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Spectrum-efficient anycast in elastic optical inter-datacenter networks ☆

Liang Zhang, Zuqing Zhu *

School of Information Science and Technology, University of Science and Technology of China, Hefei, China

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ABSTRACT

With the rapid development of cloud computing, optical inter-datacenter (inter-DC) networks have attracted intensive research attentions. Meanwhile, recent advances on the flexible-grid elastic optical networks (EONs) have demonstrated agile spectrum management in the optical layer. Therefore, we expect EONs to become a promising underlying infrastructure for optical inter-DC networks. In this paper, we investigate offline and online routing and spectrum assignment (RSA) problems for anycast requests in elastic optical inter-DC networks. For the offline problem, we formulate an integer linear programming (ILP) model and propose several heuristics based on single-DC destination selection. The optimal solutions for small-scale problems are obtained by solving the ILP, and we compare them with those from the heuristics for measuring the optimization gaps. For the online problem, we design several heuristics to consider the computing and bandwidth resources jointly for efficient service provisioning, including an algorithm that uses multi-DC destination selection. Our simulation results demonstrate that the anycast algorithm with multi-DC destination selection can fully utilize the bandwidth resources in the elastic optical inter-DC network, make computing resources become the bottleneck, and reduce the bandwidth blocking probability of anycast requests effectively.

1. Introduction

Recently, with the rapid development of new network applications, such as cloud computing and e-Science [1], inter-datacenter (DC) networks start to attract intensive interests from both academia and industry. Since the connection requests from these new applications are bandwidth-hungry and highly dynamic, inter-DC networks have exhibited the coexistence of huge peak throughput and high traffic burstiness [2]. Meanwhile, the fact that optical fibers can provide tremendous bandwidth [3] suggests that optical networks provide a viable underlying physical infrastructure for inter-DC networks [4]. More importantly, recent advances on the flexible-grid elastic optical networks (EONs) have demonstrated that with the technologies such as optical orthogonal frequency-division multiplexing (O-OFDM) [5], these optical networks can achieve over Tb/s transmission capacity as well as agile bandwidth adjustment with a granularity of 12.5 GHz or less [6]. Therefore, EONs become a promising physical-layer infrastructure to support inter-DC networks.

In order to utilize the servers in DCs intelligently, people have proposed anycast [7], with the idea that the location(s) of the destination DC(s) for a request to be served can be transparent to the customer, as long as the service-level agreements (*e.g.*, bandwidth and computing requirements) are satisfied. Since anycast refers to the communication scheme that the destination(s) of a connection is/are implicit,

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* Corresponding author.
E-mail address: zqzhu@ieee.org (Z. Zhu).

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the optical spectra on the fiber links in optical inter-DC networks can be utilized more wisely if the resource allocation algorithm is carefully designed. Previous studies have investigated the anycast schemes in traditional fixed-grid wavelength-division multiplexing (WDM) networks [8–14]. Din studied offline routing and wavelength assignment (RWA) for anycast requests in [8]. With a set of anycast requests, the author had the optimization objective as to minimize the total requirement on wavelength channels, and solved the RWA problem in three steps: (1) destination selection, (2) path routing, and (3) wavelength assignment. The same author then extended the work and proposed an algorithm to optimize the RWA solutions further [9], by combining meta-heuristics such as simulated annealing and genetic algorithm. Survivable traffic grooming for anycast in WDM networks was studied in [10]. In [11], Bhaskaran et al. investigated online RWA for anycast requests. They tried to determine the destinations of anycast requests based on the traffic distribution and proposed an algorithm that used ant colony optimization to obtain the RWA solutions. Several shared backup path protection schemes for anycast flows in WDM networks were explored in [12], where the authors proposed to use a node-link notation. Develder et al. [13] proposed to leverage anycast routing for achieving survivable optical grid dimensioning. Most recently, the advance reservation provisioning scheme of anycast requests was addressed in [14] for WDM grids.

Even though the aforementioned studies have investigated anycast in WDM networks from different perspectives, the fixed-grid nature limits the networks' capability on supporting inter-DC networks directly from the physical-layer, due to the coarse bandwidth allocation granularity and rigid spectrum management in the optical layer [15]. In order to accommodate the traffic characteristics of inter-DC networks, we need a physical-layer infrastructure that can maximize the flexibility of spectrum management in the optical layer, for which the EONs fit in much better. Moreover, EONs provide a few unique benefits for spectrum-efficient service provisioning, for instance, multi-path routing can be realized in a more cost-effective way [16]. Previous studies have investigated how to support inter-DC networks with the optical WDM infrastructure [17–20]. In [17], the authors investigated the bandwidth reconfigurable techniques for reducing the congestions in the inter-DC networks. Gharbaoui et al. [18] proposed a network management framework for provisioning the connections in dynamic inter-DC networks with QoS guarantees. They also investigated how to plan virtual machine (VM) migrations in inter-DC networks [19]. An analytical model for the inter-DC networks over WDM infrastructure was formulated in [20], where the authors provided a method to calculate the exact resources that are needed for satisfying a given set of requests. However, to the best of our knowledge, the anycast scheme in elastic optical inter-DC networks is still under-explored.

In [21], we performed a preliminary study on anycast-based online routing and spectrum assignment (RSA) in elastic optical inter-DC networks, and proposed several heuristics. In this paper, we conduct a more comprehensive study and consider both the offline and online scenarios for RSA. For the offline problem, we formulate an integer linear programming (ILP) model and propose several heuristics based on single-DC destination selection. The optimal solutions for small-scale problems are obtained by solving the ILP, and we compare them with the results of the heuristics for measuring the optimization gaps. For the online problem, we design several heuristics to consider the computing and bandwidth resources jointly for efficient service provisioning. An anycast scheme that uses multi-DC destination selection is also introduced to further improve the performance of the elastic optical inter-DC networks.

The rest of the paper is organized as follows. In Section 2, we introduce the concept of flexible-grid elastic optical inter-DC networks. Section 3 depicts the problem description for anycast in elastic optical inter-DC networks. The offline and online anycast-based RSA problems are studied in Sections 4 and 5, respectively. Finally, Section 6 summarizes the paper.

2. Elastic optical inter-datacenter networks

Today's optical networks are implemented with fixed-grid WDM systems, which operate according to fixed-bandwidth wavelength channels that have a rigid spectrum assignment. Nevertheless, these WDM networks only provide limited scalability and flexibility in the optical layer, which makes the physical-layer infrastructure too rigid to adapt to the uncertainty and heterogeneity of the traffic across the inter-DC networks. In order to address these issues properly, it needs “elastic” optical networks equipped with bandwidth-variable (BV) transponders and switches, which can allocate bandwidth with a sub-wavelength granularity and establish lightpath connections spectrum-efficiently according to the traffic demands in inter-DC networks. Fig. 1 shows the architecture of an elastic optical inter-DC network, where the geographically distributed DCs are connected to the BV wavelength-selective switches (BV-WSS′) locally while the BV-WSS′ are interconnected through optical fibers. Client traffic can

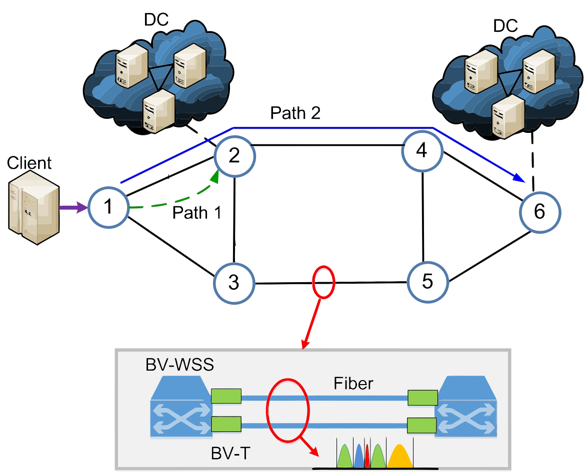

Fig. 1. Elastic optical inter-DC network, DC, datacenter; BV-T, bandwidth-variable transponder; BV-WSS, bandwidth-variable wavelength-selective switch.

be aggregated at the IP routers and then sent to the optical layer by the BV transponders (BV-Ts). Since we only focus on the provisioning process in the optical layer, the IP routers are not included in Fig. 1. When an anycast request arrives in *Node* 1, it can be routed to any of the two DCs on *Nodes* 2 or 6, using *Paths* 1 or 2, respectively. Here, *Paths* 1 and 2 are the shortest paths from the source node to the DC nodes (*i.e.*, *Nodes* 2 and 6). The optical layer is implemented with flexible-grid elastic optical networking, which divides the bandwidth resources on each fiber link into frequency slots (FS′) and provisions connection requests based on them. Specifically, an FS refers the smallest unit for bandwidth allocation and we allocate a certain number of FS′ to a lightpath connection based on its bandwidth requirement. Then, BV-Ts pack these spectrally contiguous FS′ together and set up lightpaths with them. It is known that in addition to the bandwidth requirements, the requests in inter-DC networks usually associate with computing tasks that need to be executed on the destination DCs, which are also taken care of by the anycast scheme in Fig. 1.

3. Problem description

In this section, we formulate the problem of anycast in elastic optical inter-DC networks, including the models of network and requests and the optimization objective.

We consider the physical topology of the elastic optical inter-DC network as $G(V,E)$, where V and E denote the sets of switch-nodes and fiber links, respectively. Since the optical layer uses the flexible-grid, we assume that each fiber link $e \in E$ can accommodate B FS′. In $G(V,E)$, each DC is connected with a switch-node locally, and we denote the corresponding node set as V_{DC} ($V_{DC} \subset V$). For each node $v \in V_{DC}$, the computing capacity of its DC is C_v. An anycast request is defined as $R(s,b,c)$, where $s \in V \backslash V_{DC}$ is the source node, b is the bandwidth requirement, and c is the computing requirement. The bandwidth requirement b is in terms of FS′, the computing requirement c is in number of servers. For simplification, we assume that the relation between b and c is linear [22]

$$c = \alpha \cdot b, \tag{1}$$

where α is a constant coefficient, and it is determined according to the discussion in [22]. In order to serve the anycast request $R(s,b,c)$, we need to select the destination DC d ($d \in V_{DC}$) that can satisfy the computing requirement c and then perform RSA to setup the lightpath connection from s to d. Meanwhile, the spectrum non-overlapping, continuity and contiguous constraints [23] need to be satisfied.

4. Offline anycast RSA problem

In this section, we investigate offline anycast RSA, which is essentially a static network planning problem. We assume that all anycast requests are known *a priori*, and they all have to be accommodated in the network simultaneously, *i.e.*, we do not consider request blocking in this case. In order to improve the spectral efficiency of network planning, we define the optimization objective similar to that of the offline RSA for unicast requests [23,24], as to minimize the maximum index of used FS′ on all the links in the network after serving all requests.

4.1. ILP formulation

In order to obtain the exact solution for the offline anycast RSA, we formulate an ILP model for it. The ILP model optimizes the problem based on routing paths. That is, for each feasible node-pair u–v in $G(V,E)$, where $u \in V \backslash V_{DC}$ and $v \in V_{DC}$, we pre-calculate K shortest routing paths and denote them as $\{p^{(k)}_{u,v},\ k=1,\dots,K\}$. Then, the ILP model is formulated as follows.

Notations:

- $R_i(s_i,b_i,c_i)$: the ith anycast request with source node s_i, bandwidth requirement b_i in terms of FS′, and computing requirement c_i.
- N: the total number of anycast requests.
- B_T: the total bandwidth requirement of the anycast requests as $B_T=\sum_{i=1}^{N} b_i$.
- F_G: the number of guard-band FS′ for each lightpath connection, *i.e.*, the number of FS′ that a lightpath needs in addition to its bandwidth requirement b_i for a spectral guard-band.
- P: the routing path set as $P=\{p^{(k)}_{u,v},\ \forall k, \forall u \in V \backslash V_{DC}, \forall v \in V_{DC}\}$.
- F_{max}: the upper bound of the maximum index of used FS′ on all the links in the network, as $F_{max}=B_T+F_G \cdot N$.
- $y_{p,p'}$: the boolean indicator that equals 1 if the two routing paths p and p' ($p,p' \in P$) are not link-disjoint, and 0 otherwise.

Variables:

- f_i: the integer variable that denotes the index of the starting FS assigned to the lightpath of the ith request R_i.
- d^i_v: the boolean variable that equals 1 if the DC connected to node v ($v \in V_{DC}$) is selected as the destination DC of the ith request R_i, and 0 otherwise.
- x^i_p: the boolean variable that equals 1 if the routing path p ($p \in P$) is used for carrying the ith request R_i, and 0 otherwise.
- $\delta_{i,j}$: the boolean variable that equals 1 if we have $f_i < f_j$ ($i \neq j$), and 0 otherwise.
- F: the integer variable that denotes the maximum index of the used FS′ in the network.

Objective:

Since we want to minimize the maximum index of used FS′ on all the links in the network after serving all the requests, the optimization objective is

$$\text{Minimize } F. \tag{2}$$

Constraints:

$$F \geq f_i + b_i + F_G - 1, \quad \forall i. \tag{3}$$

Eq. (3) ensures that the maximum index of used FS′ on all the links in the network, F, is obtained correctly:

$$\sum_{v \in V_{DC}} d^i_v = 1, \quad \forall i. \tag{4}$$

Eq. (4) ensures that an anycast request is routed to one destination DC:

$$\sum_{p \in \{p_{s_i,v}^{(k)}, \ \forall k\}} x_p^i = d_v^i, \quad \forall i, \ \forall v \in V_{DC}. \tag{5}$$

Eq. (5) ensures that an anycast request is routed on a single path to one destination DC:

$$\delta_{i,j} + \delta_{j,i} = 1, \forall i \neq j. \tag{6}$$

Eq. (6) ensures that the values of $\delta_{i,j}$ and $\delta_{j,i}$ are correctly chosen:

$$f_j - f_i \leq F_{max} \cdot \delta_{i,j}, \quad \forall i \neq j. \tag{7}$$

$$f_i - f_j \leq F_{max} \cdot \delta_{j,i}, \quad \forall i \neq j. \tag{8}$$

$$f_i + b_i + F_G - f_j \leq F_{max} \cdot [(1-\delta_{i,j}) + (2 - x_p^i - x_{p'}^j) + (1 - y_{p,p'})], \quad \forall i \neq j, \ \forall p, \ p' \in P. \tag{9}$$

$$f_j + b_j + F_G - f_i \leq F_{max} \cdot [(1-\delta_{j,i}) + (2 - x_p^i - x_{p'}^j) + (1 - y_{p,p'})], \quad \forall i \neq j, \ \forall p, \ p' \in P. \tag{10}$$

Eqs. (7)–(10) ensure that the spectrum assignments satisfy the spectrum non-overlapping, continuity and contiguous constraints [23]. More specifically, Eqs. (9)–(10) are for the spectrum non-overlapping constraint. If one of the variables, x_p^i, x_p^j and $y_{p,p'}$, does not equal 1, then R_i and R_j do not share a common link. In this case, Eqs. (9)–(10) are always satisfied, since we do not need to worry about the spectrum non-overlapping constraint. Eqs. (9)–(10) only become effective constraints when x_p^i, x_p^j and $y_{p,p'}$ are all equal to 1, which means that R_i and R_j share at least one common link. Without losing the generality, we can assume that $f_i < f_j$ and thus $\delta_{i,j} = 1$. Then, Eqs. (9)–(10) are reduced to Eqs. (11)–(12) as shown below. Eq. (12) is always satisfied, while Eq. (11) ensures that the ending FS of R_i is smaller than the starting FS of R_j, for satisfying the spectrum non-overlapping constraint

$$f_i + b_i + F_G \leq f_j, \quad \forall i \neq j, \ \forall p, \ p' \in P. \tag{11}$$

$$f_j + b_j + F_G \leq f_i + F_{max}, \quad \forall i \neq j, \ \forall p, \ p' \in P. \tag{12}$$

4.2. Heuristic algorithms

Even though the ILP model can optimize the offline anycast RSA, its computational complexity is also relatively high. As we will show later in the simulation results, it is not suitable for solving large-scale problems, *i.e.*, if the network size is large and/or the anycast requests are many. Hence, we need to design heuristic algorithms for obtaining feasible solutions in a reasonably short time. We first describe a simple heuristic denoted as *Anycast-SP-Single-DC*, which selects the least-used DC as the destination and uses shortest-path routing for RSA. Algorithm 1 illustrates the detailed procedure of *Anycast-SP-Single-DC*. As shown in *Line* 1, the anycast requests are sorted in descending order of their bandwidth requirements and then processed one by one. Similar to the three-phase algorithm [8] developed for anycast in WDM networks, we select the least-used DC in V_{DC} as the destination DC of each request (*Lines* 2 and 3) and then the RSA is accomplished with the shortest-path routing and first-fit spectrum assignment (*Lines* 4 and 5).

Algorithm 1. Anycast-SP-single-DC algorithm.

1: **for** all anycast requests $\{R_i(s_i, b_i, c_i)\}$ in descending order of b_i **do**
2: select the least-used DC in V_{DC} as the destination DC d_i;
3: allocate c_i servers on d_i;
4: calculate the shortest routing path from s_i to d_i;
5: allocate b_i contiguous FS′ on the shortest path with first-fit;
6: **end for**

Anycast-SP-Single-DC is straightforward, but it can cause unbalanced-usage of the bandwidth resources since it solely relies on shortest-path routing. We need to balance the utilization of the bandwidth and computing resources to achieve better network planning. In order to accomplish this, we design four metrics to describe the resource utilization on each feasible path and its corresponding destination DC, and propose a series of heuristics based on them, namely *Anycast-BL-Single-DC*. Similar to the ILP model, we still pre-calculate K shortest routing paths for each feasible source–destination pair s–d in $G(V,E)$ and denote them as $\{p_{s,d}^{(k)}, \ k = 1, \dots, K\}$. We use function $BW(\cdot)$ to get a path's available bandwidth in number of FS′, and the function $hops(\cdot)$ returns the hop-count of a path. Here, C_d is the available computing capacity of the DC connected to d ($d \in V_{DC}$). The metrics are defined as follows:

$$m_1\left(p_{s,d}^{(k)}\right) = \frac{BW(p_{s,d}^{(k)}) \cdot \sqrt{C_d}}{\sqrt{hops(p_{s,d}^{(k)})}}, \tag{13}$$

$$m_2\left(p_{s,d}^{(k)}\right) = \frac{BW(p_{s,d}^{(k)}) \cdot C_d}{\sqrt{hops(p_{s,d}^{(k)})}}, \tag{14}$$

$$m_3\left(p_{s,d}^{(k)}\right) = BW\left(p_{s,d}^{(k)}\right) \cdot C_d. \tag{15}$$

$$m_4\left(p_{s,d}^{(k)}\right) = BW\left(p_{s,d}^{(k)}\right) \cdot \sqrt{C_d}. \tag{16}$$

The above metrics are designed in such an empirical way that they weight the utilizations of bandwidth and computing resources differently during the selections of the routing path and destination DC for a request.

Algorithm 2 shows the detailed procedure of *Anycast-BL-Single-DC* that leverages the metrics defined in Eqs. (13)–(16). In *Lines* 1–3, we perform the tasks for initialization. Note that here, we set B and C_v as relatively large values and ensure that they will not cause request blocking in the subsequent steps. In *Line* 4, the anycast requests are still sorted in descending order of their bandwidth requirements. *Lines* 5–7 obtain all the possible paths for carrying the anycast request and calculate the corresponding metric. *Line* 8 selects the path that has the largest metric to proceed, and then in *Lines* 9–13, the assignments of bandwidth and computing resources are performed.

Since Algorithm 2 can use different metrics to determine the path for an anycast request, we denote the schemes that use metrics $m_1(\cdot)$, $m_2(\cdot)$, $m_3(\cdot)$ and $m_4(\cdot)$ as *Anycast-BL-Single-DC-1*, *Anycast-BL-Single-DC-2*, *Anycast-BL-Single-DC-3*, and *Anycast-BL-Single-DC-4*, respectively. The complexities of *Anycast-SP-Single-DC* and *Anycast-BL-Single-DC* are $O(N_{DC}*E^2*W)$ and $O(K*N_{DC}*E^2*W)$, respectively, where N_{DC} denotes the number of DCs, and W is the number of FS′ on each link.

Algorithm 2. Anycast-BL-Single-DC algorithms.

pre-calculate $P=\{p_{u,v}^{(k)},\ k=1,\ldots,K, \forall u \in V \backslash V_{DC}, \forall v \in V_{DC}\}$;
assign the available bandwidth resource of each link e as B FS′;
assign the available computing resource of each DC v, $v \in V_{DC}$ as C_v;
for all anycast requests $\{R_i(s_i, b_i, c_i)\}$ in descending order of b_i **do**
  for all routing paths in path set P that origin from s_i **do**
    calculate metric $m_1(\cdot)$ with Eq. (13), or $m_2(\cdot)$ with Eq. (14), or $m_3(\cdot)$ with Eq. (15), or $m_4(\cdot)$ with Eq. (16);
  end for
  select the routing path p whose metric is the largest;
  select the destination of p as the destination DC d_i;
  allocate c_i servers on d_i;
  $C_{d_i} = C_{d_i} - c_i$;
  allocate b_i contiguous FS′ on p with first-fit;
  update the available bandwidth resource of each link in p;
end for

4.3. Performance evaluation

We compare the performance of the ILP model and the heuristics with numerical simulations. We first employ the six-node topology as shown in Fig. 2, where there are two DCs in the network and $V_{DC}=\{2,6\}$. For each anycast request $R_i(s_i, b_i, c_i)$, the source node s_i is randomly chosen from $V \backslash V_{DC}$, the bandwidth requirement b_i is uniformly distributed within $[1,8]$ FS′, and the computing requirement is calculated using Eq. (1) with coefficient $\alpha=1$. Here, for simplicity, we set $\alpha=1$, but this will not limit the generality of the simulations as the selection of α will not affect the performance of the algorithms. Specifically, $\alpha=1$ means that when an anycast request requires 1 Gb/s bandwidth, we need to allocate 1 unit of computing resource in the destination DC to satisfy its computing requirement. All the simulation parameters are listed in Table 1.

We use LINGO [25] to solve the ILP and use MATLAB to implement the heuristic algorithms. All simulations are

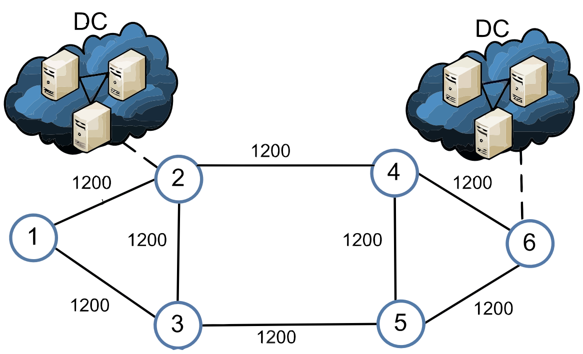

Fig. 2. Elastic optical inter-DC network based on the six-node topology (link length in km).

run on a computer with 3.1 GHz Intel Core i5-2400 CPU and 4 GB RAM. For the ILP, we stop the simulations if the optimal solution cannot be obtained within 2 h. To obtain each data point in the simulation, we run the programs for five different request sets and calculate the average value. Table 2 summarizes the simulation results. It can be seen that the ILP provides the smallest results on F, but it also consumes much longer computation time than the heuristics. Among the heuristics, *Anycast-BL-Single-DC-3* and *Anycast-BL-Single-DC-4* provide the best results on F, which are close to those from the ILP. It is interesting to notice that *Anycast-SP-Single-DC* performs better than *Anycast-BL-Single-DC-1* and *Anycast-BL-Single-DC-2* for the simulations that include 5 and 10 requests, but the situation is reversed when the number of requests is increased to 15. This is because for each anycast request, *Anycast-SP-Single-DC* chooses the destination as the least-used DC without considering the spectrum utilization on the path between the source and the DC, while *Anycast-BL-Single-DC-1* and *Anycast-BL-Single-DC-2* consider the balance between spectrum and computing resource utilizations. The distribution of computing resource utilization in the two DCs for a 15-request case is shown in Fig. 3. ILP provides the most unbalanced computing load distribution, which is due to the fact that its optimization objective is to minimize the required bandwidth resources. On the other hand, as *Anycast-SP-Single-DC* only cares about the load-balancing of computing loads, it achieves the most balanced distribution. All the proposed algorithms are between these two extremes. These observations verify that the proposed algorithms can balance the utilizations of the computing and bandwidth resources.

We then perform similar simulations with the NSFNET topology in Fig. 4 and the results are summarized in Table 3. It is interesting to notice that even though the network topology becomes larger, the time consumed by the ILP become shorter. This observation can be explained as follows. There are more candidate destination DCs in NSFNET, and the connectivity of NSFNET is much better than the six-node topology. Therefore, it is easier for LINGO to find link-disjoint routing paths for more requests, which facilitate it to solve the ILP much faster. For this case, the results on F from the series of *Anycast-BL-Single-DC* are all not worse than those from *Anycast-SP-Single-DC*. The distribution of computing resource utilization in the DCs for a 15-request case is shown in Fig. 5, and we can see that the heuristics provide more balanced utilization of the DCs than the ILP. We also run simulations for 1000 requests in NSFNET to further investigate the performance of the heuristics. The results are shown in Table 4 and Fig. 6. As expected, we observe that *Anycast-BL-Single-DC-3* and *Anycast-BL-Single-DC-4* provide comparable results on F, which are the smallest ones. Moreover, the distributions of the computing tasks from them are also balanced. Note that for the 1000-request case, we run the simulations with $B=1300$ FS′ and $C_v=4800$ servers for each link and DC, respectively.

5. Online anycast RSA problem

In this section, we study the online anycast RSA problem, *i.e.*, dynamic network provisioning. In this case, the anycast requests are dynamic and unknown, which can

Table 1
Simulation parameters for offline anycast RSA.

Network topology	Six-node	NSFNET
Average node degree	2.67	3.14
B, fiber link capacity (FS′)	260	260
Capacity of an FS	12.5 Gb/s	12.5 Gb/s
V_{DC}, set of DC nodes	{2, 6}	{3,5,8,10,12}
b, bandwidth requirement of a request (FS′)	[1, 8]	[1, 8]
F_G, guard-band FS′ per lightpath	1	1
α, linear coefficient (servers/FS)	1	1
K, number of shortest paths for each node-pair	3	3

Table 2
Results on offline anycast in six-node topology.

Algorithms	5 Requests		10 Requests		15 Requests	
	F (FS′)	Time (s)	F (FS′)	Time (s)	F (FS′)	Time (s)
ILP	7.6	1.40	11.2	1200	16.0	1200
Anycast-SP-Single-DC	12.0	0.06	17.6	0.01	28.8	0.01
Anycast-BL-Single-DC-1	15.2	0.04	19.6	0.01	23.4	0.01
Anycast-BL-Single-DC-2	15.2	0.02	19.6	0.01	23.4	0.01
Anycast-BL-Single-DC-3	8.2	0.02	12.8	0.01	18.2	0.01
Anycast-BL-Single-DC-4	8.2	0.02	12.6	0.01	18.0	0.01

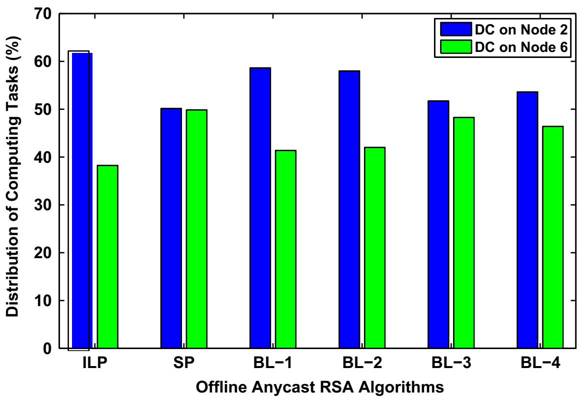

Fig. 3. Computing task distribution in the six-node topology (15 requests).

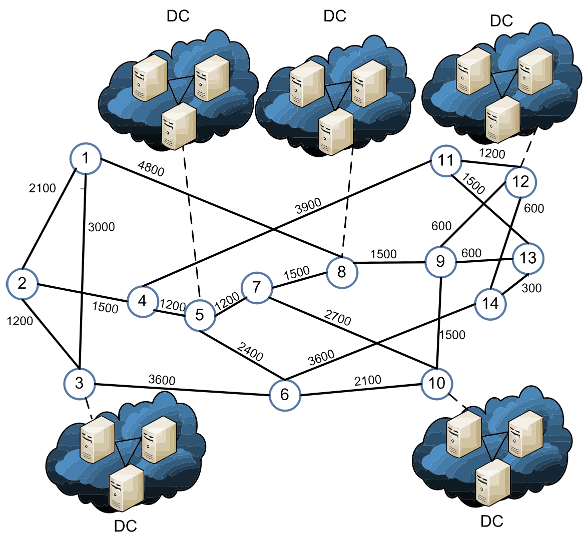

Fig. 4. Elastic optical inter-DC network based on the NSFNET topology (link length in km).

arrive and leave on-the-fly during network operation. Moreover, since the network is already designed and operational, the maximum values of the available bandwidth resource on each fiber link and the available computing resource on each DC are fixed. Therefore, some requests can be blocked due to insufficient resources. In order to improve the spectral efficiency of network provisioning, we set the optimization objective as to minimize the bandwidth blocking probability (BBP), which is defined as the ratio of blocked to total requested bandwidth.

5.1. Design constraints and objective

During the dynamic network provisioning, we still use function $BW(p_{s,v}^{(k)})$ to get the available bandwidth of $p_{s,v}^{(k)}$ in number of FS′, and use function $hops(p_{s,v}^{(k)})$ to obtain the hop-count of $p_{s,v}^{(k)}$. We need to select DC node(s) as the destination(s), determine the amounts of computing capacity to allocate, and perform RSA to set up lightpath(s) to serve the anycast request $R(s,b,c)$. The computing capacity allocated on $v \in V_{DC}$ for the request is denoted as c_v, and if v is not a destination DC for the request, we have $c_v = 0$. We denote the bandwidth allocated on the path $p_{s,v}^{(k)}$ for the request as $b_{s,v}^{(k)}$, and $b_{s,v}^{(k)} = 0$ if $p_{s,v}^{(k)}$ is not selected.

Constraints:

$$b_{s,v}^{(k)} \le BW(p_{s,v}^{(k)}), \quad \forall k,\ v \in V_{DC}. \tag{17}$$

Table 3
Results on offline anycast in NSFNET topology.

Algorithms	5 Requests		10 Requests		15 Requests	
	F (FS′)	Time (s)	F (FS′)	Time (s)	F (FS′)	Time (s)
ILP	7.6	0.40	7.8	246.6	8.6	312.6
Anycast-SP-Single-DC	12.2	0.07	13.0	0.01	18.0	0.01
Anycast-BL-Single-DC-1	7.8	0.04	13.0	0.01	15.2	0.02
Anycast-BL-Single-DC-2	7.8	0.02	13.6	0.01	15.6	0.02
Anycast-BL-Single-DC-3	7.6	0.02	8.8	0.01	11.2	0.02
Anycast-BL-Single-DC-4	7.6	0.02	8.6	0.01	10.4	0.02

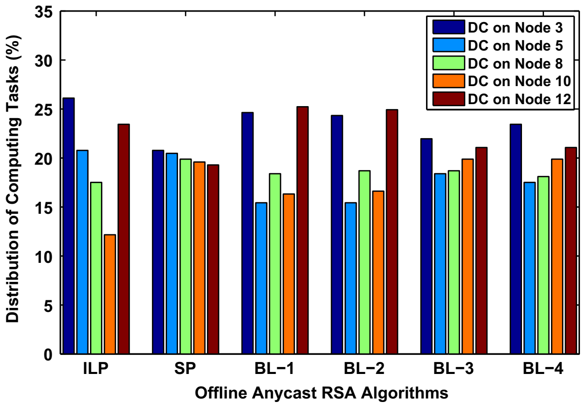

Fig. 5. Computing task distribution in NSFNET topology (15 requests).

Table 4
Results on offline anycast in NSFNET topology.

Algorithms	1000 requests	
	F (FS′)	Time (s)
Anycast-SP-Single-DC	742.2	0.95
Anycast-BL-Single-DC-1	686.6	1.92
Anycast-BL-Single-DC-2	688.4	1.90
Anycast-BL-Single-DC-3	486	1.90
Anycast-BL-Single-DC-4	482	1.89

Eq. (17) ensures that for the request, the bandwidth allocated on a path does not exceed its available bandwidth:

$$b_{s,v}^{(k)} \geq g \quad \left\{v, k: b_{s,v}^{(k)} > 0\right\}. \tag{18}$$

Eq. (18) ensures that when we employ the multi-path routing scheme for serving the request, the minimum number of FS′ allocated on each sub-path is not smaller than the granularity g:

$$c_v \leq C_v, \quad \forall v \in V_{DC}. \tag{19}$$

Eq. (19) ensures that the computing resource allocated on each DC does not exceed its current available computing capacity:

$$c_v = \sum_{k=1}^{K} \alpha \cdot b_{s,v}^{(k)}. \tag{20}$$

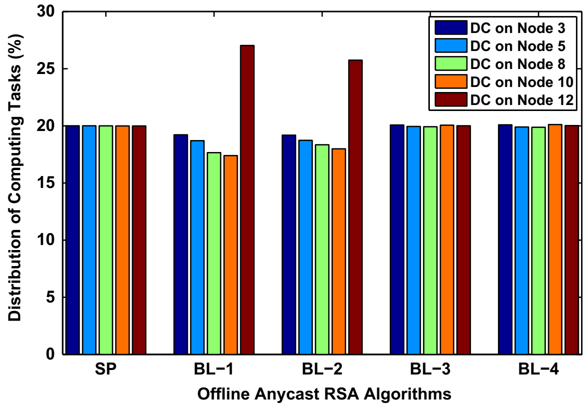

Fig. 6. Computing task distribution in NSFNET topology (1000 requests).

Eq. (20) ensures that there is a linear relation between the bandwidth and computing resource allocations, which follows the expression in Eq. (1):

$$c = \sum_{v \in V_{DC}} c_v. \tag{21}$$

Eq. (21) ensures that the requested resources are allocated as a whole to the request for satisfying the service-level agreement.

Objective: For dynamic provisioning, each anycast request is dynamic and associated with two time parameters, *i.e.*, the arrival time and the holding period, since it can arrive and leave on-the-fly. If sufficient resources (both bandwidth and computing) cannot be provided at an anycast request's arrival time, it is blocked. In this work, we try to minimize the bandwidth blocking probability (BBP) of dynamic provisioning, and this objective can be formulated as

$$\text{Minimize } p_b = \lim_{T \to \infty} \frac{N_b(T)}{N(T)}, \tag{22}$$

where $N_b(T)$ and $N(T)$ are the numbers of blocked and total requested FS′ from the requests arrived during $[0, T]$ respectively.

5.2. Online anycast with single-DC destination selection

Similar to the offline cases, the online anycast RSA problem can be solved by selecting a single DC as the destination for each anycast request. Hence, the algorithms that are proposed for the offline anycast RSA problem in Section 4 can also be adapted to the online case. Consequently, the performance of the heuristics, *e.g.*, *Anycast-SP-Single-DC* and the series of *Anycast-BL-Single-DC*, will be evaluated for dynamic network provisioning in this section too. Note that the ILP model will not be introduced due to its high computational complexity, which makes it difficult to satisfy the real-time requirement from the dynamic network provisioning.

5.3. Online anycast with multi-DC destination selection

It is known that compared with single-path routing, multi-path routing can achieve better utilization of the bandwidth resources in optical networks [16]. Meanwhile, in dynamic provisioning, spreading the computing requirement of an anycast request over multiple DCs can help us to reduce the fragmentation of computing resources in the DCs. To this end, we design an algorithm with multi-DC destination selection to reduce BBP further. Algorithm 3 shows the detailed procedure. It tries to assign the largest block of contiguous FS′ on a path to the request in each loop (*Lines* 7–26). In order to avoid the situation that an anycast request is split over too many paths, we define a path bandwidth granularity g and implement the constraint in Eq. (18). Specifically, when a request is provisioned over more than one paths, *i.e.*, $n_p > 1$, the minimum number of FS′ to allocate on each path is g. We refer Algorithm 3 as *Anycast-BL-Multi-DC*. The complexity of *Anycast-BL-Multi-DC* is $O(M{*}K{*}N_{DC}{*}E^2{*}W)$, where M denotes the number of paths can be used for each request, N_{DC} is for the number of DCs, and W denotes the number of FS′ on each link.

Algorithm 3. Dynamic anycast with multi-DC destination selection.

1: pre-calculate $P = \{p_{u,v}^{(k)},\ k = 1, \ldots, K, \forall u \in V \backslash V_{DC}, \forall v \in V_{DC}\}$;
2: **while** the network is operational **do**
3: get the current network status;
4: collect an anycast request $R_i(s_i, b_i, c_i)$;
5: release the resources of expired requests;
6: $n_p = 0$;
7: **while** $b_i \ge g$ OR $n_p = 0$ **do**
8: **for** all routing paths in path set P that origin from s_i **do**
9: calculate metric $m_4(\cdot)$ with Eq. (16);
10: **end for**
11: select the routing path p whose metric is the largest;
12: find the largest block of available contiguous FS′ on p;
13: obtain the size of the block as b_p;
14: **if** $b_p < g$ **then**
15: break;
16: **else**
17: allocate $\min(b_p, b_i)$ FS′ on the path;
18: try to allocate $\alpha \cdot \min(b_p, b_i)$ servers on the destination of p;
19: **if** computing allocation is not successful **then**
20: break;
21: **else**
22: $b_i = b_i - \min(b_p, b_i)$;
23: $n_p = n_p + 1$;
24: **end if**
25: **end if**
26: **end while**
27: **if** $b_i = 0$ **then**
28: update network status;
29: **else**
30: mark R_i as blocked;
31: **end if**
32: **end while**

5.4. Performance evaluation

The NSFNET topology in Fig. 4 is used for the simulations, and we have $V_{DC} = \{3, 5, 8, 10, 12\}$. In each DC, we assume that the maximum value of C_v is 4800, which means that there are 4800 servers available initially. For each request, the bandwidth requirement b is uniformly distributed within $[1, 16]$ FS′. The rest of the simulation parameters are the same as those in Section 4.3. The computing requirement c is still calculated using Eq. (1) with $\alpha = 1$. Table 5 lists the simulation parameters. The dynamic anycast requests arrive according to the Poisson traffic model, where the average arrival rate is $\lambda$and the holding period of each request follows the negative exponential distribution with an average of $1/\mu$. Then, the traffic load can be quantified with λ/μ in Erlangs.

Fig. 7 shows the simulation results on BBP from all the algorithms with single-DC destination selection, where each data point is obtained by averaging the results from 10 independent simulations. It can be seen that that *Anycast-SP-Single-DC* provides the highest BBP among all the anycast algorithms. This is due to the fact that it only considers the computing resources for destination DC selection. Although choosing the DC that is least-used can make computing loads be distributed evenly among the DCs, a valid RSA solution may not be found in the consequent step due to insufficient bandwidth resources. On the other hand, the other algorithms consider computing and bandwidth resources jointly and therefore can provide lower BBP results. Among the series of *Anycast-BL-Single-DC*, *Anycast-BL-Single-DC-4* provides the best performance on BBP. These results suggest that when choosing the destination DC and routing path for an anycast request, we should pay more attention to the path's bandwidth resources, while the hop-count could be weighted less. This relation among the BBP results is also the reason why we only use metric $m_4(\cdot)$ in *Anycast-BL-Multi-DC*.

We also investigate the performance of *Anycast-BL-Multi-DC*, and plot the BBP results in Fig. 8. As expected, we observe that *Anycast-BL-Multi-DC* provides the lowest BBP among all the algorithms when its path bandwidth allocation granularity is one FS (*i.e.*, $g = 1$). These results

Table 5
Simulation parameters for online anycast RSA.

B, fiber link capacity	260 FS′
Capacity of an FS	12.5 Gb/s
V_{DC}, set of DC nodes	{3,5,8,10,12}
C_v, computing capacity of a DC	4800 servers
b, bandwidth requirement of each request	[1, 16] FS′
F_G, guard-band FS′ for a lightpath	1
α, linear coefficient (servers/FS)	1
K, number of shortest paths for each node-pair	5
g, path bandwidth allocation granularity	[1, 9] FS′

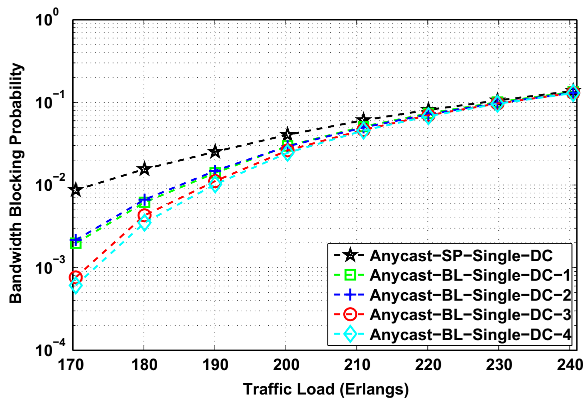

Fig. 7. Results on BBP from algorithms with single-DC destination selection.

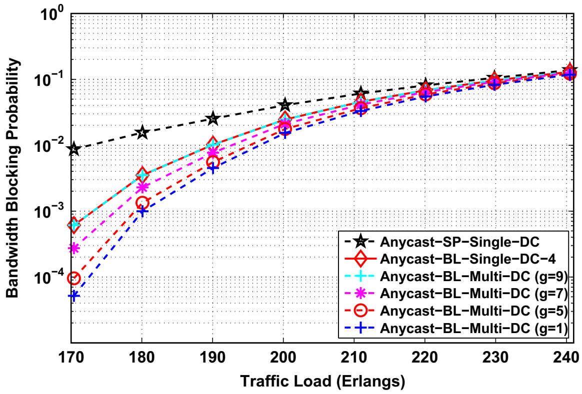

Fig. 8. Results on BBP from algorithms with single-/multi-DC destination selection.

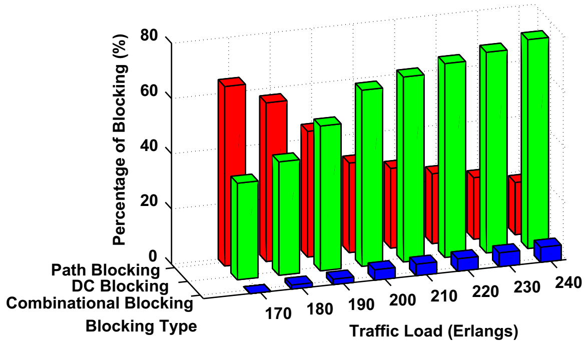

Fig. 10. Percentages of blocking cases when using *Anycast-BL-Single-DC-4*.

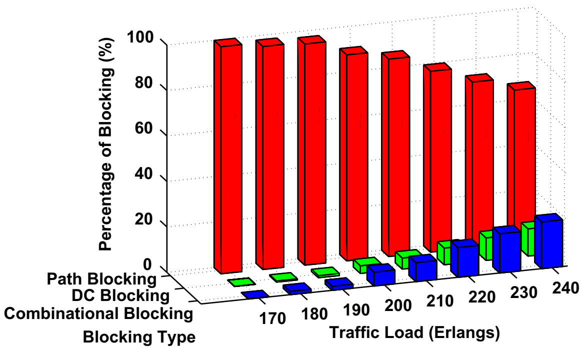

Fig. 9. Percentages of blocking cases when using *Anycast-SP-Single-DC*.

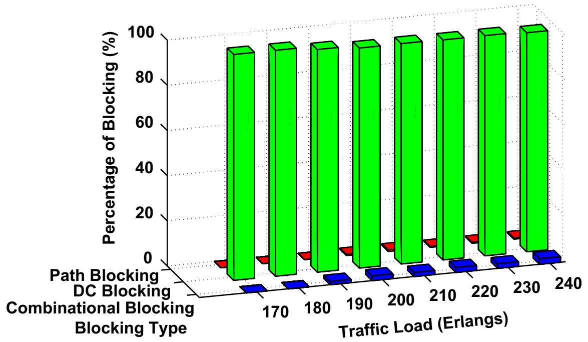

Fig. 11. Percentages of blocking cases when using *Anycast-BL-Multi-DC* ($g=1$).

verify that *Anycast-BL-Multi-DC* makes better utilization of both the computing and bandwidth resources in the elastic optical inter-DC network. We also can see that when $g=9$, *Anycast-BL-Multi-DC* achieves the comparable BBP results as those from *Anycast-BL-Single-DC-4*. This is because with a larger g, the constraint in Eq. (18) is tighter and does not allow path-splitting for a larger portion of the requests. Therefore, when serving the dynamic anycast requests, we have a tradeoff between the BBP and operation complexity. In other words, for a lower BBP, we have to implement a smaller g and allow more path-splittings for a request, while more path-splittings lead to more BV-Ts allocated to the request and hence increase the operation complexity.

Finally, we investigate the reasons for request blocking. In the simulations, an anycast request can be blocked for three reasons: (1) the bandwidth resources on the path(s) are sufficient, but the computing resources in the destination DC(s) are not (*DC Blocking*), (2) the computing resources are sufficient, but the bandwidth resources are not (*Path Blocking*), and (3) both resources are insufficient (*Combinational Blocking*). We analyze the percentages of these three blocking cases for *Anycast-SP-Single-DC*, *Anycast-BL-Single-DC-4*, and *Anycast-BL-Multi-DC*, and plot the results in Figs. 9, 10 and 11, respectively. In Fig. 9, we find that the majority of the request blockings are due to *Path Blocking*, which is a clear indication that the algorithm cannot utilize the bandwidth resources in the network intelligently. *Anycast-BL-Single-DC-4* improves the situation in Fig. 10, and when the traffic load increases, the percentage of *DC Blocking* increases rapidly. Fig. 11 shows that the majority of the request blockings are due to *DC Blocking* when we use *Anycast-BL-Multi-DC*. Therefore, the bandwidth resources are fully utilized, which makes the computing resources become the bottleneck. Note that in inter-DC networks, upgrading the DCs by putting in more servers in is much easier and less expensive than upgrading the physical optical network infrastructure.

6. Conclusion

In this paper, we investigated both offline and online anycast RSA problems in elastic optical inter-DC networks. For the offline problem, we formulated an ILP model and proposed several heuristics based on single-DC destination selection. The optimal solutions for small-scale problems were obtained by solving the ILP, and we compared them with those from the heuristics for measuring the optimization gaps. For the online problem, we designed several heuristics to consider the computing and bandwidth resources jointly for efficient service provisioning, including an algorithm that uses multi-DC destination selection. Our simulation results indicated that the anycast algorithm with multi-DC destination selection could fully utilize the bandwidth resources in elastic optical inter-DC networks, make computing resources become the bottleneck, and reduce the bandwidth blocking probability of anycast requests effectively.

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