FSs from $c^{p_{opt}}_{t_{opt},t_{opt}+(t_e-t_s)}$ as f_{opt};
  set $r^{p',f'}_{t'_s,t'_e,t_d}$ as $t'_s = t_{opt}$, $t'_e = t_{opt} + (t_e - t_s)$, $p' = p_{opt}$ and $f' = f_{opt}$.

The time complexity of RS-RF-RR is O(($t_d - (t_e - t_s) - t_{pres}$)*k), where t_d is the deadline time, t_s and t_e are the scheduled start and end time respectively, t_{pres} is the present time and k is the number of the paths we want to get from KSP algorithm. In the worst case, the maximum value of $t_d - (t_e - t_s) - t_{pres}$ is T, which is the number of the predictable time slots. Hence, the final complexity of RS-RF-RR is O(T*k). Based on this policy, the overall time complexity of RPO algorithm can be expressed as O($|E|$*T)+ O($|E|$*T) + O($|E|$*T*F) + O($|E|$*T*F)*O(T*k), and it can be concluded as O(k*$|E|$*T^2*F). Hence, RPO is guaranteed to run in polynomial time.

IV. DEMONSTRATION AND NUMERIC RESULTS

In order to verify the performance and feasibility of the proposed control framework, we build a SDN based testbed as described in section 2. The TSDN controller is developed on the basis of ONOS, and we add additional time-aware features to support AR requests. SSE is implemented as a northbound application on TSDN controller, and RPO algorithm is embedded in SSE. The AR-C is integrated into SSE to provide the interface for issuing AR requests. Fig. 6 (a) shows the graphic user interface (GUI) of SSE, which is

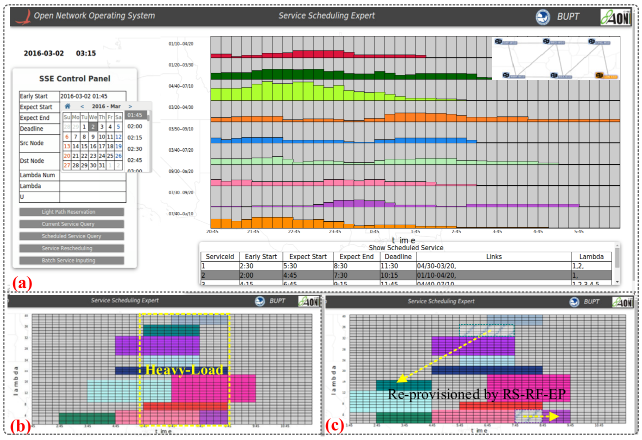

FIGURE 6. GUI of SSE and demonstration results.

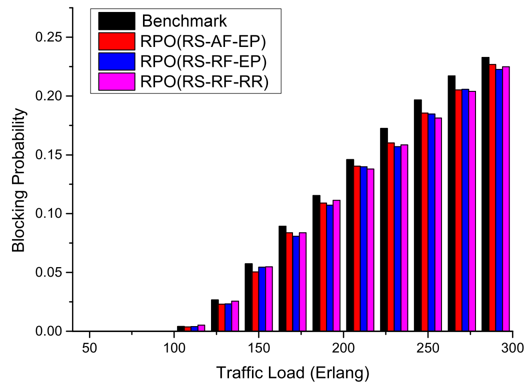

FIGURE 7. Performance of PRO policies in terms of BP.

composed of two parts. The first part is the SSE control panel used for inputting users' parameters for issuing AR requests and re-provisioning, and the second part is two-dimensional grid board which shows the FCR in time and link dimension dynamically. The second, an AR request generator is implemented in SSE to generate batched AR requests. The network substrate in this demonstration is constructed by Linc-OE [17], which is an open source network element simulator for optical networks [16]. The top-right part of Fig. 6 (a) depicts the transport topology we use in this demonstration. It is composed of 6 Linc-OE nodes and 9 fiber links, and each link is configured with 40 FSs.

On the testbed above, we demonstrate the feasibility and benefit of the proposed control framework. Firstly, we issue a set of AR requests using AR request generator, and the controller reserves FS resources for them one by one. After multiple requests being scheduled, the predicted FCR of each fiber link is shown by the two-dimensional grid board in Fig. 6 (a). When clicking one link on the visible GUI of SSE in Fig. 6 (a), the gird board would be transformed to show the FS occupation status for the link. As shown in Fig. 6 (b), the colored block depicts the reserved time-FS resource for each scheduled AR request in time and spectrum dimension. Fig. 6 (b) shows that heavy load occurs at the remarked area, where is difficult to accommodate any other requests. After being optimized by RS-AF-EP, the resource condition of the same link is updated as Fig. 6 (c). It is notable that some AR requests are re-provisioned to release the resources in the heavy load area for upcoming requests, which may require the released resource specifically. In general, the proposed framework can not only accommodate AR requests, but also evacuate the crowded requests by re-provisioning them during their initial-delay periods.

In addition to the demonstration above, we also evaluate the performance of re-provisioning algorithm via simulation on NSFNET topology with 14 nodes and 21 links. Each link is configured with 80 FSs. Time dimension is discretized as continuous time slots, and we always maintain the resource status at the future 500 time slots. With time going on, the FSs at past time (which is earlier than present time) slots are abandoned and new FSs are supplemented at the end of predictable time slots. AR connection requests are modeled as quasi-Poisson process, in which the arrival, hold and deadline time are rounded down as integers. In addition, the deadline time of each request is generated as $t_d = t_{arrival} + t_{hold} + t_{sliding}$, and $t_{sliding}$ is generated as the same negative exponential distribution with t_{hold}. The source and destination nodes of each request are generated randomly among all the nodes on NSFNET. The required bandwidth of each request is simplified as the number of FSs, which is evenly distributed between 1 and 5. With the fixed departure rate 0.025, we issue 50000 connection requests for each case, in which the arrival rate various, to evaluate the performance of the proposed RPO algorithm and re-provisioning policies.

The performances of RPO algorithm with the re-provision policies are compared with a benchmark in terms of blocking probability (BP), transmitted data volume (TDV), average initial delay (AID) of each AR request, and average running time (ART) for re-provisioning one AR request. The benchmark is a well optimized AR provisioning algorithm, which aims to find the optimal path, time-spectrum resource for each arrival AR request via time-aware RSA, whose procedures are similar with that in RS-RF-RR. In re-provision optimization enabled scenario, the RPO algorithm is trigged when any arrival AR request is blocked when being provisioned by the benchmark.

Fig. 7 and Fig. 8 compare the performances of RPO algorithm with benchmark in terms of BP and TDV respectively. As is shown in Fig. 7, RPO policies can reduce about 5% BP as compared with benchmark. That is because RPO algorithm takes the advantage of re-provision opportunity in AR scenario, and it has the ability to avoid resource conflicts via re-provisioning multiple scheduled AR request from the overall perspective. It is reasonable that the reduction of BP result in the TDV improvement in Fig. 8. Generally speaking, the same network can transmit 3.5% more data with the optimization of RPO. In terms of these two metrics, the proposed three policies of RPO have almost same performance.

Fig. 9 compares the performances of three RPO policies with benchmark in terms of AID. It is notable that

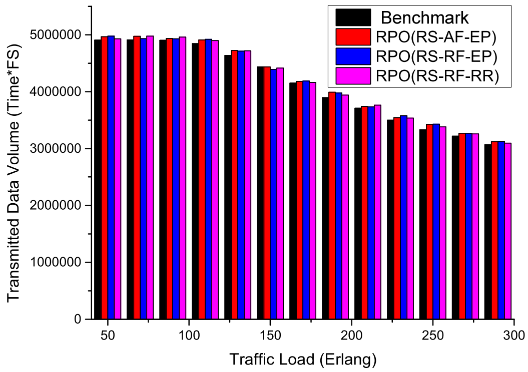

FIGURE 8. Performance of PRO policies in terms of TDV.

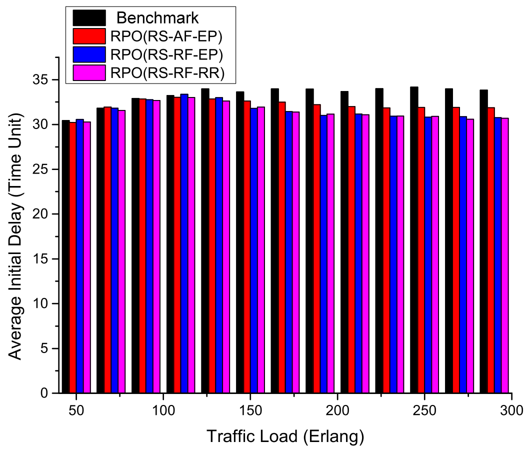

FIGURE 9. Performance of PRO policies in terms of AID.

RPO has about 5% lower average initial delay than the benchmark, because time dimension is considered in all the re-provisioning policies. In details, we set t_{std} in formulation (11) as the original scheduled start time of the candidate AR request, and it means that the time slot, which is earlier than the original start time, has positive impact on the final priority metric. Consequently, the RPO algorithm tries to re-accommodate the request with the resource in an earlier time-spectrum area, and the initial delay can be reduced accordingly. Compared with RS-AF-EP, RS-RF-EP and RS-RF-RR policies perform better. It is because keeping the FSs unchanged is a very strict constraint for RS-AF-EP, and many re-provisioning actions cannot be done for lacking of original FSs. Thus RS-RF-RR can reduce less initial delay as compared with the other two policies. Fig. 10 shows the ART for re-provisioning one AR request in milliseconds. It is notable that RS-RF-RR runs three times as long as RS-AF-EP and RS-RF-EP. It is because RS-RF-RR needs to find the optimal resource among multiple candidate paths. However, RS-RF-RR has almost the same performance in terms of BP, TDV, and AID even though it tries to make further optimization in path dimension. That is because RS-RF-RR may re-accommodate the candidate request with a higher-priority path with more hops, and it in turn has negative impact on the network efficiency due to more FSs occupation.

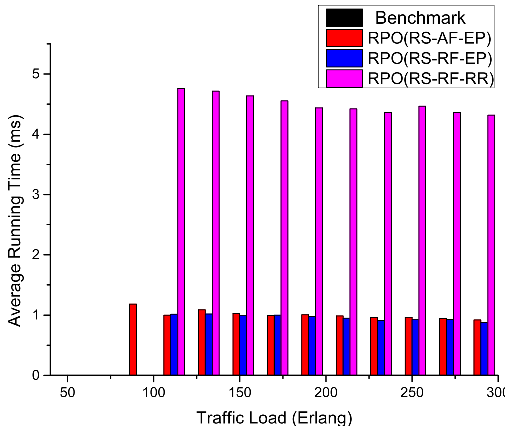

FIGURE 10. Performance of PRO policies in terms of ART.

In general, re-provisioning is a valuable approach for network optimization, and the proposed RPO algorithm with policies can reduce network BP and AID significantly. Among the three proposed policies, RS-RF-EP is the best choice.

V. CONCLUSION

This paper studied the re-provisioning problem for AR applications in elastic optical networks (EON). We introduced a re-provisioning enabled control framework based on SDN, and a re-provisioning optimization (RPO) algorithm with three re-provisioning policies. The proposed algorithm and policies have been verified via both demonstration and simulation. A testbed has been setup for demonstration, which verified that re-provisioning was a valuable approach for transport network optimization. Simulation results have evaluated the proposed algorithm and policies in numeric results, which show that RPO can reduce requests blocking and initial-delay. Among the proposed re-provisioning policies, re-schedule and re-allocate FSs on existing path (RS-RF-EP) performed the best.

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WEI WANG received the B.S. degree in communication engineering from Beijing University of Posts and Telecommunications, China, in 2013, where he is currently pursuing the Ph.D. degree in information and communications engineering. He is also a Visiting Research Scholar with the University of California at Davis, CA, USA. His research interests include software-defined networking, network function virtualization, and mobile edge computing.

YONGLI ZHAO (SM'15) received the B.S. degree in communications engineering and the Ph.D. degree in electromagnetic field and microwave technology from Beijing University of Posts and Telecommunications (BUPT), China. From 2016 to 2017, he was a Visiting Associate Professor with University of California, Davis, CA, USA. He is currently an Associate Professor with the Institute of Information Photonics and Optical Communications, BUPT. He has authored more than 300 international journal and conference papers. His research focuses on software-defined optical networking, elastic optical networks, datacenter networking, and optical network security.

HAORAN CHEN received the B.S. degree from the Department of Electrical Engineering, Beijing University of Posts and Telecommunications, Beijing, China, in 2011, where he is currently pursuing the Ph.D. degree with the State Key Laboratory of Information Photonics and Optical Communications. His research interest is in software-defined networks.

JIE ZHANG received the bachelor's degree in communication engineering and the Ph.D. degree in electromagnetic field and microwave technology from Beijing University of Posts and Telecommunications (BUPT), China. He is currently a Professor and the Vice Dean of the Information Photonics and Optical Communications Institute, BUPT. He has authored more than 300 technical papers, authored eight books, and submitted 17 ITU-T recommendation contributions and six IETF drafts. He holds 17 patents. His research focuses on architecture, protocols, and standards of optical transport networks. He has served as a TPC Member for a number of conferences, such as ACP, OECC, PS, ONDM, COIN, and ChinaCom.

HAOMIAN ZHENG received the B.S. degree in electrical engineering from Shanghai Jiao Tong University, China, in 2006, the M.S. degree in electrical engineering from The Hong Kong University of Science and Technology in 2008, and the Ph.D. degree from the Department of Computing, The Hong Kong Polytechnic University, in 2012. He first joined Huawei Technologies Co., Ltd., for transport network research and is currently a Senior Researcher and Standard Engineer. As a standard delegate, his major working scope is control plane of transport network, such as OTN/WSON control, ASON/GMPLS protocols, PCEP protocols, and the ACTN and YANG models. He is an Editor of the ITU-T G.873.1 standard, and more than ten IETF drafts.

YI LIN received the B.S. degree in electronical information science and technology and the M.S. degree in radio physics from Sun Yat-sen University, China, in 2005 and 2007, respectively. He joined Huawei Technologies Co., Ltd. in 2007 and is currently a Senior Research Engineer. His main research topic is intelligent control of transport networks, including ASON/GMPLS, PCE, and transport SDN.

YOUNG LEE is currently a Principal Technologist with the Huawei Technologies Company, USA Division, Plano, TX, USA. He is leading optical transport control plane technology research and development. His research interests include distributed path computation architecture, multilayer traffic engineering methodology, network optimization modeling, and new concept development in optical control plane signaling and routing.