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Static Routing and Spectrum Assignment for Deadline-Driven Bulk-Data Transfer in Elastic Optical Networks

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ABSTRACT Inter-datacenter services such as data replication and virtual machine migration contribute significantly to the underlying network traffic. These bulk-data transfer services can tolerate certain delay if the completion time is guaranteed with a pre-defined deadline. In this paper, we propose joint frequency- and time-domain optimization algorithms of static routing and spectrum assignment (RSA) for these deadline-driven bulk-data transfer requests in elastic optical networks. We formulate the problem as an integer linear program (ILP) and then propose six scheduling schemes, which combine three request ordering strategies with two RSA algorithms. Simulation results show that compared with ILP, our schemes can achieve the same performance in terms of spectrum utilization with efficient time complexity. Furthermore, based on the numerical results and computational efficiency, we provide a guideline on choosing scheduling schemes.

INDEX TERMS Bulk-data transfer, elastic optical networks (EONs), integer linear program (ILP), routing and spectrum assignment (RSA).

I. INTRODUCTION

Novel inter-datacenter bulk-data transfer services in cloud computing platforms such as user data replication, application data synchronization and virtual machine (VM) migration, are making significant contributions to the network traffic and driving the improvement of the underlying optical network [1], [2]. These bulk-data transfer services always occupy a long transmission time and a number of network bandwidth resources. Different from immediate reservation services, they are not latency-sensitive and allow a certain initial delay as long as tasks are finished before a preset deadline. Introduction of time domain extends the dimension of network resource allocation and enables scheduling for services.

Elastic optical network (EON), which can be empowered by the optical orthogonal frequency-division multiplexing (O-OFDM) technology [3], is becoming a promising underlying network due to its operations at heterogeneous line rates by allocating spectrum resources in a flexible and dynamic manner. In such network, the optical spectrum is further divided into a number of narrow spectrum segments, leading to flexible subcarrier operations for operators [4]–[10]. In order to accommodate terabit-scale bulk-data traffic in the cloud era efficiently, we expect that future EONs can support deadline-driven services and complete effective routing and spectrum assignment (RSA) with consideration of both frequency and time domains.

In order to decrease the operational/control cost introduced by RSA reconfigurations and ensure the completeness of data transmission, assume that 1) deadline-driven requests can only be scheduled once; 2) deadline-driven requests are provisioned completely or blocked, which means that partial data volume transmission is not allowed. Our previous work proposed time spectrum consecutiveness (TSC) to describe the status of spectrum fragments [11]. Based on TSC, heuristic algorithms were designed to evaluate the blocking probability and initial-latency (delay) [12], [13] in dynamic provisioning. However, in a real data center (e.g., Googles datacenter), bulk-data transfer requests are known to the owner. These requests can be collected and scheduled in advance, hence further studies are necessary on the static RSA problem.

In this paper, we present joint optimization of both frequency and time domains for static provisioning in EONs. We first formulate the problem mathematically as an ILP with the objective of minimizing the spectrum utilization. Then, by combining 3 request ordering strategies: i) Smallest Arrival Time First (SATF), ii) Largest Data Capacity First (LDCF), and iii) Largest Minimum Feasible Bandwidth First (LMFBF), with 2 RSA algorithms (i.e., Soonest Completion (SC), and Least Spectrum Resource Usage (LSRU)), we present 6 scheduling schemes. These schemes are evaluated in terms of spectrum usage, capacity blocking percentage (CBP), initial delay and computational efficiency. Numerical evaluations over a small-scale network as well as a large-scale network show that LSRU provides the same optimal results compared to the ILP on the small-scale network, and better performance than SC in terms of CBP on the large-scale network. Among 3 ordering strategies, LMFBF achieves the best performance in efficiently utilizing the spectrum resources. Furthermore, based on the numerical results and computational complexity analysis, we provide a guideline on choosing the optimal scheme.

The rest of the paper is organized as follows. In Section 2, a survey on related work is presented. In Section 3, we describe the joint frequency and time model. Section 4 describes the ILP formulation of the problem along with the definition of the constraints. Section 5 presents the proposed ordering strategies and RSA algorithms. In Section 6, we show the computational complexity analysis. In Section 7, numerical evaluations of the ILP and the proposed schemes as well as the guideline discussion are presented and we conclude the paper on Section 8.

II. RELATED WORK

There have been numerous research works on the RSA problem for deadline-driven bulk-data transfer requests. The majority of them consider the provisioning in WDM networks. In [14], a mixed integer linear program (ILP) model was formulated to optimize the network resource allocation. In [15], an ILP model was formulated and three heuristics were proposed for multicast deadline-driven requests to improve wavelength utilization. In [16], three heuristics for variable bandwidth advance reservation were proposed to efficiently utilize network resources. Research in [17] proposed service differentiated algorithms to improve the performance in terms of resource efficiency and network blocking. In [18], a two-phase approach for dynamic scheduling was introduced with the objective of reducing network blocking. In the latest studies, dynamic provisioning of deadline-driven requests over EON was studied. In [19], dynamic service provisioning algorithms were proposed to improve the performance in terms of blocking probability and average initial delay. Research in [20] proposed dynamic time-related heuristics to increase the spectrum efficiency. Research in [21] and [22] investigated how to recycle the spectrum fragments via enabling RSA reconfigurations to maximize transmitted data and improve the spectrum utilization. Research in [23] presented hybrid immediate reservation (IR) and advance reservation (AR) service provisioning in EONs to minimize IR/AR conflicts, which is a practical problem in the real network. Evaluated results showed the proposed algorithms achieved more performance gain from AR flexibility compared with baseline. Meanwhile, some research works investigated static provisioning. Research in [24] formulated a multi-hour routing and spectrum allocation optimization problem for time-varying traffic and solved it by both ILP model and heuristic algorithms. The proposed spectrum Expansion/Reduction showed efficient performance in spectrum allocation. However, the requirements of time-varying traffic demands are different with deadline-driven bulk-data transfer. They are predictable and periodic along some time period when deadline-driven requests specify data volume and deadline in our study. Lu *et al.* [25] presented a mixed ILP model for offline optimization with objectives of maximizing the average data-transfer percentage and minimizing the incompletable data transfers. Nevertheless, incompletable data transfer may lead to irreversible data loss, which is unacceptable for some significant data (e.g., financial/government data).

III. JOINT FREQUENCY AND TIME MODELING

A pending deadline-driven bulk-data request has the form $r(s, d, \theta, t_a, t_d)$, where (s, d) is the source-destination pair, θ is the data volume, t_a is the arrival time, and t_d is the deadline of the request. Define that Δt_m is the maximum duration time (MDT), $\Delta t_m = t_d - t_a$. t_s and t_e are the start and end time of the scheduled provisioning time window (TW) respectively. Time domain is broken down into discrete time slots (TSs), and each TS represents some unit of real time (e.g., 1 h). The minimum duration of a request is assumed to be one TS.

For a deadline-driven request r, upon arrival, routing paths are calculated between s and d for the request. After the provisioning TW $[t_s, t_e]$ is determined, data volume θ is mapped to N frequency slots (FSs) within TW $[t_s, t_e]$ as Eq. (1).

$$N = \left\lceil \frac{\theta}{C_{slot} \times (t_e - t_s)} \right\rceil + N_g \tag{1}$$

where N_g is the number of guard-band FSs, and C_{slot} denotes the capacity of each FS. The allocated spectrum must follow 2 constraints: 1) consistency constraint 2) contiguity constraint, which mean the allocation of the same continuous FSs on each fiber link along the routing path. Note that allocated TSs are also required to follow consistency and contiguity constraints. Assume that the modulation format of all the requests is BPSK. Fig. 1 shows an intuitive example of spectrum assignment. In the *frequency-time* diagram, link l is traversed by AR requests A-G in the network. For example, A is provisioned with FS 1 within serving TW [1, 3]. D is provisioned with FSs 3-5 within TW [3, 4]. All the A-G requests are allocated with consecutive TSs and consecutive FSs.

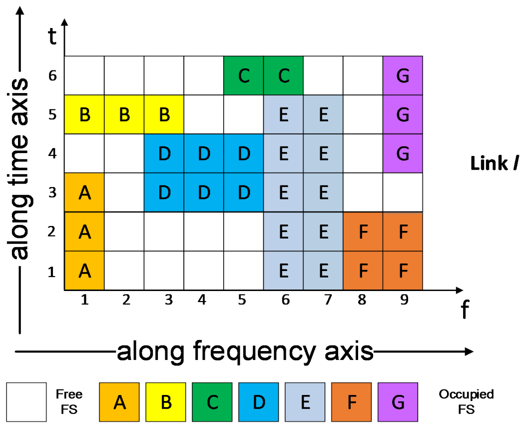

FIGURE 1. AR requests in *frequency-time* diagram.

We define Spectrum Resource Usage (SRU) U as Eq. (2). SRU considers total FSs used within TW $[t_s, t_e]$ along the routing path, and represents the spectrum resource usage of a deadline-driven request.

$$U = (t_e - t_s) \times N \times hop(r) \tag{2}$$

where $hop(r)$ is the hop number of the routing path for request r. We also define Minimum Feasible Bandwidth (MFB) M as Eq. (3). MFB indicates the minimum bandwidth requirement of the request. A large data volume or a small MDT Δt_m will lead to a large MFB.

$$M = \frac{\theta}{\Delta t_m} \tag{3}$$

IV. INTEGER LINEAR PROGRAM FORMULATION

In this section, we develop a formulation to model the problem using an ILP. Our objective is to minimize the total SRU of the network.

Input parameters:

- $\boldsymbol{V}$: the set of nodes in the network.
- $\boldsymbol{E}$: the total links in the network.
- (k, l): the link (k, l) between node k and node l ($k, l \in \boldsymbol{V}, (k, l) \in \boldsymbol{E}$).
- $\boldsymbol{R}$: the set of deadline-driven bulk-data requests.
- t_a^r, t_d^r: the arrival time and deadline of request r.
- N_g: the number of FSs in a guard-band to separate two optical paths.
- F: the maximum number of FSs on a link.
- T: the maximum number of TSs of a cycle.
- Φ: a large positive constant.

Variables:

- $X_{k,l}^{r,t,f}$: binary variable. It takes on the value of 1 if the routing path of request r uses FS f at TS t on link (k, l) and takes on the value 0 otherwise.
- $Y_{k,l}^{r,t}$: binary variable. It takes on the value of 1 if request r is provisioned at TS t on link (k, l) and takes on the value 0 otherwise.
- $Z_{k,l}^{r}$: binary variable. It takes on the value of 1 if request r is provisioned on link (k, l) and takes on the value 0 otherwise.
- $\Psi_{k,l}$: the total *SRU* on link (k, l).

Objective function: minimize the total SRU in the network

$$Minimize : \sum_{(k,l)} \Psi_{k,l} \tag{4}$$

The total SRU of the link (k, l) is denoted as follows:

$$\Psi_{k,l} = \sum_{r,t} \left(\sum_{f} X_{k,l}^{r,t,f} + Y_{k,l}^{r,t} \times N_g \right) \quad \forall (k, l) \tag{5}$$

The relationship between $X_{k,l}^{r,t,f}$ and $Y_{k,l}^{r,t}$ is described:

$$\sum_{f} X_{k,l}^{r,t,f} / \Phi \le Y_{k,l}^{r,t} \le \sum_{f} X_{k,l}^{r,t,f} \quad \forall (k, l), t, r \tag{6}$$

Constraint (6) sets the value of $Y_{k,l}^{r,t}$. The value is 1 if at least one FS at TS t is used by link (k, l).

The relationship between $X_{k,l}^{r,t,f}$ and $Z_{k,l}^{r}$ is described:

$$\sum_{t,f} X_{k,l}^{r,t,f} / \Phi \le Z_{k,l}^{r} \le \sum_{t,f} X_{k,l}^{r,t,f} \quad \forall (k, l), r \tag{7}$$

Constraint (7) uses the same method of (6) to set the value of $Z_{k,l}^{r}$.

Flow conservation constraint:

$$\sum_{t,f} \sum_{k} X_{k,d}^{r,t,f} - \sum_{t,f} \sum_{k'} X_{d,k'}^{r,t,f} \ge \theta \quad \forall r \tag{8}$$

$$\sum_{k,l} X_{k,l}^{r,t,f} - \sum_{l',k} X_{l',k}^{r,t,f} = 0 \quad k \notin \{s, d\}\, \forall r, t, f \tag{9}$$

Constraint (8) ensures the provisioned spectrum volume is larger than the required data volume at the destination. Constraint (9) is used to keep the flow conservation at nodes except source and destination. Meanwhile, it ensures the spectrum and time consistency.

Single route constraint:

$$\sum_{k,l} Z_{k,l}^{r} = 1 \quad \forall r, l = d \tag{10}$$

FS clash constraint:

$$\sum_{r} X_{k,l}^{r,t,f} \le 1 \quad \forall (k, l), f, t \tag{11}$$

Provisioning TW constraint:

$$\sum_{t \in [t_d^r + 1, T]} X_{k,l}^{r,t,f} = 0 \quad \forall (k, l), r, f \tag{12}$$

$$\sum_{t \in [1, t_a^r]} X_{k,l}^{r,t,f} = 0 \quad \forall (k, l), r, f \tag{13}$$

Constraint (12) and (13) ensure the provisioning time window is between t_a^r and t_d^r.

Time and spectrum continuity constraints ($\forall r, f, t, (k, l)$):

$$\sum_{f' \in [f+1, F]} X_{k,l}^{r,t,f'} \le (X_{k,l}^{r,t,f} - X_{k,l}^{r,t,f+1} - 1) * (-\Phi) \tag{14}$$

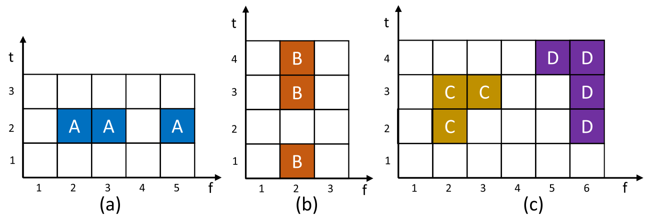

FIGURE 2. 3 unconstrained examples.

$$\sum_{t' \in [t+1,T],f} X_{k,l}^{r,t',f} \leq (X_{k,l}^{r,t,f} - X_{k,l}^{r,t+1,f} - 1) * (-\Phi) \quad (15)$$

$$\sum_{t' \in [1,t],f} X_{k,l}^{r,t',f} \leq (X_{k,l}^{r,t,f} - X_{k,l}^{r,t+1,f} + 1) * \Phi \quad (16)$$

Constraint (14) is used to ensure the continuity in the frequency domain, eliminating the case of request A in Fig. 2(a). Constraint (15) keeps the time continuity to avoid the case in Fig. 2(b). However, only (14) and (15) can not guarantee the joint continuity since they are independent in different domains. Fig. 2(c) illustrates two cases which are not constrained. In order to keep the joint continuity of both frequency and time domain, constraint (16) is introduced. Constraints (14)-(16) guarantee that the assigned FSs are contiguous. The lower bound for Φ is equal to the value $T * F$.

V. SCHEDULING SCHEMES

Since ILP model is not computationally efficient for large-scale networks, we rely on sub-optimal algorithms to obtain practical solutions within reasonable time-scale. Considering that in static scenario, all the requests with their attributes are known in advance, we propose 3 ordering strategies:

A. ORDERING STRATEGIES

1) SMALLEST ARRIVAL TIME FIRST (SATF)

In this strategy, pending requests are under the ascending order of t_a. The request with the smallest arrival time will be selected first.

2) LARGEST DATA CAPACITY FIRST (LDCF)

This strategy considers the data volume θ of the request. Requests are with the descending order of θ. The one with the largest data volume will be served first.

3) LARGEST MFB FIRST (LMFBF)

In this method, requests are selected according to the descending order of the MFB value.

We give an intuitive example to explain 3 ordering strategies. For example, we have 3 deadline-driven requests, i.e., $A(s_A, d_A, 100, 10, 20)$, $B(s_B, d_B, 200, 20, 60)$, and $C(s_C, d_C, 300, 30, 50)$. Following SATF strategy, the order is $\{A, B, C\}$ because $t_a^A (= 10) < t_a^B (= 20) < t_a^C (= 30)$. With LDCF stategy, we have the order $\{C, B, A\}$ because $300 > 200 > 100$. While with LMFBF, MFB values of request A-C are 10, 5, 15, respectively, thus the order of LMFBF is $\{C, A, B\}$.

B. RSA ALGORITHMS

We propose 2 algorithms to implement RSA. The routing path and spectrum allocation are based on one of the following 2 algorithms.

1) SC (SOONEST COMPLETION)

For a deadline-driven request, if the service provisioning process is completed as soon as possible, as long as the deadline permits, more available FSs can be provisioned for the following requests. In light of this, SC algorithm is proposed. For each request, we search for a routing path from the K shortest routing path set, and select the suitable FSs that can minimize the t_e. The SC algorithm is described in Algorithm 1.

Algorithm 1 Soonest Completion

Input: Deadline-driven request r
Output: allocated FSs and TW $[t_s, t_e]$
use KSP algorithm to calculate feasible routing paths for each r;
foreach *candidate path* **do**
  for *starting time* $t_s = t_a$ *to* t_d **do**
    for *duration time* $\Delta t = 1$ *to* $t_d - t_s$ **do**
      calculate the number of required FSs with Eq. (1);
      search for B as candidate which can accommodate the request from t_s to $t_s + \Delta t$;
      if *B exits* **then**
        record the end time in candidate set $\mathbf{t_e} = \{t_e^1, ..., t_e^i\}$;
        break;
      end
    end
  end
end
if $\mathbf{t_e} = \emptyset$ **then**
  mark the request as blocked;
else
  select the end time $t_e = min\{t_e^i\}$; reserve the corresponding available consecutive FSs within TW $[t_s, t_e]$;
end

2) LSRU (LEAST SPECTRUM RESOURCE USAGE)

In order to reduce global SRU in the network, we propose LSRU algorithm. For each deadline-driven request, we search for a routing path from the K shortest routing path set, select the FSs, and calculate SRU with Eq. (2). TW $[t_s, t_e]$ and the corresponding number of FSs N which achieve the least SRU are selected. Algorithm 2 illustrates the detailed procedures.

VI. COMPLEXITY ANALYSIS

Note that in order to reduce the computational complexity, the candidate routing paths of all source-destination pairs can

Algorithm 2 Least Spectrum Resource Usage

```
   Input: Deadline-driven request r
   Output: allocated FSs and TW [t_s, t_e]
1  use KSP algorithm to calculate feasible routing paths for
   each r;
2  foreach candidate path do
3      calculate the hop count of the routing path hop(r);
4      for starting time t_s = t_a to t_d do
5          for duration time Δt = 1 to t_d − t_s do
6              calculate the number of required FSs with
               Eq. (1);
7              search for B as candidate which can
               accommodate the request from t_s to t_s + Δt;
8              if B exits then
9                  calculate the SRU with Eq. (2), and
                   record it in candidate set
                   U = {U^1, ..., U^i};
10             end
11         end
12     end
13 end
14 if U = Ø then
15     mark the request as blocked;
16 else
17     select the SRU U = min{U^i}; reserve the
       corresponding available consecutive FSs within TW
       [t_s, t_e];
18 end
```

be pre-calculated with K Shortest Path (KSP) algorithm once network is initiated. For each request $r(s, d, \theta, t_a, t_d)$ in SC, the worst case computational complexity of scheduling and allocating spectrum resources (Line 2-18) is $O(K * T^2 * F * |E|)$, where T and F denote the allowed maximum number of provisioned TSs and FSs, respectively, and $|E|$ represents the number of total links. Similarly, we can calculate the computational complexity of LSRU in the worst case is the same as SC. Nevertheless, in the average case, complexity of SC is lower than that of LSRU because SC stops the loop once a feasible solution is found as in Line 9.

VII. SIMULATION RESULTS AND DISCUSSIONS

In this section, we evaluate the performance of the proposed scheduling schemes in small-scale (6-node) and large-scale (NSFNet) networks, respectively. Routing paths are calculated with $K = 3$ in KSP for the proposed schemes. The number of guard-band FSs is set to $N_g = 1$, and each FS is assumed to have a granularity of 12.5 GHz. We denote the proposed scheduling schemes with abbreviations, which combine the ordering strategies and RSA algorithms. For instance, LDCF-SC represents the scheduling scheme that uses the LDCF ordering strategy and the SC RSA algorithm. Each simulation runs 10 times and data points represent the average value.

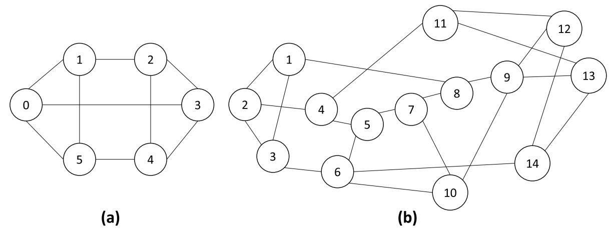

FIGURE 3. (a) 6-node network (b) NSFNet.

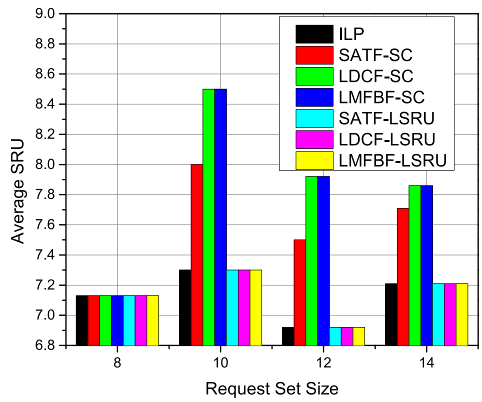

FIGURE 4. Average SRU (6-node network).

A. SMALL-SCALE NETWORK

Due to the complexity of solving ILP, we have to run it over small-scale networks. To compare the performance between the ILP model and the scheduling schemes, we evaluate them on a 6-node network as shown in Fig. 3(a). The ILP model is solved by CPLEX V12.2 on an IBM x3650 M2 server with 2.266 GHz Intel Xeon processor and 24 GB RAM. We run the ILP for a maximum of 12-h each run. We assume 30 FSs for each fiber, uniform distribution to choose the (s, d) pair of each request, and (2-10 GB) data transfer volume. Arrival time of requests are generated using the rules of Poisson model with an average MDT of 3 TSs. We evaluate the performance of the ILP and the proposed schemes in terms of average SRU and runtime. Average SRU is the ratio of the sum of SRU of all the provisioned requests over the total number of requests.

Fig. 4 shows the results of average SRU. It is observed that the schemes with LSRU are able to achieve the same optimal performance as the ILP, while those with SC achieve higher average SRU. The results indicate that the LSRU schemes perform well in terms of average SRU in the small-scale network. This is because LSRU aims at minimizing global SRU. Especially when the request set size is at a small value, there are enough available spectrum resources for pending requests. Fig. 5 illustrates runtimes of the ILP and the schemes. As expected, the runtime of ILP grows rapidly as the request set size increases. This shows that the ILP is not practical. In contrast, the proposed schemes have sub-second runtimes. Results indicate that the computational efficiency of scheduling schemes are far better than the ILP model.

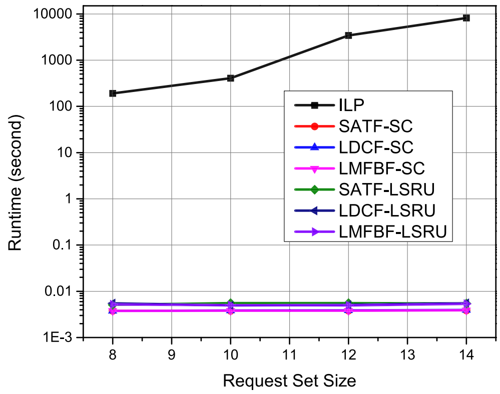

FIGURE 5. Average runtimes (6-node network).

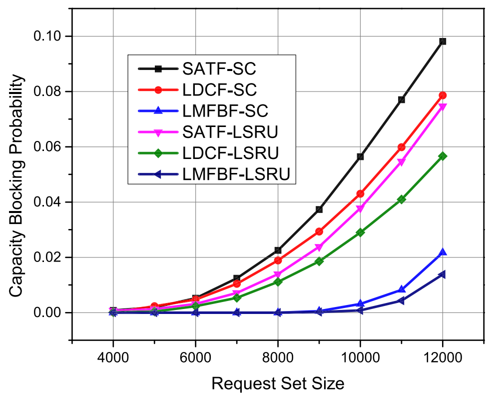

FIGURE 6. CBP of the proposed schemes.

B. LARGE-SCALE NETWORK

To address the scalability and efficiency, we use a realistic-size network to evaluate the proposed schemes. The NSFNet (14 nodes), as shown in Fig. 3(b), is used as the simulation topology, with the assumption that the network is deployed in the C-Band. Each fiber link has 4.475 THz bandwidth to allocate, which corresponds to 358 subcarrier slots. In the simulation, we use uniform distribution for the data volume (15-50 GB) and the average MDT (60 TSs).

Fig. 6 shows the results on CBP of the proposed schemes. Here we define CBP as the ratio of the data volume of the blocked requests over that of total requests. The results show that with the same ordering strategy, LSRU achieves lower CBP than SC. It means compared to SC scheme, LSRU is able to utilize spectrum more effectively. This is because LSRU considers the global spectrum resource allocation incorporating the hop number of the routing path. Furthermore, SATF, as the baseline ordering strategy, achieves the highest CBP. This is intuitive to understand because SATF only considers arrival time of each request. When comparing LDCF with LMFBF, we can see that LMFBF outperforms LDCF in terms of CBP, and the difference of CBP increases with the request set size increasing. This is because when provisioning a pending request, time is the factor which has an significant impact on CBP besides data volume.

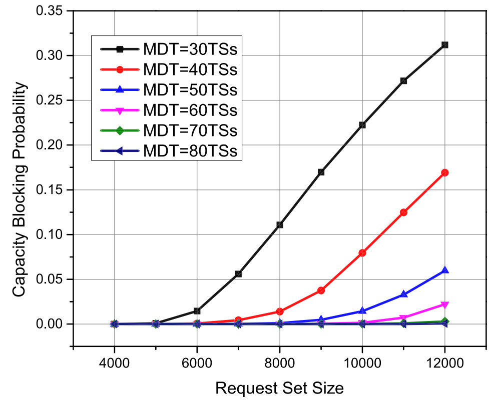

FIGURE 7. CBP of LMFBF-LSRU with different MDT.

Our proposed metric MFB, calculated according to both time and data volume, represents the relationship between spectrum requirement and initial delay tolerance of a deadline-driven request. A large data volume or a small value of MDT will lead to a large MFB value. In LMFBF, we select requests according to the descending order of MFB, so requests with lower spectrum requirement and higher initial delay tolerance are at the rear of the request queue. Therefore, LMFBF achieves a lower CBP compared with LDCF and SAFT schemes. Moreover, we see the differences of the 6 schemes are not significant when request set size is at a small value (e.g., 4000), and it increases as the request set size ascends. The reason is that when the request set size is at a small value, the available spectrum resources are sufficient for pending requests. Scheduling schemes can provision the requests soon, thus the ordering strategies slightly impact the results. In contrast, ordering strategies have a more heavy impact on the results at a large request set size (e.g., 12000).

Table 1 shows the average MFB and average data volume of blocked requests for the proposed schemes. To make the scheme's name clean, the table illustrates abbreviations with first one or two letters. For example, SA-S represents SATF-SC scheme. From the table, it is observed that LMFBF achieves the lowest average MFB of the blocked requests, which is as expected because LMFBF sorts requests according to the descending order of MFB. Meanwhile, LMFBF achieves the lowest average data volume of blocked requests among the proposed schemes. This can be explained that although LDCF is with the descending order of θ, request with a large data volume can be blocked due to its low MDT. In contrast, LMFBF considers joint frequency and time domain. Note that there are sufficient spectrum resources for requests at the front of the request queue while requests at the rear are delay-tolerant. Hence, LMFBF can efficiently utilize the spectrum resources.

Fig. 7 depicts the simulation results of CBP with different average MDT (30-80 TSs) in LMFBF-LSRU scheme. Since the results in other proposed schemes follow the same trend, we only plot those for LMFBF-LSRU. It is observed that with the same request set size, a larger duration time achieves

TABLE 1. Average data capacity and MFB of blocked requests for 6 scheduling schemes.

Request Set Size	Average MFB of Blocked Requests(GB/TS)						Average Data Capacity of Blocked Requests(GB)					
	SA-S	LD-S	LM-S	SA-L	LD-L	LM-L	SA-S	LD-S	LM-S	SA-L	LD-L	LM-L
4000	25.7	14	0	29.6	14	0	34.3	14	0	44.5	14	0
5000	21.1	2.1	0	23.7	2.6	0	37.1	17.3	0	31.6	15.0	0
6000	11.2	1.4	0	13	1.5	0	31.8	17.4	0	32.6	17.2	0
7000	7.5	1.2	0	7.6	1.2	0	30.7	18.5	0	31	17.	0
8000	5.8	1.1	0	5.6	1.1	0	30.7	19.7	0	31.1	19.0	0
9000	4.6	1	0.2	4.2	0.9	0.2	31.2	20.2	15.1	31.4	19.3	15.7
10000	3.7	0.9	0.2	3.7	0.9	0.2	31.7	21	16.9	31.8	20.2	16.4
11000	3.1	0.8	0.2	3.1	0.8	0.2	31.6	21.4	18.5	31.7	20.6	18.6
12000	2.625	0.7	0.2	2.7	0.7	0.2	32.0	21.8	19.7	32.1	21.1	19.5

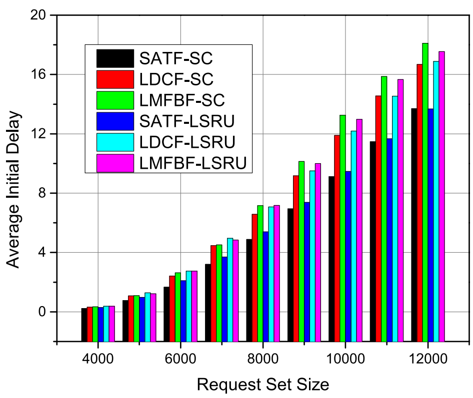

FIGURE 8. Average initial delay of the proposed schemes.

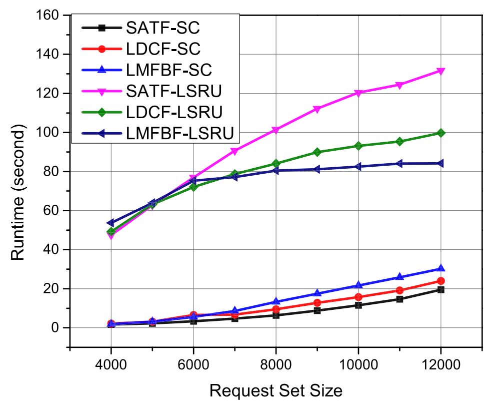

FIGURE 9. Average runtimes of the proposed schemes.

a smaller value of CBP. This is because that a large duration time can provide more delay tolerance and decrease the bandwidth requirement of the request. Meanwhile, when the duration time is large enough (e.g., $\geq$70 TSs), CBP is close to 0.

Fig. 8 illustrates the average initial delay of the proposed schemes. We observe that considering the same RSA algorithm, both LDCF and LMFBF achieve larger average initial delay than SATF. This can be explained that compared to SATF, LDCF and LMFBF first provision requests with a larger MFB and data volume, respectively. These requests occupy more FSs, which results in that more pending requests will be delayed. Meanwhile, requests at the rear of the ordered queue are delay-tolerant. LDCF and LMFBF increase the average initial delay, however, improve the blocking probability as a trade-off.

Fig. 9 illustrates the average runtimes of the proposed scheduling schemes. From the figure, runtime in LSRU is at least 50s less than in SC. The results verify the analysis that average computational complexity of SC is lower than LSRU.

C. DISCUSSION

The performance evaluations show that in small-scale networks, LSRU can achieve the same optimal average SRU as ILP and lower runtime than ILP. In large-scale networks, LSRU achieves better performance in terms of CBP than SC considering the same ordering strategy at a large request size set (e.g., $\geq$ 6000), and LMFBF is the best ordering strategy among 3 strategies for efficient spectrum utilization. In contrast, the average computational complexity of SC is lower than that of LSRU. To this end, if the request set size is small (e.g. $\leq$ 4000), LMFBF-SC can be selected as the scheduling scheme to save the computational time. Otherwise, LMFBF-LSRU is a better choice because of the efficient spectrum utilization.

VIII. CONCLUSION

In this paper, we studied the static service provisioning of deadline-driven bulk-data requests in EONs and presented a joint frequency and time optimization. We formulated it as an ILP model, proposed 6 scheduling schemes combined ordering strategies with RSA algorithms for each strategy. Numerical simulations were performed to evaluate the ILP model and the scheduling schemes in order to decrease blocking probability and enhance spectrum utilization. Simulation results showed that LSRU schemes could achieve the same optimal results as the ILP model in a small-scale network, and consume much less computational time than the ILP. In the realistic network, LMFBF led to better performance in terms of CBP compared to both SATF and LDCF due to the joint frequency and time domain optimization. Based on the simulation results and complexity analysis, LMFBF-SC should be selected for a small set of requests to reduce the computational time. When the request set size is large and computational efficiency is not an issue, we can use LMFBF-LSRU to improve the spectrum utilization.

REFERENCES

[1] M. D. Dikaiakos, D. Katsaros, P. Mehra, G. Pallis, and A. Vakali, "Cloud computing: Distributed Internet computing for IT and scientific research," *IEEE Internet Comput.*, vol. 13, no. 5, pp. 10–13, Sep./Oct. 2009.

[2] A. Greenberg, J. Hamilton, D. A. Maltz, and P. Patel, "The cost of a cloud: Research problems in data center networks," *ACM SIGCOMM Comput. Commun. Rev.*, vol. 39, no. 1, pp. 68–73, 2009.

[3] J. Armstrong, "OFDM for optical communications," *J. Lightw. Technol.*, vol. 27, no. 3, pp. 189–204, Feb. 1, 2009.

[4] M. Jinno, H. Takara, B. Kozicki, Y. Tsukishima, Y. Sone, and S. Matsuoka, "Spectrum-efficient and scalable elastic optical path network: Architecture, benefits, and enabling technologies," *IEEE Commun. Mag.*, vol. 47, no. 11, pp. 66–73, Nov. 2009.

[5] J. Zheng and H. T. Mouftah, "Routing and wavelength assignment for advance reservation in wavelength-routed WDM optical networks," in *Proc. ICC*, 2002, pp. 2722–2726.

[6] Y. Wang, X. Cao, and Y. Pan, "A study of the routing and spectrum allocation in spectrum-sliced elastic optical path networks," in *Proc. ICC*, 2011, pp. 1503–1511.

[7] A. N. Patel, P. N. Ji, J. P. Jue, and T. Wang, "Defragmentation of transparent flexible optical WDM (FWDM) networks," in *Proc. OFC*, 2011, pp. 1–3, paper OTuI8.

[8] Y. Sone, A. Hirano, A. Kadohata, M. Jinno, and O. Ishida, "Routing and spectrum assignment algorithm maximizes spectrum utilization in optical networks," in *Proc. ECOC*, 2011, pp. 1–3, paper Mo.1.

[9] K. Christodoulopoulos, I. Tomkos, and E. A. Varvarigos, "Elastic bandwidth allocation in flexible OFDM-based optical networks," *J. Lightw. Technol.*, vol. 29, no. 9, pp. 1354–1366, May 1, 2011.

[10] N. Sambo, F. Cugini, G. Bottari, P. Iovanna, and P. Castoldi, "Distributed setup in optical networks with flexible grid," in *Proc. ECOC*, 2011, pp. 1–3, paper We.10.

[11] H. Chen *et al.*, "Time-spectrum consecutiveness based scheduling with advance reservation in elastic optical networks," *IEEE Commun. Lett.*, vol. 19, no. 1, pp. 70–73, Jan. 2015.

[12] M. Gharbaoui, I. Cerutti, B. Martini, and P. Castoldi, "An orchestrator of network and cloud resources for dynamic provisioning of mobile virtual network functions," in *Proc. NetSoft*, 2016, pp. 98–101.

[13] B. Martini, M. Gharbaoui, I. Cerutti, and P. Castoldi, "Network and datacenter resource orchestration strategies for mobile virtual networks over telco clouds," in *Proc. ICTON*, 2016, pp. 1–3.

[14] D. Andrei, M. Tornatore, M. Batayneh, C. U. Martel, and B. Mukherjee, "Provisioning of deadline-driven requests with flexible transmission rates in WDM mesh networks," *IEEE/ACM Trans. Netw.*, vol. 18, no. 2, pp. 353–366, Apr. 2010.

[15] N. Charbonneau and V. M. Vokkarane, "Static routing and wavelength assignment for multicast advance reservation in all-optical wavelength-routed WDM networks," *IEEE/ACM Trans. Netw.*, vol. 20, no. 1, pp. 1–14, Feb. 2012.

[16] A. Patel and J. Jue, "Routing and scheduling for variable bandwidth advance reservation," *IEEE/OSA J. Opt. Commun. Netw.*, vol. 3, no. 12, pp. 912–923, Dec. 2011.

[17] A. Muhammad, C. Cavdar, L. Wosinska, and R. Forchheimer, "Service differentiated provisioning in dynamic WDM networks based on set-up delay tolerance," *IEEE/OSA J. Opt. Commun. Netw.*, vol. 5, no. 11, pp. 1250–1261, Nov. 2013.

[18] L. Shen, X. Yang, A. Todimala, and B. Ramamurthy, "A two-phase approach for dynamic lightpath scheduling in WDM optical networks," in *Proc. ICC*, 2007, pp. 2412–2417.

[19] W. Lu and Z. Zhu, "Dynamic service provisioning of advance reservation requests in elastic optical networks," *J. Lightw. Technol.*, vol. 31, no. 10, pp. 1621–1627, May 15, 2013.

[20] B. H. Ramaprasad, T. Schöndienst, and V. M. Vokkarane, "Dynamic continuous and non-continuous advance reservation in SLICE networks," in *Proc. ICC*, 2014, pp. 3319–3324.

[21] W. Lu, Z. Zhu, and B. Mukherjee, "Data-oriented malleable reservation to revitalize spectrum fragments in elastic optical networks," in *Proc. OFC*, 2015, pp. 1–3, paper W1I.6.

[22] W. Lu and Z. Zhu, "Malleable reservation based bulk-data transfer to recycle spectrum fragments in elastic optical networks," *J. Lightw. Technol.*, vol. 33, no. 10, pp. 2078–2086, May 15, 2015.

[23] W. Lu, Z. Zhu, and B. Mukherjee, "On hybrid IR and AR service provisioning in elastic optical networks," *J. Lightw. Technol.*, vol. 33, no. 22, pp. 4659–4670, Nov. 15, 2015.

[24] M. Klinkowski, M. Ruiz, L. Velasco, D. Careglio, V. Lopez, and J. Comellas, "Elastic spectrum allocation for time-varying traffic in FlexGrid optical networks," *IEEE J. Sel. Areas Commun.*, vol. 31, no. 1, pp. 26–38, Jan. 2013.

[25] W. Lu, Z. Zhu, and B. Mukherjee, "Optimizing deadline-driven bulk-data transfer to revitalize spectrum fragments in EONs [invited]," *IEEE/OSA J. Opt. Commun. Netw.*, vol. 7, no. 12, pp. B173–B183, Dec. 2015.

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