Dynamic Service Provisioning of Advance Reservation Requests in Elastic Optical Networks

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***Abstract*—The elastic optical network (EON) based on the optical orthogonal frequency-division multiplexing (O-OFDM) technology is a promising candidate for accommodating the uncertainty and heterogeneity of the traffic across future Internet. Advance reservation (AR) is essential to support initial-delay-tolerant services, such as e-science and grid computing, which are making significant contributions to the Internet traffic. Therefore, we expect that it is necessary for future EONs to support AR requests. In this paper, we study dynamic service provisioning of AR requests in EONs. These AR requests permit certain initial-delay during setting-up, as long as the resources are allocated before a preset deadline. We propose several algorithms that combine request scheduling in the time domain with routing, modulation and spectrum assignment (RMSA) in the spectrum domain. Specifically, with the combination of a routing path selection policy and a request scheduling strategy, the algorithm constructs a weight matrix for each pending AR request and provisions the request with it. We design numerical simulations to investigate the algorithms' performance in terms of three metrics, i.e., blocking probability, average spectrum efficiency, and average initial-delay. Based on the simulation results and computational complexity analysis, we provide suggestions on how to choose routing path selection policy and request scheduling strategy for provisioning AR requests dynamically in EONs. To the best of our knowledge, this is the first attempt to address dynamic service provisioning of AR requests in EONs.**

***Index Terms*—Advance reservation (AR), AR request scheduling, dynamic routing, elastic optical networks, modulation and spectrum assignment (RMSA).**

I. Introduction

RECENTLY, elastic optical networks (EONs) have attracted intensive research interests. Based on the optical orthogonal frequency-division multiplexing (O-OFDM) technology [1], [2], sub-wavelength switching granularity and high bandwidth efficiency can be realized in EONs. Similar to the routing and wavelength assignment (RWA) in wavelength-division multiplexing (WDM) networks, routing and spectrum assignment (RSA) is a crucial task for resource management in O-OFDM based EONs. Furthermore, with the considerations of quality of transmission (QoT) and receiver sensitivity, an O-OFDM transponder can make the modulation-level of its subcarrier slots be distance-adaptive [3], [4]. Consequently, the RSA problem evolves to routing, modulation and spectrum assignment, i.e., RMSA.

Previous works have proposed a few RSA/RMSA algorithms for planning and provisioning of EONs [5]–[11]. However, all of these previous works only considered the RSA/RMSA of requests that need to be served immediately upon arrival. These requests, which have zero initial-delay tolerance, are referred as immediate reservation (IR) requests, since they will either be served immediately upon arrival or be blocked. Besides IR requests, there are advance reservation (AR) requests in optical networks [12]. These AR requests allow certain initial-delay during setting up, as long as the resources are allocated before a preset deadline. The AR scheme is essential to support initial-delay-tolerant services, such as video-on-demand and grid computing [13].

However, the service provisioning of AR requests in EONs has not yet been investigated. Recent research has forecasted that the EON would be a promising candidate for accommodating the uncertainty and heterogeneity of the traffic across next-generation Internet [14]. Its flexible bandwidth allocation scheme can provide seamless support to the applications whose bandwidth requirements are relatively large but can vary with a fine granularity, such as in cloud computing, e-science, grid computing and etc. Meanwhile, it is known that a significant portion of the requests originated from these applications are AR requests [13]. To this end, we expect that it is necessary for future EONs to support AR requests. Therefore, it is important for us to develop efficient service provisioning algorithms for AR requests in EONs, especially for dynamic operation cases where the uncertainty and heterogeneity of the traffic are significant.

Previously, researchers have investigated service provisioning of AR requests in WDM networks [12], [15]–[24]. In [12], Zheng *et al.* designed several RWA algorithms for serving AR requests in WDM networks. Kuri *et al.* proposed a tabu-search based algorithm for routing of AR requests in [15], and later designed an algorithm that employed K shortest path routing and the first-fit wavelength assignment for performing request scheduling and RWA jointly in [16]. Wallace *et al.* used simulated annealing to optimize wavelength resource allocation of AR requests in [17], and later formulated a mixed integer linear programming (MILP) model to minimize average initial-delay of AR requests in [18]. A Lagrangian relaxation (LGR) approach was proposed in [19] to reduce the number of rejected AR requests and to increase the revenue. For provisioning AR requests in WDM networks dynamically, Shen

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et al. designed several scheduling strategies with different considerations in [20], [21]. Tanwir *et al.* also proposed several AR request scheduling strategies in [22]. The investigation in [23] considered scheduling and provisioning of dynamic AR requests that have variable bandwidth. In [24], [25], Vokkarane *et al.* studied dynamic and static RWA for AR multicast in WDM networks. A comprehensive survey of RWA for AR requests in WDM networks can be found in [13].

In this paper, we study joint optimization of scheduling and distance-adaptive RMSA for dynamic AR service provisioning in EONs. As we have to consider several special constraints from O-OFDM, the problem is intrinsically more complicated than its counterpart in WDM networks. To the best of our knowledge, this is the first attempt to address dynamic service provisioning of AR requests in EONs. In order to investigate the trade-off between average initial-delay and blocking probability, we propose several dynamic service provisioning algorithms that combine request scheduling with RMSA, and design simulations to evaluate their performance in term of three metrics, i.e., blocking probability, average spectrum efficiency, and average initial-delay.

The rest of the paper is organized as follows. Section II formulates the problem of dynamic service provisioning of AR requests in EONs. The proposed service provisioning algorithms are discussed in Section III. In Section IV, we show the simulation setup and results for performance evaluation. Finally, Section V summarizes the paper.

II. Dynamic Service Provisioning of AR Requestsin EONs

In this section, we formulate the problem of dynamic service provisioning of AR requests with scheduling and RMSA in EONs, and define several design metrics.

We consider a EON network topology as $G(V, E)$, where V is the node set, E is the set of fiber links, and each fiber link can accommodate B subcarrier slots at most. The bandwidth capacity of a slot can be denoted as $M \cdot C_{slot}$ Gb/s, where M is the modulation-level and C_{slot} is its capacity when $M = 1$ (e.g., BPSK). In the context of this work, we assume M can be 1, 2, 3 and 4 for BPSK, QPSK, eight quadrature-amplitude modulation (8-QAM), and 16-QAM, respectively.

For a pending AR request for a capacity of C Gb/s, we denote it as $LR(s, d, C, t_a, d_{\max}, \Delta t)$, where s–d is the source-destination pair, t_a is the arrival time, $d_{\max}$ is the maximum initial-delay, and Δt is the service duration. We assume that the EON operates according to discrete time units. We define $[t_s, t_e]$ as the reserved service window, where t_s is the scheduled service start time, and $t_e = t_s + \Delta t$ is the time when the service ends. Apparently, the following constraint applies to t_s based on the principle of AR:

$$t_a \leq t_s \leq t_a + d_{\max}. \tag{1}$$

In order to provision an AR request LR, we need to determine a routing path $R_{s,d}$ that can accommodate its capacity C within a valid service window $[t_s, t_e]$. On $R_{s,d}$, the capacity C is mapped to N contiguous subcarrier slots that are available within $[t_s, t_e]$ on each link $e,\ e \in R_{s,d}$. We assume there is no spectrum conversion in the network, and hence the N contiguous subcarrier slots have to occupy the same frequency range on each link $e,\ e \in R_{s,d}$ (i.e., the spectrum continuity constraint). Note that for different routing paths, the required number of slots N can be different. Here, N is determined with the highest modulation level M that a path can support with the considerations of transmission distance and receiver sensitivity [3], as follows,

$$N = \left\lceil \frac{C}{M \cdot C_{slot}} \right\rceil + N_g, \tag{2}$$

where N_g is the number of guard-band slots.

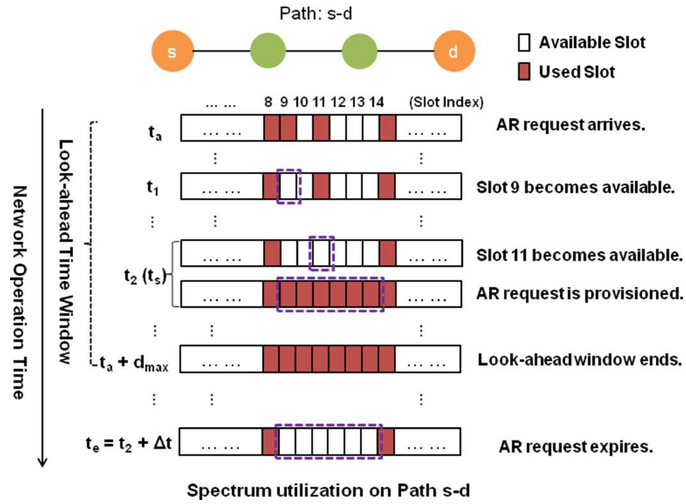

Fig. 1. An example of provisioning AR requests in EONs.

Fig. 1 illustrates an intuitive example of provisioning AR requests in EONs. At t_a, an AR request from s to d comes in and asks for $N = 6$ contiguous slots. The spectrum utilization on the routing path $s \rightarrow d$ is then determined for time t_a. While the request cannot be provisioned immediately due to insufficient bandwidth resource, the scheduler performs a look-ahead based on the information of the requests that are currently using the slots. Then, the scheduler finds that Slots 9 and 11 will be available from t_1 and t_2 ($t_2 > t_1 > t_a$), respectively, and it also determines that Slots 9–14 can be used to accommodate the pending AR request from t_2. Since we have $t_2 < t_a + d_{\max}$, the scheduler schedules the request to be provisioned from t_2 ($t_s = t_2$) using Slots 9–14.

In order to assist the design of dynamic service provisioning algorithms, we define three design metrics.

Definition (Blocking Probability): Since the principle of AR brings the dimension of time into consideration, we redefine the blocking probability of service provisioning as,

$$P_b = \frac{\sum\limits_{i \in I_R} C_i \cdot \Delta t_i}{\sum\limits_{i \in I} C_i \cdot \Delta t_i}, \tag{3}$$

where i is the unique index of AR requests, C_i and Δt_i are the required capacity and service duration of request LR_i, I is the set of request indices, and I_R ($I_R \subset I$) is the set of indexes for requests that are blocked.

Definition (Average Spectrum Efficiency): The average spectrum efficiency of service provisioning is defined as,

$$\overline{\eta} = \frac{\sum\limits_{i \in I - I_R} C_i \cdot \Delta t_i}{\sum\limits_{i \in I - I_R} N_i \cdot \Delta t_i \cdot C_{slot}} \cdot \eta_{BPSK}, \tag{4}$$

where N_i is the number of contiguous slots required by request LR_i, and η_{BPSK} is the spectrum efficiency of BPSK modulation ($M = 1$) in bits/s/Hz.

Definition (Average Initial-Delay): The average initial-delay of provisioned AR requests can be calculated as,

$$\overline{d} = \frac{\sum\limits_{i \in I - I_R} t_{s,i} - t_{a,i}}{|I - I_R|}, \tag{5}$$

where $t_{a,i}$ and $t_{s,i}$ are the arrival time and service start time of request LR_i, respectively, and $|\cdot|$ returns the number of elements in a set.

III. Request Scheduling and RMSA of AR Requests in EONs

In this section, we discuss several dynamic service provisioning algorithms for AR request scheduling and RMSA in EONs. We propose three AR request scheduling strategies, and for each of them, two routing path selection policies are investigated for RMSA. The scheduling strategies operate based on a weight matrix $[\mathbf{W}]_{K \times T}$, where K is the number of routing path candidates for an AR request, and T is the number of time slots in the future over which we can schedule the AR request. Each element $w_{k,j}$ in $\mathbf{W}$ represents the scheduling weight for provisioning the request over the k-th path candidate from the j-th start time.

A. Routing Path Selection Policies

In order to reduce the overhead of path computation, all feasible routing paths for each s–d pair in $G(V, E)$ are precalculated during network initialization. When scheduling an AR request, the routing path candidate set is chosen from them based on one of the following path selection policies.

1) Shortest Path First (SPF): For this policy, we select K paths that have the shortest transmission distance among all feasible paths. A shorter path may support higher modulation-level, and hence can reduce the number of subcarrier slots reserved for a pending request.

2) Smallest Slot-Bandwidth Product First (SSBPF): This policy considers the link usage on-the-fly. Let $hop(R_{s,d})$ denote the hop count of a routing path $R_{s,d}$, then the total number of slots along $R_{s,d}$ for provisioning a capacity unit is

$$N_{unit} = \left\lceil \frac{1}{M \cdot C_{slot}} + N_g \right\rceil \cdot hop(R_{s,d}), \tag{6}$$

where M is the highest modulation-level that $R_{s,d}$ can support, and N_g is the number of guard-band slots. We also define the used bandwidth over the path at time t as $bw(t)$, in terms of subcarrier slots. Then, the K routing path candidates are selected according to the ascending order of $N_{unit} \cdot (bw(t) + 1)/B$.

B. Request Scheduling Strategies

After finalizing the K routing path candidates, the dynamic service provisioning algorithm constructs the weight matrix $[\mathbf{W}]_{K \times T}$, and utilizes it to guide request scheduling. Hence, by using different methods to calculate each element $w_{k,j}$ in $\mathbf{W}$, we can achieve different request scheduling strategies.

1) Least Time to Wait (LTW): As its name suggests, the LTW strategy aims to serve an AR request as early as possible. If the AR request can be provisioned over the k-th path candidate from the j-th start time, we set t_s as the j-th start time and assign $w_{k,j} = t_s - t_a$. Otherwise, we assign $w_{k,j} = +\infty$. Then, we find the smallest $w_{k,j}$ in $\mathbf{W}$, and use its k and j to provision the AR request. If more than one $w_{k,j}$ has the same smallest value, we choose the one with the smallest k to provision the request. If we cannot find a $w_{k,j} < +\infty$ in $\mathbf{W}$, the request is blocked.

2) Least Slots to Reserve (LSR): The LSR strategy aims to serve an AR request with the least spectrum slots, as long as its maximum initial-delay $d_{\max}$ permits. If the AR request can be provisioned over the k-th path candidate (i.e., $R_{s,d,k}$) from the j-th start time, we assign $w_{k,j} = N_k \cdot hops(R_{s,d,k})$, where N_k is the number of subcarrier slots we need to allocate for this request if the routing path is $R_{s,d,k}$ (calculated with (2)). Otherwise, we assign $w_{k,j} = +\infty$. Then, we find the smallest $w_{k,j}$ in $\mathbf{W}$, and use its k and j to provision the AR request. If more than one $w_{k,j}$ has the same smallest value, we choose the one with the smallest j to provision the request. If we cannot find a $w_{k,j} < +\infty$ in $\mathbf{W}$, the request is blocked.

3) Least Spectrum to Reserve and Load Balancing (LSRALB): For the LSRaLB strategy, if the AR request can be provisioned over the k-th path candidate (i.e., $R_{s,d,k}$) from the j-th start time, we assign $w_{k,j} = N_k \cdot hops(R_{s,d,k}) + bw(t_j)/B$, where $bw(t_j)$ returns the number of used subcarrier slots over $R_{s,d,k}$ at the j-th start time t_j, and B is the total number of subcarrier slots on each fiber link. After determining $\mathbf{W}$, the rest procedures of LSRaLB are the same as those of LSR.

C. Overall Algorithm

Algorithm 1 illustrates the detailed procedures of the proposed dynamic service provisioning algorithm for serving AR requests in EONs.

Algorithm 1 Dynamic Service Provisioning Algorithms for Serving AR Requests in EONs

Phase I: Network Initialization

for all s–d pairs in $G(V, E)$, $s, d \in V$ **do**

calculate all feasible routing paths;

record the paths in $\mathfrak{R}_{s,d}$;

end for

Phase II: Dynamic Network Operation

while the network is operational **do**

restore network resources used by expired requests;

get parameters of $LR(s, d, C, t_a, d_{\max}, \Delta t)$;

8: determine valid start time $\{t_j\}$ based on t_a and $d_{\max}$;

9: **for** all valid start time t_j **do**

10: choose K routing path candidates from $\mathfrak{R}_{s,d}$ based on the path selection policy;

11: **for** the K path candidates $\{R_{s,d,k}\}$ **do**

12: determine the highest modulation level M_k it can support based on its transmission distance;

13: determine the number of subcarrier slots N_k to allocate based on C and M_k;

14: check whether there is N_k available contiguous slots on $R_{s,d,k}$ for service window $[t_j, t_j + \Delta t]$;

15: **if** the slots exist **then**

16: set the value of $w_{k,j}$ based on the request scheduling strategy;

17: **else**

18: set $w_{k,j} = +\infty$;

19: **end if**

20: **end for**

21: **end for**

22: **if** all $w_{k,j}$ in $\mathbf{W}$ are $+\infty$ **then**

23: mark the request as blocked;

24: **else**

25: select k and j based on $\mathbf{W}$ and the request scheduling strategy;

26: reserve slots along $R_{s,d,k}$ for reservation window $[t_a, t_j + \Delta t]$;

27: schedule to serve the request from t_j;

28: **end if**

29: **end while**

D. *Complexity Analysis*

The computational complexity of provisioning an AR request $LR(s, d, C, t_i, d_{\max}, \Delta t)$ can be derived from the procedures of *Algorithm* 1. The complexity of routing path selection (Line 10) is $O(|\mathfrak{R}_{s,d}|)$, where $\mathfrak{R}_{s,d}$ is the set of all feasible loopless routing paths in $G(V, E)$ from s to d. In the worst case, the complexity of modulation and spectrum assignments (Lines 12–14) is $O(B - (\lceil C/4C_{slot} \rceil + N_g))$, when the modulation-level is 4. Hence, in the worst case, the complexity of Lines 9–21 is $O(T \cdot (|\mathfrak{R}_{s,d}| + K \cdot (B - (\lceil C/4C_{slot} \rceil + N_g) + 1)))$, where T is the number of t_s that t_a and $d_{\max}$ permit. The worst case complexity of Lines 22–28 is $O(T \cdot K)$. Therefore, the computational complexity of provisioning an AR request is $O(T \cdot (|\mathfrak{R}_{s,d}| + K \cdot (B - (\lceil C/4C_{slot} \rceil + N_g) + 2)))$.

If we are using the SPF path selection policy, *Algorithm* 1 can be further optimized by pulling Line 10 out of the loop and putting it after Line 8, since the path selection results are the same for all valid start time. Then, the computational complexity is $O(|\mathfrak{R}_{s,d}| + T \cdot K \cdot (B - (\lceil C/4C_{slot} \rceil + N_g) + 2))$.

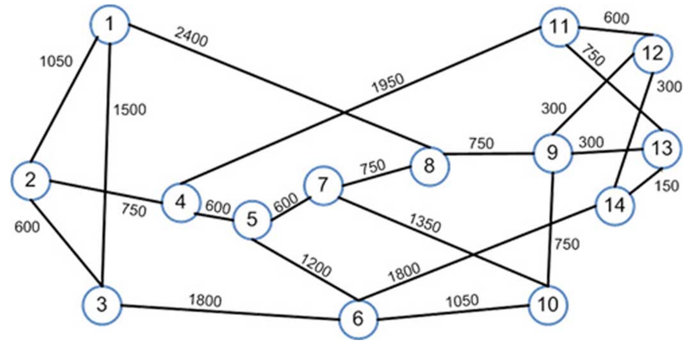

Fig. 2. NSFNET topology with fiber lengths in kilometers marked on links.

TABLE I
SIMULATION PARAMETERS.

B, number of subcarrier slots per link	358
C_{slot}, bandwidth of a frequency slot	12.5 Gb/s
N_g, number of slots for guard-band per request	1
Transmission reach of BPSK ($M = 1$)	5,000 km
Transmission reach of QPSK ($M = 2$)	2,500 km
Transmission reach of 8-QAM ($M = 3$)	1,250 km
Transmission reach of 16-QAM ($M = 4$)	625 km
K, number of path candidates for scheduling	5
d_{max}, maximum initial-delay	[3,9], [9,15], [3,15]
Average service duration Δt	20
Range of requested capacity (C)	12.5 - 200 Gb/s
η_{BPSK}, spectrum efficiency of BPSK	1 $bits/s/Hz$

IV. PERFORMANCE EVALUATION

In this section, we evaluate the performance of the proposed dynamic service provisioning algorithms with simulations using the 14-node NSFNET topology shown in Fig. 2, and Table I summarizes the simulation parameters.

A. *Simulation Setup*

We assume that the bandwidth of a subcarrier slot is 12.5 GHz, which is a typical value in O-OFDM networks. If the network is deployed in the C-Band, each fiber link has ~ 4.475 THz bandwidth to allocate, which corresponds to 358 subcarrier slots. We also assume that the spectrum efficiency of BPSK is $\eta_{BPSK} = 1$ bits/s/Hz, and hence C_{slot} is 12.5 Gb/s. We set the transmission reach for BPSK, QPSK, 8-QAM, and 16-QAM signals as 5000 km, 2500 km, 1250 km and 625 km,respectively, according to the experimental results in [3]. In the simulations, we create all requests as AR requests. The AR requests are generated using the Poisson traffic model with an average service duration Δt as 20 time-units. For each request, the s–d pair is randomly chosen, the requested capacity C is uniformly distributed within 12.5–200 Gb/s, the value of $d_{\max}$ is also randomly chosen within a range. We test three ranges for $d_{\max}$ in the simulations, i.e., $[3, 9]$, $[9, 15]$, and $[3, 15]$ time-units. We carry out all simulations in MATLAB R2011b environment on a computer with 2.94 GHz Intel Core 2 and CPU 2 GB RAM.

We evaluate the performance of the algorithms using the three metrics defined in Section II. We denote the proposed algorithms with the combination of the abbreviations of its path

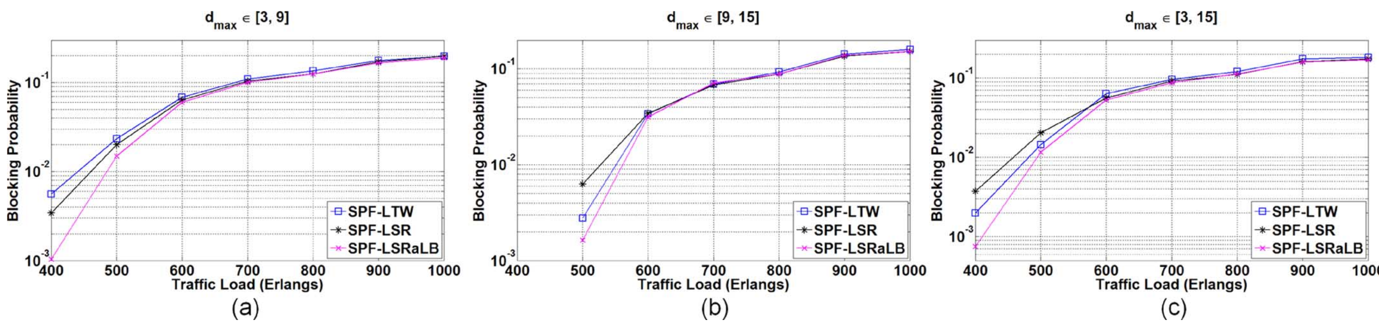

Fig. 3. Simulation results on blocking probability for the shortest path first (SPF) path selection policy with a) $d_{\max} \in [3, 9]$, b) $d_{\max} \in [9, 15]$, and c) $d_{\max} \in [3, 15]$.

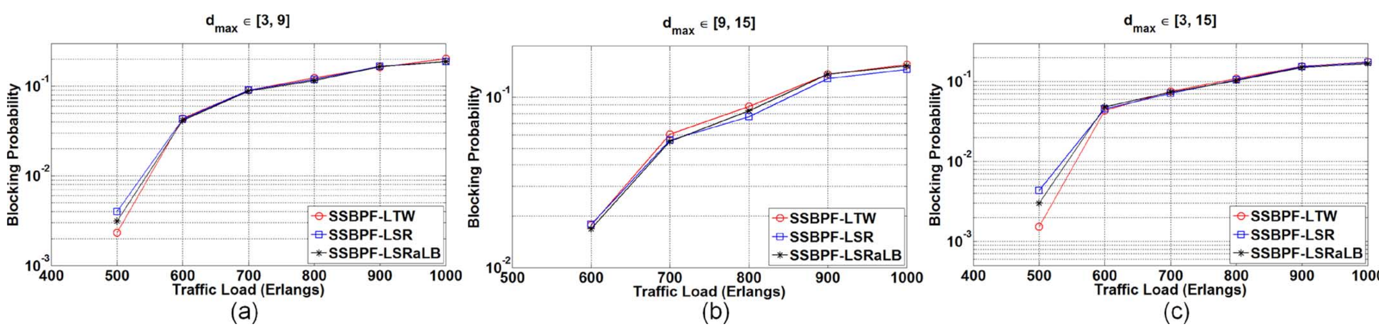

Fig. 4. Simulation results on blocking probability for the smallest slot-bandwidth product first (SSBPF) path selection policy with a) $d_{\max} \in [3, 9]$, b) $d_{\max} \in [9, 15]$, and c) $d_{\max} \in [3, 15]$.

selection policy and request scheduling strategy. For instance, SPF-LTW stands for the service provisioning algorithm that uses the "shortest path first" path selection policy and the "least time to wait" request scheduling strategy.

B. Blocking Probability

We first investigate the performance of proposed schemes in terms of blocking probability. Note that we redefine the blocking probability to consider the service durations of the requests, and therefore a lower blocking probability here means that the scheme achieves higher resource utilization in terms of the product of spectrum and time. Fig. 3 shows the results on blocking probability when the path selection policy is SPF. We observe that among the three scheduling strategies, LSRaLB achieves the lowest blocking probability. When comparing SPF-LTW with SPF-LSR, we can see that SPF-LSR achieves lower blocking probability when the maximum initial-delay $d_{\max}$ is small, i.e., $d_{\max} \in [3, 9]$ in Fig. 3(a). According to the principle of AR, we can categorize the slots used for a request along the time axis into two parts, 1) the fragmented slots that are reserved in advance for duration $[t_a, t_s]$, and 2) the contiguous slots that are provisioned to the request for duration $[t_s, t_e]$. The LTW strategy can only reduce the slots for the first part. Therefore, when $d_{\max}$ is small and the first part is not dominate, it provides higher blocking probability than the LSR strategy. In Fig. 3(b) and (c), it is interesting to observe that for $d_{\max} \in [9, 15]$ and $d_{\max} \in [3, 15]$, SPF-LTW achieves lower blocking probability when the traffic load is low (≤ 600 Erlangs). This is because that in these scenarios, the first part is dominate. However, when the traffic load keeps

TABLE II
RESULTS ON BLOCKING PROBABILITY WITH $d_{\max} \in [3, 15]$.

Traffic Load (Erlangs)	Blocking Probability (%)					
	LTW		LSR		LSRaLB	
	SPF	SSBPF	SPF	SSBPF	SPF	SSBPF
500	1.45	0.15	2.04	0.43	1.17	0.30
600	6.37	4.37	5.62	4.53	5.27	4.81
700	9.64	7.52	9.14	7.09	8.70	7.37
800	12.05	10.88	11.13	10.45	11.31	10.30
900	17.33	15.59	16.03	15.36	15.90	15.06
1000	18.24	17.57	17.38	17.45	17.03	16.75

increasing, the overall initial-delay of all requests increases and the advantage from reducing the slots in the first part decreases. Therefore, in Fig. 3(b) and (c), the blocking probabilities of SPF-LTW are higher than those of SPF-LSR when the traffic load is 700 Erlangs or higher.

Fig. 4 shows the results when the path selection policy is SSBPF. The results suggest that the three strategies achieve almost the same blocking probability performance. This is because that SSBPF has considered bandwidth utilization and spectrum efficiency in the path selection stage already and this compensates the differences among the scheduling strategies. Table II compares the blocking probabilities from SPF and SSBPF when $d_{\max} \in [3, 15]$. It can be seen that the schemes with SSBPF outperform those with SPF in terms of blocking probability, while the relative difference decreases when the traffic load increases. The results in Figs. 3 and 4 also suggest that the blocking probability of AR provisioning is lower when the requests allow larger maximum initial-delay.

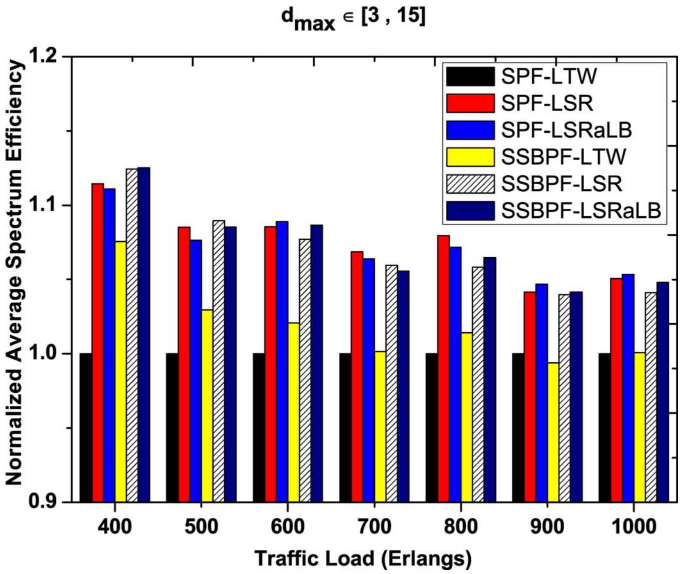

Fig. 5. Simulation results on normalized average spectrum efficiency when $d_{\max} \in [3, 15]$.

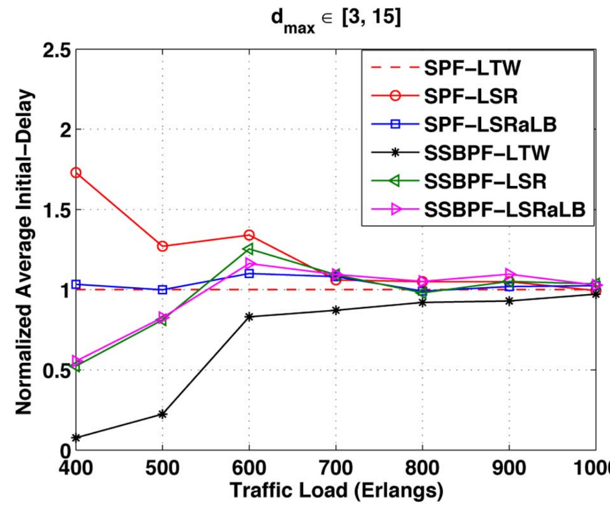

Fig. 6. Simulation results on normalized average initial-delay when $d_{\max} \in [3, 15]$.

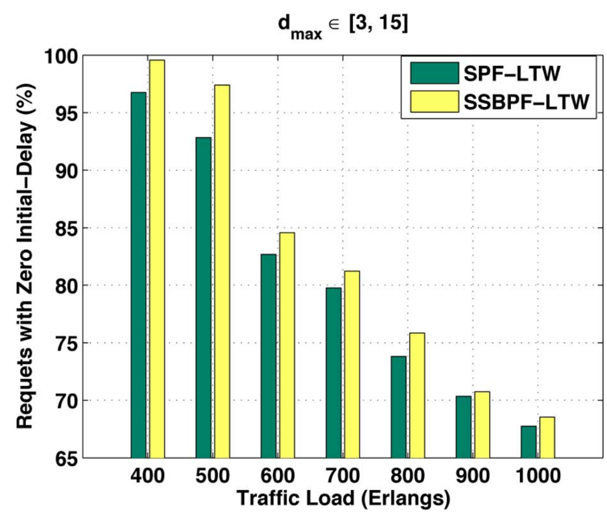

Fig. 7. Percentage of requests served with zero initial-delay from SPF-LTW and SSBPF-LTW when $d_{\max} \in [3, 15]$.

C. Average Spectrum Efficiency

Fig. 5 illustrates the simulation results on average spectrum efficiency when $d_{\max} \in [3, 15]$. Since the results on average spectrum efficiency follow the similar trend for $d_{\max} \in [3, 9]$, $d_{\max} \in [9, 15]$, and $d_{\max} \in [3, 15]$, we only plot those for $d_{\max} \in [3, 15]$ here. In order to present the results in an illustrative way, we normalize the results according to those from the SPF-LTW scheme.

The average spectrum efficiency from schemes using the LSR or LSRaLB scheduling strategy is higher than that from those using LTW. This is because that both LSR and LSRaLB optimize the AR request scheduling with the consideration of spectrum efficiency. The results also indicate that the schemes with SSBPF achieve higher spectrum efficiency than those with SPF when the traffic load is 500 Erlangs or less. However, when the traffic keeps increasing, the situation is reversed. When the network is relatively empty, SSBPF tends to select paths with higher spectrum efficiency since it considers N_{unit} in (6), which is directly related to spectrum efficiency. As the network becomes more crowded, SSBFP may select routing paths with low spectrum efficiency for the purpose of load-balancing. Therefore, the average spectrum efficiency from SSBFP can be lower than those from SPF. Meanwhile, SSBFP manages to accommodate more requests in the network and trades spectrum efficiency for blocking probability.

D. Average Initial-Delay

Fig. 6 shows the simulation results on average initial-delay when $d_{\max} \in [3, 15]$. Since the results follow the similar trend for $d_{\max} \in [3, 9]$, $d_{\max} \in [9, 15]$, and $d_{\max} \in [3, 15]$, we only plot those for $d_{\max} \in [3, 15]$ here. We also normalize the results according to those from the SPF-LTW scheme. As expected, we can see that the LTW strategy provides the smallest average initial-delay among the three scheduling strategies. For the schemes using LTW, SSBPF-LTW achieves smaller average initial-delay. Fig. 7 plots the percentage of AR requests that are provisioned with zero initial-delay from SPF-LTW and SSBPF-LTW. It can be seen that with SSBPF-LTW, more AR requests can be provisioned with zero initial-delay. It is interesting to notice that compared with SPF-LSR, SPF-LSRaLB can achieve smaller average initial-delay for all traffic cases. This is because that SPF-LSRaLB considers load-balancing, which reduces local congestion in the time domain and consequently makes more requests be served immediately. The results in Fig. 6 also suggest that for high traffic loads (≥ 800 Erlangs), the values of average initial-delay from different provisioning schemes do not have significant difference.

E. Discussions

The performance evaluations above indicate that the SSBPF policy achieves better performance than SPF, in terms of blocking probability and average initial-delay. However, the computational complexity of SPF is much lower than that of SSBPF, since SPF is a static path selection policy and needs only be executed once for each s–d pair. To this end, we should choose SPF as the path selection policy if there is a strict system constraint on computational complexity. Among the three provisioning schemes that use SPF, the SPF-LSRaLB is a promising candidate, since it can provide the lowest blocking probability to maximize the revenue of service provisioning. Meanwhile, even though the average initial-delay from SPF-LSRaLB is larger than that from SPF-LTW, the actual values are very close and the deviation is less than 10%. Therefore, SPF-LSRaLB achieves the best tradeoff between blocking probability and average initial-delay. On the other hand, when computational complexity is not an issue, we can use the SSBPF policy to further reduce the blocking probability. Since the blocking probabilities from the three schemes that use SSBPF have no significant difference, we can only consider their performance on average initial delay. Therefore, we suggest to choose SSBPF-LTW, since it provides the smallest average initial-delay.

V. Conclusion

We studied dynamic service provisioning of AR requests in EONs, and proposed several algorithms that combined request scheduling with routing, modulation and spectrum assignment (RMSA). With the combination of a routing path selection policy and a request scheduling strategy, the algorithm constructs a weight matrix for each pending AR request and provisions the request with it. We performed numerical simulations to evaluate the algorithms' performance in terms of three metrics, i.e., blocking probability, average spectrum efficiency, and average initial-delay. Simulation results showed that the smallest slot-bandwidth product first (SSBPF) routing path selection policy could achieve lower blocking probability than the shortest path first selection (SPF) policy. Based on the simulation results and computational complexity analysis, we provided suggestions on how to choose routing path selection policy and request scheduling strategy for provisioning AR requests dynamically in EONs.

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