SCIENCE CHINA
Information Sciences

• RESEARCH PAPER •
Special Focus on All Optical Networks

October 2016, Vol. 59 102304:1–102304:16
doi: 10.1007/s11432-016-0312-7

Investigation on static routing and resource assignment of elastic all-optical switched intra-datacenter networks

Limei PENG[1*], Kiejin PARK[2] & Chan-Hyun YOUN[3]

[1]*Department of Industrial Engineering, Ajou University, Suwon* 443-749*, South Korea;*
[2]*Department of Integrative Systems Engineering, Ajou University, Suwon* 443-749*, South Korea;*
[3]*Department of Electrical Engineering, Korea Advanced Institute of Science and Technology, Daejeon* 34141*, South Korea*

Received May 13, 2016; accepted July 13, 2016; published online September 12, 2016

Abstract In this paper, we explore the issue of static routing and spectrum/IT resource assignment (RSIA) of elastic all-optical switched intra-datacenter networks (intra-DCNs) by proposing anycast- and manycast-based integer linear programming (ILP) models. The objective is to jointly optimize the DCN resources, i.e., network transmission bandwidth and IT resources, under different situations. First, for given service-request matrices with unknown network transmission bandwidth and IT resources, we propose anycast and manycast ILP models to minimize the maximum numbers of required network and IT resources to accommodate all the service requests. For anycast RSIA issue, we proposed two different ILP models that are based on node-arc and link-path methods, respectively. Node-arc based manycast ILP model is also proposed for the first time to our knowledge. Second, for given network transmission bandwidth and IT resources and known service-request matrices, we propose node-arc based anycast ILP models to maximize the total number of successfully served service requests. To evaluate the efficiency of anycast and manycast models, all proposed ILP models are evaluated and compared with unicast ILP models. Simulation results show that anycast and manycast ILP models perform much better in efficiently using DCN resources and successfully accommodating more service requests when compared to unicast ILP models under the same network conditions.

Keywords datacenter networks (DCNs), intra-DCN, RSIA, ILP models, anycast, manycast

Citation Peng L M, Park K, Youn C-H. Investigation on static routing and resource assignment of elastic all-optical switched intra-datacenter networks. Sci China Inf Sci, 2016, 59(10): 102304, doi: 10.1007/s11432-016-0312-7

1 Introduction

Cloud service requests exhibit features different with traffic demands of traditional transport networks in that, in addition to network transmission bandwidth resources, they also require IT resources, such as computing, storage, virtual machine (VM), etc., to compute or store for service requests in distributed end-servers. Datacenters (DCs), which provide a large number of such IT resources, are interconnected with each other to form a datacenter network (DCN), which then performs as a substrate transmission layer for Cloud computing. Therefore, DCNs play a pivotal role to Cloud computing since they provide

* Corresponding author (email: auroraplm@ajou.ac.kr)

the two-dimensional DCN resources for Cloud service requests, say the network transmission bandwidth for transmitting massive service requests and IT resources at the end-servers for computing, storage, etc.

Nonetheless, most of existing studies on DCNs concentrated on considering the network transmission bandwidth. More specifically, Cloud service requests have exhibited tremendous growth in the past years and showed no sign of stopping. These ever-increasing Cloud service requests, such as text or video messages, albums, and interaction activities, show diverse attribute features. Their arrival rates, sizes, distributions and attributes are quite bursty and dynamic. The above features have driven us to construct DCNs with rich transmission bandwidth and flexible switching capabilities [1–3]. A lot of efficient DCN interconnection architectures have been proposed with huge transmission bandwidth and flexible switching capabilities by applying various all-optical switching technologies, such as optical circuit switching (OCS), optical packet switching (OPS), optical burst switching (OBS), and coherent optical-orthogonal frequency division multiplexing (CO-OFDM)/optical-orthogonal frequency division multiplexing (O-OFDM) [4,5].

Amongst them, OCS suffers from long switching latency and lacking of switching flexibility; OPS and OBS are still far away from practical use due to lacking of economical fast and effective optical buffers. Waiving from the above disadvantages, CO-OFDM/O-OFDM based DCNs have received tremendous attention due to their expanded transmission bandwidth capacities and flexible switching capabilities. Comparing to the traditional fixed-grid based wavelength division multiplexing (WDM) technology, CO-OFDM/O-OFDM technology uses flexible mini-grids and allows spectrum overlapping among adjacent frequency grids [6–8]. These features can significantly expand the transmission bandwidth of optical fibers and provide flexible switching granularities, which can cope with the bursty and diverse Cloud computing service requests well. CO-OFDM/O-OFDM technology has been applied to inter-DCNs and explored a lot. However, their application to intra-DCNs has not received as sufficient attention as that for inter-DCNs.

Inter-DCNs and intra-DCNs differ with each other in aspects of communication scales, interconnection topologies, request features, etc. Inter-DCNs are generally deployed directly above the public Internet. Several DC nodes connect to the backbone network nodes and then form an inter-DCN together with backbone nodes that are not connecting to any DC nodes. In contrast, intra-DCNs interconnect a large number of geographically adjacent pods that are connecting to hundreds of thousands of servers which provides IT resources. Thus, most of existing work on intra-DCNs has focused on proposing regular interconnection topologies that are scalable with huge transmission capacity and flexible switching capability. For inter-DCNs, since they are physically deployed based on existing backbone networks which is not easy to reconfigure, few effort has been made on their interconnection architectures and great efforts have been made on addressing the routing and resource assignment (RRA) issues. Some of existing studies on RRA for inter-DCNs are similar to the routing and wavelength assignment (RWA) or routing and spectrum assignment (RSA) issues for traditional backbone networks. Nonetheless, such kind of effort for intra-DCNs is far from sufficient so far as we know and therefore, we will address the RRA issue for intra-DCNs, more specifically, the static routing and spectrum/IT resource assignment (RSIA) issue in this paper.

Existing studies on RRA issues for inter-DCNs can be classified according to whether they consider network resource (network-resource oriented), IT resource (IT-resource oriented), or both (joint network- and IT-resource oriented). Note that through all this paper, unless otherwise specified, network resource refers to transmission bandwidth in terms of wavelengths or frequency slots.

As an example of network-oriented work, Al-Fares et al. [9] presented a scalable and dynamic flow-scheduling system called Hedera, which can adaptively schedule a multi-stage switching fabric to efficiently utilize aggregate network resources. Hedera collects flow information from constituent switches, computes non-conflicting paths for flows, and instructs the switches to re-route traffic accordingly. Its objective is to maximize the aggregated bisection bandwidth with minimal scheduler overhead.

As an example of IT-oriented work, Chandra et al. [10] discusses dynamic resource allocation for web applications running on shared datacenters. It focused on assigning the datacenters' server resources. A server-resource model using a time-domain description of a generalized processor sharing (GPS) server was proposed to capture the transient behavior of the application workloads. The parameters of this model were continuously updated using an online monitoring and prediction framework.

Many other researchers are interested in joint network- and IT-oriented works. As representatives, Wang et al. [11] advocated a joint optimization framework for both virtual-machine assignment and traffic engineering, aiming to achieve energy efficiency for DCNs by exploring the applications' communication patterns and the network topologies' regularities. Gharbaoui et al. [12] also considered the joint management of network and IT resources for inter-DCNs. Different network-resource allocation and release policies across an inter-datacenter interconnection network have been proposed, aiming at a balanced accommodation of network resources to improve performance. Li et al. [13] proposed several heuristic mapping algorithms to efficiently allocate DCN resources by referring to both the workloads and the hops of the substrate paths. A novel mapping algorithm called TK-Match was proposed, which consists of a node-mapping stage and a link-mapping stage.

Further, the existing work can also be classified based on whether an anycast method is used. Anycast service-request routing entails finding a data channel that best suits both the connectivity and IT resource requirements. Some studies [9–11,13] did not consider anycast routing; traditional unicast routing was used instead. Other studies [12] adopted the anycast approach, which was deemed to better match the DCN service-request features.

Inspired by the above studies, we also consider to jointly optimize network and IT resources for intra-DCNs and explore both anycast and manycast routing to address the static intra-DCN RSIA issues. This is because that the features of intra-DCN service requests are different with that of the traditional transport traffic demands in the following aspects. First, traditional transport network traffic demands only require the transmission bandwidth on fiber links to be satisfied. In contrast, intra-DCN service requests also require the IT resources to be satisfied in addition to the transmission bandwidth. This feature drives us to jointly consider both network and IT resources. Second, the source-destination (SD) node pairs for all traffic demands of traditional transport networks are dedicated, which indicates that unicast method is more appropriate. However, for an intra-DCN service request, any node or multiple nodes that can provide efficient IT resources can be selected as its destination node or nodes. This feature drives us to apply anycast and manycast approaches.

The key contributions of this paper are as follows. First, for given service-request matrices with known numbers of required frequency slots and IT resources but unknown network and IT resources, we propose node-arc based and link-path based anycast ILP models, respectively, to simultaneously minimize the maximum numbers of network transmission bandwidth and IT resources that can accommodate all the service requests. Consequently, we propose node-arc based manycast ILP model with the same objective. Second, for given number of network and IT resources and known service-request matrices, we proposed node-arc based anycast ILP models to maximize the total number of successfully served service requests. The number of successfully served service requests is evaluated by investigating the numbers of served frequency slots and IT resources. The results of the proposed ILP models are compared with that of the unicast ILP models. Their complexity are also analyzed and compared.

It is necessary to emphasize the difference between our work and existing studies such as [12,13] which also consider anycast routing and joint network- and IT- resources. First, our work concentrates on the joint optimization problem for intra-DCNs, which has not received as much attention as that for inter-DCNs. Second, existing studies biased to address the static routing and spectrum assignment (RSA) issue for inter-DCNs in [12,13]. They proposed ILP models with the objective of minimizing the maximum number of required network resources. None of them considered to minimize the maximum number of both network and IT resources. Third, none of them have addressed the manycast issue for inter-DCNs or intra-DCNs. Manycast service-request routing entails finding multiple data channels that can best suit both the network connectivity and IT resource requirements in an integrated manner. Finally, none of them considered to maximize the number of successfully served service requests under given number of DCN resources.

The rest of the paper is organized as follows. In Section 2, with given service-request matrices but unknown DCN resources, we propose node-arc based and link-path based anycast ILP models, respectively,

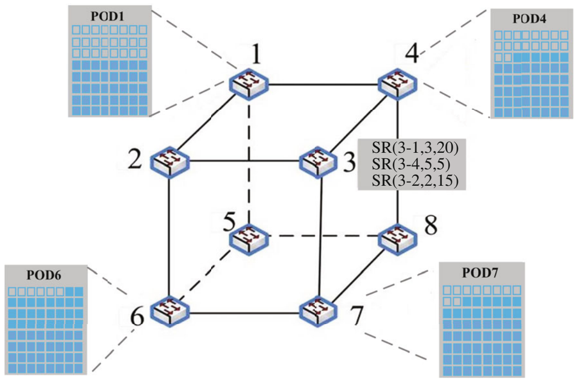

Figure 1 (Color online) 3-cube elastic intra-DCN architecture.

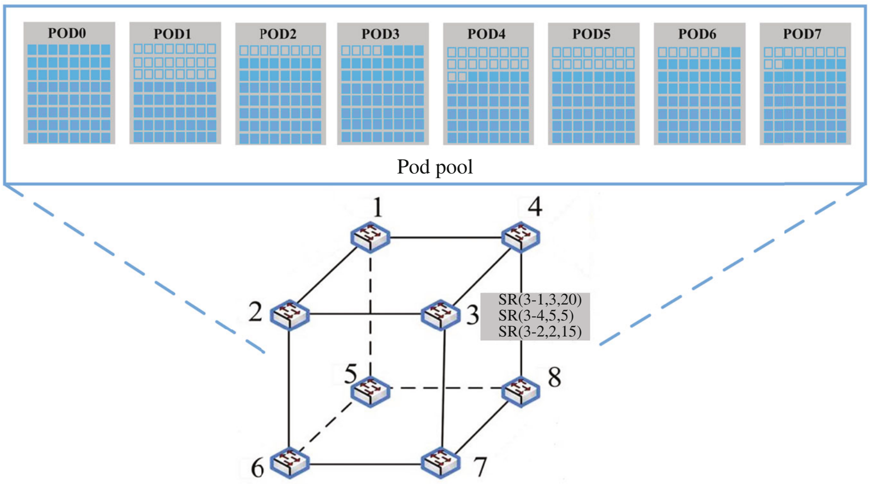

Figure 2 (Color online) Illustrative example of a V-pod pool.

and node-arc based manycast models to minimize the maximum numbers of required network and IT resources that can successfully accommodate all the service requests. In Section 3, for given number of network and IT resources and service-request matrices, we propose node-arc based anycast ILP models to maximize the number of successfully served service requests in terms of the served frequency slots and IT resources. Section 4 analyzes and compares the results and complexity of the above ILP models. Section 5 concludes the paper.

2 ILP models to minimize the maximum number of required DCN resources

2.1 Problem statement

Assume that a network topology $(V,\ L)$ is given as a prior. We consider a regular 3-cube topology with eight pods and twelve links as shown in Figure 1. The switching technology among pods are based on O-OFDM technology. Each pod is supposed to connect with a large number of servers that provide IT resources. To more efficiently use the DCN resources, we assume that all the pods together form a pod pool virtually, within which all the IT resources can be shared by all the service requests as shown in Figure 2. For IT resources in the pod pool, we normalize them as IT units. Each IT unit is represented by a small grid. The solid grids represent busy units and the blank ones represent unused ones as shown in Figures 1 and 2.

To represent the service requests of intra-DCNs, a 3-tuple denoted by $SR(SRC, BW, IT)$ is used, where SR, SRC, BW and IT represent service request, source node of a service request, required frequency slots, and required IT units, respectively. For example, $SR(2, 50, 10)$ means that the service request is from source node 2, the required numbers of frequency slots and IT units are 50 and 10 units, respectively.

Assume that the service-request matrices with required numbers of frequency slots and IT units for each service request are given as a prior too. The objective is to minimize the maximum number of required frequency slots of each fiber link and meanwhile the maximum number of required IT units of each destination node that are able to accommodate all the intra-DCN service requests. Since any node or nodes that can provide the required number of IT resources can be selected as a destination node or destination nodes, the problem can be normalized to anycast and manycast routing issues. The node-arc based and link-path based anycast ILP models, and node-arc based manycast models are described as follows first. Node-arc based unicast ILP model is also proposed as a reference to evaluate the efficiency of anycast and manycast ILP models. Since all the ILP models in this section aims to minimize the maximum numbers of required frequency slots and IT resources (minFI), and they differ with each other in whether anycast, manycast, or unicast routing is used and whether node-arc (NA) or link-path (LP) method is used, we name them as NA-$Anycast$-$minFI$, LP-$Anycast$-$minFI$, NA-$Manycast$-$minFI$, and NA-$Unicast$-$minFI$, respectively. The ILP models proposed in this paper refer to the models in [14,15].

2.2 Anycast ILP model to minimize the maximum numbers of frequency slots and IT units (minFI)

2.2.1 *Node-arc based anycast ILP model* (*NA-anycast-minFI*)

The node-arc based anycast ILP model with the objective of minimizing the maximum number of DCN resources is proposed as following.

(1) Sets.

- V : Set of intra-DCN nodes.
- L : Set of intra-DCN links.
- R : Set of service request indices, $1, 2, \ldots, N$.
- LK_i : Set of links that start or end at node i.

(2) Parameters.

- SRC_i: Source node of service request i.
- BW_i: Number of frequency slots required by service request i.
- IT_i: Number of IT units required by service request i.
- $F_{\max}$: Total number of required frequency slots by all the intra-DCN service requests. It is calculated as the sum of the required spectrum slots of all the service requests.
- G: Guard band required in the frequency slot unit between two spectrally neighboring elastic optical channels.

(3) Variables.

- PL^i_{mn}: A binary value. The value is equal to 1 if the lightpath for service request i traverses physical link mn; zero, otherwise.
- PN^i_m: A binary value. The value is equal to 1 if the lightpath for service request i traverses physical node m; zero, otherwise.
- FN^i_m: A binary value. The value is equal to 1 if m is the final physical node, i.e., destination node, traversed by the lightpath for service request i; zero, otherwise.
- f_i: Starting frequency slot index of service request i.
- $\beta_{i,j}$: A binary value that takes the value one if $f_i < f_j$; zero, otherwise.
- F: Maximum index of required frequency slots among all the fiber links of the entire intra-DCN.
- I: Maximum number of required IT units among all the destination nodes of the entire intra-DCN.

(4) Objective.

$$\text{Minimize } F + I.$$

(5) Constraints.

$$\Sigma_{mn\in LK_{SRC_i}} PL^i_{mn} = 1,\ \forall i \in R, \tag{1}$$

$$\Sigma_{m\in N}FN^i_m = 1,\ \forall i \in R, \tag{2}$$
$$FN^i_m \leqslant PN^i_m,\ \forall i \in R,\ \forall m \in V, \tag{3}$$
$$\Sigma_{mn\in LK_w}PL^i_{mn} = 2PN^i_w - FN^i_w,\ \forall i \in R,\ w! = SRC_i, \tag{4}$$
$$PN^i_m + PN^i_n \geqslant 2 * PL^i_{mn},\ \forall i \in R,\ \forall m,\ n \in V,\ \forall mn \in L, \tag{5}$$
$$F \leqslant F_{\max}, \tag{6}$$
$$F \geqslant f_i + BW_i + G,\ \forall i \in R, \tag{7}$$
$$F \geqslant \Sigma_{i\in R}PL^i_{mn} * BW_i,\ \forall mn \in L, \tag{8}$$
$$\beta_{i,j} + \beta_{j,i} = 1,\ \forall i,\ j \in R, \tag{9}$$
$$f_i + BW_i + G - f_j \leqslant F_{\max}(1 - \beta_{i,j} + 2 - PL^i_{mn} - PL^j_{mn}),\ \forall i,\ j \in R,\ \forall mn \in L, \tag{10}$$
$$\Sigma_i FN^i_m * IT_i \leqslant I,\ \forall i \in R,\ \forall m \in V, \tag{11}$$
$$IT_i \leqslant I,\ \forall i \in R. \tag{12}$$

Constraint (1) ensures that the lightpath for service request i starts from the source node of service request i. Constraint (2) ensures that only one destination is selected for each service request. Constraint (3) ensures that a selected node is either a destination node or an intermediate node. It constrains that if physical node m is the destination node of service request i, which indicates that the value for FN^i_m is one, then it should also be traversed by the lightpath for service request i, which indicates that the value for PN^i_m is also one. However, the reverse is not always the case, i.e., when node m is traversed by the lightpath of service request i, say PN^i_m=1, it does not mean that m is always the destination node of the lightpath of service request i. Therefore, the value of FN^i_m should be no larger than the value of PN^i_m.

Constraint (4) ensures that, for any *intermediate* node traversed by a lightpath, two links are associated with the node, i.e., one ends at the node and the other starts from the node. For any *destination* node traversed by a lightpath, only one link is associated with the node, i.e., the link should end at the destination node. More specifically, if w is an *intermediate* node but not a destination node, then the values for PN^i_w and FN^i_w should be one and zero, respectively. Thus, the final value of the right term of constraint (4) is two, which indicates that two links are traversing *intermediate* node w. In contrast, if w is a *destination* node but not an intermediate node, then the values for both PN^i_w and FN^i_w should be one. Thus, the final value of the right term of constraint (4) is one, which indicates only one link is traversing *destination* node w.

Constraint (5) ensures that if the lightpath for service request i traverses a physical link mn, it must also traverse physical nodes m and n. Constraint (6) ensures that the maximum required number of spectrum slots, say F, does not exceed the total number of required spectrum slots of all the service requests. Constraint (7) ensures that the maximum required number of spectrum slots, say F, should be larger than the ending spectrum-slot index that is assigned to any service request. Constraint (8) ensures that the total number of spectrum slots required by all the service requests that traverse the same physical link mn should be no larger than F. Constraints (9) and (10) ensure that any two service requests that share the same physical link for establishing their lightpaths do not overlap in the spectrum slots during the spectrum-assignment process. Constraint (11) ensures that the total number of IT units required by all the service requests destined for the same destination node should be no larger than the maximum number of IT units provided by all the destination nodes, say I. Constraint (12) ensures that, for any request, the required number of IT units should be no larger than the maximum number of IT units of all the destination nodes, say I.

2.2.2 *Link-path based anycast ILP model (NA-anycast-minFI)*

(1) Sets and parameters. The sets required by link-path based ILP model are V and R which are the same with those in *NA-Anycast-minFI*. All the same parameters listed in *NA-Anycast-minFI*, say SRC_i, BW_i, IT_i, $F_{\max}$, and G, are required here. In addition, a new parameter called $w^{s,d}_p$ is needed. It is a binary value that takes value one if s and d are the source and destination nodes of shortest path p; zero, otherwise.

(2) Variables. The same variables, say f_i, $\beta_{i,j}$, F and I, listed in *NA-Anycast-minFI* are also needed here. PL^i_{mn}, PN^i_m and FN^i_m are not needed. Besides, two new variables, say x^i_p and y^i_d, are needed, where x^i_p is a binary value that takes value one if the shortest path p is selected for service request i and takes value zero, otherwise; y^i_d is a binary value that takes value of one if node d is selected as the destination node for service request i and takes value of zero, otherwise. Note that for both of the two new variables, the source node of service request i, say SRC_i, is not equal to d.

(3) Objective.

$$\text{Minimize } F + I.$$

(4) Constraints.

$$\Sigma_{p\in P} x^i_p = 1,\ \forall i \in R, \tag{13}$$
$$F \geqslant f_i + BW_i + G,\ \forall i \in R, \tag{14}$$
$$\beta_{i,j} + \beta_{j,i} = 1,\ \forall i,\ j \in R, \tag{15}$$
$$f_i + BW_i + G - f_j \leqslant F_{\max}(1 - \beta_{i,j} + 2 - x^i_{p1} - x^j_{p2}), \tag{16}$$
$$\Sigma_{d\in V} y^i_d = 1,\ \forall i \in R, \tag{17}$$
$$y^i_d = x^i_p,\ \forall i,\ d \in V,\ p \in P,\ w_p^{SRC_i,d} = 1, \tag{18}$$
$$I \geqslant \Sigma_{i\in R} y^i_d * IT_i,\ \forall d \in V, \tag{19}$$
$$I \geqslant IT_i,\ \forall i \in R. \tag{20}$$

Constraint (13) ensures that only one routing path is selected for each service request. Constraint (14) ensures that for any service request i, its ending frequency slot index does not exceed the maximum index of the required frequency slots, say F. Constraints (15) and (16) ensures that any two service requests which share the same physical link to establish their lightpaths do not overlap in frequency slots. Constraint (17) ensures that the number of destination nodes selected for each service request is no larger than 1. Constraint (18) ensures that the destination node d selected for service request i is the end node of shortest path p that has been selected for service request i. In other words, the selected destination node d and selected shortest path p are in consistent. Constraint (19) ensures that the maximum number of required IT units of any destination node d is larger than the total number of IT units required by different service requests that are destined to the same destination node d. Constraint (20) ensures that the number of required IT units of any destination node does not exceed the maximum number of IT units provided by any destination node, say I.

2.2.3 *Node-arc based manycast ILP model (NA-manycast-minFI)*

For manycast ILP model, since each service request can select more than one destination node, we virtually divide a service request into several sub-requests that are destined to different destination nodes. Each sub-request affords a proportional part of the required frequency slots and IT units, with the total of all can sum to the total numbers of frequency slots and IT units required by the original service request. The details of manycast ILP model are described as follows.

(1) Sets and parameters. All the same sets listed in *NA-Anycast-minFI*, say V, L, R, and LK_i, are required by manycast ILP model. In addition, a new set called D is needed, which is a set of integers and represents the number of destination nodes a service request selects. All the same parameters listed in *NA-Anycast-minFI*, say SRC_i, BW_i, IT_i, $F_{\max}$, and G, are required here. In addition, a new parameter called M is needed, which is an integer and indicates the maximum number of destination nodes that can be selected by a service request. Note that the range of D is [1, M]. The variables, objective, and constraints that are used in manycast ILP model are as follows.

(2) Variables.

- $PL^{i,k}_{mn}$: A binary value. The value is equal to 1 if the lightpath for the kth sub-request of service request i traverses physical link mn; 0, otherwise.

- $PN_m^{i,k}$: A binary value. The value is equal to 1 if the lightpath for the kth sub-request of service request i traverses node m; 0, otherwise.
- $FN_m^{i,k}$: A binary value. The value is equal to 1 if m is the final physical node (i.e., destination node) traversed by the lightpath of the kth sub-request of service request i; 0, otherwise.
- $bw_{i,k}$: The frequency slots afforded by the kth sub-request of service request i.
- $it_{i,k}$: The IT units afforded by the kth sub-request of service request i.
- $f_{i,k}$: The starting frequency slot of the kth sub-request of service request i.
- $\beta_{i,k,j,q}$:A binary value. The value is equal to 1 if $f_{i,k} < f_{j,q}$; zero, otherwise.
- F: Maximum index of required frequency slots on fiber links of the entire intra-DCN.
- I: Maximum number of required IT units on destination nodes of the entire intra-DCN.

(3) Objectives.

$$\text{Minimize } F + I.$$

(4) Constraints.

$$\Sigma_{mn\in LK_{SRC_i}} PL_{mn}^{i,k} = 1,\ \forall i \in R,\ k \in D, \tag{21}$$

$$\Sigma_{k\in D}\Sigma_{mn\in LK_{SRC_i}} PL_{mn}^{i,k} \leqslant M,\ \forall i \in R, \tag{22}$$

$$\Sigma_{m\in V} FN_m^{i,k} = 1,\ \forall i \in R,\ k \in D, \tag{23}$$

$$\Sigma_{k\in D}\Sigma_{m\in V} FN_m^{i,k} \leqslant M,\ \forall i \in R, \tag{24}$$

$$FN_m^{i,k} \leqslant PN_m^{i,k},\ \forall i \in R,\ k \in D,\ m \in V, \tag{25}$$

$$\Sigma_{mn\in LK_w} PL_{mn}^{i,k} = 2PN_w^{i,k} - FN_w^{i,k},\ \forall i \in R,\ k \in D,\ w! = SRC_i, \tag{26}$$

$$PN_m^{i,k} + PN_n^{i,k} \geqslant 2PL_{mn}^{i,k},\ \forall i \in R,\ k \in D,\ m,\ n \in V,\ mn \in L, \tag{27}$$

$$F \leqslant F_{\max}, \tag{28}$$

$$\Sigma_{k\in D} bw_{i,k} = BW_i,\ \forall i \in R, \tag{29}$$

$$F \geqslant f_{i,k} + bw_{i,k} + G,\ \forall i \in R,\ k \in D, \tag{30}$$

$$F \geqslant \Sigma_{i\in R}\Sigma_{k\in D} PL_{mn}^{i,k} * bw_{i,k},\ \forall mn \in L, \tag{31}$$

$$\beta_{i,k,j,p} + \beta_{j,p,i,k} = 1,\ \forall i,\ j \in R,\ k,\ p \in D,\ i! = j,\ k! = p, \tag{32}$$

$$f_{i,k} + BW_{i,k} + G - f_{j,p} \leqslant F_{\max}(1 - \beta_{i,k,j,p} + 2 - PL_{mn}^{i,k} - PL_{mn}^{j,p}), \forall i, j \in R, k, p \in D, i! = j, k! = p, \tag{33}$$

$$\Sigma_{k\in D} it_{i,k} = IT_i,\ \forall i \in R, \tag{34}$$

$$\Sigma_{i\in R}\Sigma_{k\in D} FN_m^{i,k} * it_{i,k} \leqslant I,\ \forall m \in V. \tag{35}$$

Constraint (21) ensures that the number of lightpaths for the kth sub-request of service request i should be one and the lightpath starts from the source node of service request i. Constraint (22) ensures that the total number of lightpaths for sub-requests of service request i does not exceed M. Constraint (23) ensures that only one destination node is selected for the kth sub-request of service request i. Constraint (24) ensures that the total number of destination nodes selected by all the sub-requests of service request i does not exceed M.

Constraint (25) ensures that a selected node is either a destination node or an intermediate node for the kth sub-request of service request i. It constrains that if physical node m is the destination node of the kth sub-request of service request i, which indicates that the value for $FN_m^{i,k}$ is one, then it should also be traversed by the lightpath for the kth sub-request of service request i, which indicates that the value for $PN_m^{i,k}$ is also one. However, the reverse is not always the case, i.e., when node m is traversed by the lightpath of the kth sub-request of service request i, say $PN_m^{i,k} = 1$, it does not mean that m is always the destination node of the lightpath of the kth sub-request of service request i. Therefore, the value of $FN_m^{i,k}$ should be no larger than the value of $PN_m^{i,k}$.

Constraint (26) ensures that, for any *intermediate* node traversed by a lightpath, two links are associated with the node, i.e., one ends at the node and the other starts from the node. For any *destination* node traversed by a lightpath, only one link is associated with the node, i.e., the link should end at the destination node. More specifically, if w is an *intermediate* node but not a destination node, then the values for $PN_w^{i,k}$ and $FN_w^{i,k}$ should be one and zero, respectively. Thus, the final value of the right term of constraint (26) is two, which indicates that two links are traversing intermediate node w. In contrast, if w is a *destination* node but not an intermediate node, then the values for both $PN_w^{i,k}$ and $FN_w^{i,k}$ should be one. Thus, the final value of the right term of constraint (26) is one, which indicates only one link is traversing destination node w.

Constraint (27) ensures that if the lightpath for the kth sub-request of service request i traverses a physical link mn, it must also traverse physical nodes m and n. Constraint (28) ensures that the maximum number of required frequency slots, say F, does not exceed the total number of frequency slots required by all the service requests. Constraint (29) ensures that the total number of frequency slots required by all the sub-requests of service request i should be equal to the number of frequency slots required by service request i. Constraint (30) ensures that the maximum number of required frequency slots, say F, should be larger than the ending spectrum-slot index that is assigned to any service request or sub-request.

Constraint (31) ensures that the total number of frequency slots required by all the service requests/sub-requests that traverse the same physical link mn should be no larger than F. Constraints (32) and (33) ensure that any two service requests/sub-requests that share the same physical link for establishing their lightpaths do not overlap in the frequency slots during the spectrum-assignment process. Constraint (34) ensures that the total number of IT units required by all the sub-requests of service request i should be equal to the number of IT units required by service request i. Constraint (35) ensures that the total number of IT units required by all the service requests destined to the same destination node should be no larger than the maximum number of IT units provided by all the destination nodes, say I.

2.2.4 *Node-arc based unicast ILP model (NA-unicast-minFI)*

To evaluate the efficiency of our proposed anycast and manycast ILP models for intra-DCN static RSIA, we compare it with the unicast ILP model. Nonetheless, even though researchers have investigated unicast ILP models for static RSA issues of elastic optical networks, with the objective of minimizing the maximum number of required frequency slots [14,15], no unicast ILP model exists for addressing static RSIA issues of intra-DCNs, with the objective of minimizing the maximum numbers of both required frequency slots and required IT units. For a fair comparison, we propose a node-arc based unicast ILP model.

Similarly, assume that a network topology (V, L) and service request matrices that inform the required numbers of frequency slots and IT units for all service requests, are given as a prior. We consider the same regular 3-cube topology with eight nodes and twelve links, and a 3-tuple DCN service-request (SR) representation as SR (SD, BW, IT) where SD, BW, and IT indicate the source-destination node pair, the required transmission bandwidth in terms of frequency slots, and the required IT units. We aim to minimize the maximum number of required frequency slots of all fiber links and the maximum number of required IT units of all destination nodes that are able to accommodate all the intra-DCN service requests.

Note that the unicast ILP model mainly refers to the model in [14]. Except for parameter IT_{sd}, variable I, and constraint (45), most of the rest of the sets, parameters, variables, and constraints are the same as or only slightly different from those in [14]. The main purpose for listing all the repeated parts here is to increase the readability of the paper. The unicast ILP model based on a node-arc approach for intra-DCN static RSIA is described as follows.

(1) Sets.

- V : Set of intra-DCN nodes.
- L : Set of intra-DCN links.
- SD : Set of intra-DCN source-destination node pairs.
- LK_i : Set of links that start or end at node i.

(2) Parameters.

- BW_{sd} : Number of spectrum slots required by node pair sd.
- IT_{sd} : Number of C/S units required by node pair sd.
- $F_{\max}$: Total number of required spectrum slots of all the intra-DCN service requests.
- G: Guard band required in the spectrum slot unit between two spectrally neighboring elastic optical channels.

(3) Variables.

- PL_{mn}^{sd}: A binary value. The value is equal to 1 if the lightpath for node pair sd traverses physical link mn; zero, otherwise.
- PN_{m}^{sd}: A binary value. The value is equal to 1 if the lightpath for node pair sd traverses physical node m; zero, otherwise.
- f_{sd}: Starting spectrum-slot index for a service request between node pair sd.
- $\beta_{sd1,sd2}$: A binary value that takes value one if $f_{sd1} < f_{sd2}$; zero, otherwise.
- F: Maximum index of required spectrum slots among all the fiber links of the entire intra-DCN.
- I: Maximum number of required C/S units among all the destination nodes of the entire intra-DCN.

(4) Objective.

$$\text{Minimize } F + I.$$

(5) Constraints.

$$\Sigma_{mn\in LK_s} PL_{mn}^{sd} = 1,\ \forall sd \in SD, \tag{36}$$
$$\Sigma_{mn\in LK_d} PL_{mn}^{sd} = 1,\ \forall sd \in SD, \tag{37}$$
$$\Sigma_{mn\in LK_w} PL_{mn}^{sd} = 2PN_{w}^{sd},\ \forall sd \in SD,\ w! = s,\ d, \tag{38}$$
$$PN_{m}^{sd} + PN_{n}^{sd} \geqslant 2 * PL_{mn}^{sd},\ \forall sd \in SD,\ \forall m,\ n \in V,\ \forall mn \in L, \tag{39}$$
$$F \leqslant F_{\max}, \tag{40}$$
$$F \geqslant f_{sd} + BW_{sd} + G,\ \forall sd \in SD, \tag{41}$$
$$F \geqslant \Sigma_{sd\in SD} PL_{mn}^{sd} * BW_{sd},\ \forall mn \in L, \tag{42}$$
$$\beta_{sd1,\ sd2} + \beta_{sd2,\ sd1} = 1,\ \forall sd \in SD, \tag{43}$$
$$f_{sd1} + BW_{sd1} + G - f_{sd2} \leqslant F_{\max}(1 - \beta_{sd1,\ sd2} + 2 - PL_{mn}^{sd} - PL_{mn}^{sd}),\ \forall sd \in SD,\ \forall mn \in L, \tag{44}$$
$$\Sigma_{s\in V} IT_{sd} \leqslant I,\ \forall sd \in SD. \tag{45}$$

Constraint (36) ensures that the lightpath for the service request between node pair sd starts from source node s. Constraint (37) ensures that the lightpath for the service request between node pair sd ends at destination node d. Constraint (38) ensures that for any *intermediate* node traversed by a lightpath, two links are associated with the node, i.e., one ends at the node and the other starts from the node. Constraint (39) ensures that if the lightpath for the service request of source-node pair sd traverses a physical link mn, it should also traverse physical nodes m and n.

Constraint (40) ensures that the maximum required number of spectrum slots, say F, does not exceed the total number of required spectrum slots of all the service requests. Constraint (41) ensures that the maximum required number of spectrum slots, say F, should be larger than the ending spectrum slot index that is assigned to any service request. Constraint (42) ensures that the total number of spectrum slots required by all service requests that traverse the same physical link mn should be no larger than F. Constraints (43) and (44) ensure that any two service requests that share the same physical link for establishing their lightpaths do not overlap in the spectrum slots during the spectrum-assignment process. Constraint (45) ensures that, for any destination node d, the total number of IT units required by all the service requests destined for the same destination node d should be no larger than the maximum number of IT units of all the destination nodes, say I.

3 ILP models to maximize the number of successfully served service requests

In the previous section, we assume the service-request matrices are given as a prior but the total number of DCN resources, say frequency slots and IT units, is unknown. The objective is to minimize the maximum number of required DCN resources to accommodate all the requests. In this section, we assume that both the service-request matrices and the total number of DCN resources in terms of frequency slots and IT units are given as a prior. Alternatively, the objective is to maximize the number of service requests that can be successfully served under the given number of DCN resources. Both of node-arc based anycast and unicast ILP models are developed. Since both of them aim to maximize the numbers of served frequency slots and IT units (maxSFI) and differ with each other in whether anycast or unicast is used, we name them as NA-*Anycast-max*SFI and NA-$Unicast$-*max*SFI, respectively. Similarly, we also assume that a network topology (V, L) is given as a prior and consider a given regular 3-cube topology as shown in Figure 1.

3.1 Node-arc based anycast ILP model (NA-anycast-maxSFI)

The node-arc based anycast ILP model with the objective of maximizing the total number of successfully served service requests is described as follows.

(1) Sets and parameters. All of the same sets and parameters listed in NA-*Anycast-min*FI, say V, L, R, LK_i, SRC_i, BW_i, IT_i, $F_{\max}$, and G, are all needed here. No new set is needed. For parameters, since we assume the number of available frequency slots and IT units are given as a prior, two new parameters called F and I, respectively, are required. F denotes the total number of available frequency slots per fiber link and I denotes the total number of available IT units per destination node.

(2) Variables. The same variables such as f_i, $\beta_{i,j}$, PL^i_{mn}, PN^i_m and FN^i_m listed in NA-*Anycast-min*FI are also needed here. F and I as variables are not needed since they are given as two parameters. Instead, two new variables, say SF_i and SI_i, are used. SF_i denotes the number of successfully served frequency slots for service request i. SI_i denotes the number of successfully served IT units for service request i.

(3) Objective.

$$\text{Maximize}\Sigma_{i\in R}(SF_i + SI_i).$$

(4) Constraints.

$$SF_i \leqslant BW_i,\ \forall i \in R, \tag{46}$$

$$SI_i \leqslant IT_i,\ \forall i \in R, \tag{47}$$

$$\Sigma_{i\in R} FN^i_m * SI_i \leqslant I,\ \forall m \in V, \tag{48}$$

$$F \geqslant f_i + SF_i + G,\ \forall i,\ j \in R, \tag{49}$$

$$\beta_{i,j} + \beta j, i = 1,\ \forall i,\ j \in R, \tag{50}$$

$$f_i + SF_i + G - f_j \leqslant F(1 - \beta_{i,j} + 2 - PL^i_{mn} - PL^j_{mn}),\ \forall i,\ j \in R,\ mn \in L. \tag{51}$$

Constraint (46) ensures the number of successfully served frequency slots for service request i does not exceed the total number of frequency slots required by service request i. Constraint (47) ensures the number of successfully served IT units for service request i does not exceed the total number of IT units required by service request i. Constraint (48) ensures that the total number of successfully served IT units for all service requests that are destined to the same destination node m does not exceed the maximum IT capacity, say I. Constraint (49) ensures for any service request, the ending frequency slot index required by a physical link does not exceed the link transmission capacity, say F. Constraints (50) and (51) ensure that any two service requests that share the same physical link to establish their lightpaths do not overlap in frequency slots during the spectrum assignment process.

3.2 Node-arc based unicast ILP model (NA-unicast-maxSFI)

The node-arc based unicast ILP model with the objective of maximizing the total number of successfully served service requests is described as follows.

(1) Sets and parameters. All of the same sets and parameters listed in *NA-Unicast-minFI*, say V, L, SD, LK_i, BW_{sd}, IT_{sd}, $F_{\max}$, and G, are all needed here. No new set is needed. For parameters, since we assume the number of available frequency slots and IT units are given as a prior, two new parameters called F and I, respectively, are required. F denotes the total number of available frequency slots per fiber link and I denotes the total number of available IT units per destination node.

(2) Variables. The same variables of PL^{sd}_{mn}, PN^{sd}_{m}, f_{sd} and $\beta_{sd1,sd2}$ listed in *NA-Unicast-minFI* are also needed here. F and I as variables are not needed since they are given as two parameters. Instead, two new variables, say SF_{sd} and SI_{sd}, are used. SF_{sd} denotes the number of successfully served frequency slots for service requests between source-destination (SD) node pair sd. SI_{sd} denotes the number of successfully served IT units for service request between SD node pair sd.

(3) Objective.

$$\text{Maximize}\Sigma_{i\in R}(SF_i + SI_i).$$

(4) Constraints.

$$\Sigma_{s\in V} SI_{sd} \leqslant \Sigma_{s\in V} IT_{sd},\ \forall d\in V,\ sd\in SD, \tag{52}$$

$$SI_{sd} \leqslant IT_{sd},\ \forall sd\in SD, \tag{53}$$

$$SF_{sd} \leqslant BW_{sd},\ \forall sd\in SD, \tag{54}$$

$$F \geqslant f_{sd} + SF_{sd} + G,\ \forall sd\in SD, \tag{55}$$

$$\Sigma_{sd\in SD} SF_{sd} * PL^{sd}_{mn} \leqslant F,\ \forall mn\in L, \tag{56}$$

$$\beta_{sd1,sd2} + \beta_{sd2,sd1} = 1,\ \forall sd\in SD, \tag{57}$$

$$f_{sd} + SF_{sd1} + G - f_{sd2} \leqslant F_{\max}(1-\beta_{sd1,sd2} + 2 - PL^{sd1}_{mn} - PL^{sd2}_{mn}),\ \forall sd1,\ sd2\in SD,\ mn\in L. \tag{58}$$

Constraint (52) ensures that for any destination node d, the total number of required IT units by all service requests that are destined to d should be no larger than the total number of available IT units in node d. Constraint (53) ensures that for any SD node pair sd, the number of successfully served IT units should be no larger than the number of IT units required by service request of node pair sd. Constraint (54) ensures that for any SD node pair sd, the number of successfully served frequency slots should be no larger than the number of frequency slots required by service request of SD node pair sd. Constraint (55) ensures that the number of available frequency slots per link, say F, should be larger than the maximum ending frequency slot index that is assigned to any service request of any node pair sd. Constraint (56) ensures that the total number of frequency slots required by all service requests that traverse the same physical link mn should be no larger than F. Constraints (57) and (58) ensures that any two service requests that share the same physical link to establish their lightpaths do not overlap in frequency slots during the spectrum-assignment process.

4 Performance evaluation

In this section, we compare the results for the proposed ILP models. We consider the same 3-cube intra-DCN topology as shown in Figures 1 and 2 and the same service-request matrices for all the anycast, manycast, and unicast ILP models.

4.1 Result comparisons for minimizing the maximum number of intra-DCN resources

For all the ILP models with the objective of minimizing the maximum number of DCN resources, we assume the number of service requests varies as 10, 12, 14 and 16. First, for unknown DCN resources but known service-request matrices, we evaluate and compare the maximum numbers of required frequency slots and IT units, say F and I, respectively, for anycast, manycast, and unicast ILP models,

Table 1 Comparison of the minimum values of Fs and Is. SRs means No. of service requests

Model name	SRs = 10		SRs = 12		SRs = 14		SRs = 16	
	F	I	F	I	F	I	F	I
NA-Anycast-minFI	209	76	209	76	289	76	289	76
LP-Anycast-minFI	209	76	209	76	289	76	289	76
NA-Manycast-minFI	150	40	189	52	248	58	253	63
NA-Unicast-minFI	257	114	277	118	405	118	450	118

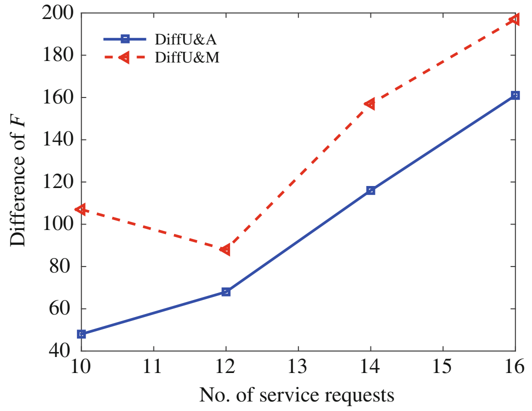

Figure 3 (Color online) Difference of F Between Unicast and Anycast (DiffU&A), Unicast and Manycast (DiffU&M).

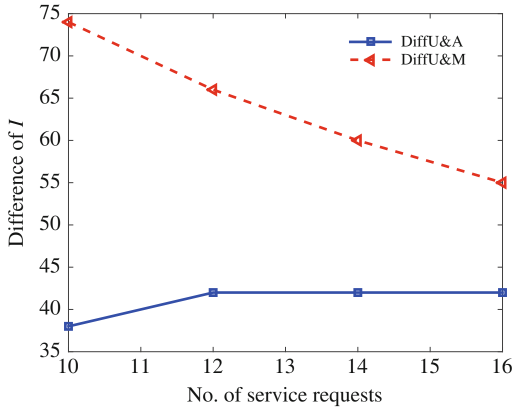

Figure 4 (Color online) Difference of I Between Unicast and Anycast (DiffU&A), Unicast and Manycast (DiffU&M).

i.e., *NA-Anycast-minFI*, *LP-Anycast-minFI*, *NA-Manycast-minFI*, and *NA-Unicast-minFI*. The result comparison is shown in Table 1. Then in Figures 3 and 4, we set the results of *NA-Unicast-minFI*/*LP-Anycast-minFI* (both of them show exactly the same results) as a normalized one and show the performance differences between unicast and anycast (DiffU&A), and unicast and manycast (DiffU&M) in terms of Fs and Is, respectively.

From the results shown in Table 1, Figures 3 and 4, we can see that the values of Fs and Is under anycast and manycast ILP models are much smaller than that of unicast ILP model for all different numbers of service requests. Between anycast and manycast ILP models, manycast shows much better performance than anycast. More specifically, from the values of Fs shown in Table 1 and Figure 3, the differences between unicast and anycast, and unicast and manycast increases with the increasing numbers of service requests. Especially, when the number of service requests is 16, the value of F under manycast ILP model is 253, which approaches to half of that of unicast model, say 450.

For numbers of IT units, i.e., Is, as shown in Table 1 and Figure 4, the difference between unicast and anycast (DiffU&A) maintains under different numbers of service requests, since both of the two models requires almost the same number of IT units under different numbers of service requests. Nonetheless, the difference between unicast and manycast (DiffU&M) is more dynamic under smaller number of service requests. As the number of service request increases, the differences shrink slightly, which is due to the increasing values of Is of manycast ILP model but constant Is of unicast ILP model.

The above results indicate that it is much more efficient to adopt anycast or manycast routing in intra-DCNs since they require much smaller number of DCN resources even for accommodating the same number of service requests when compared to unicast routing. The results are reasonable because when using anycast or manycast routing, both of the required numbers of frequency slots and IT units of any service request would be provisioned by simultaneously selecting an available destination node/multiple destination nodes and an available lightpath/multiple lightpaths in a just-fit and best-effort manner. However, for unicast method, since the destination is fixed, either the insufficient frequency slots on a lightpath or the insufficient IT units of a destination node would lead to another choice which requires larger provisions in both frequency slots and IT units. It is also expected that manycast ILP model

Table 2 Comparison of the maximum values of SFs and SIs. SRs means No. of service requests

Model name	SRs = 10			SRs = 13			SRs = 16		
	SF	SI	TOTAL	SF	SI	TOTAL	SF	SI	TOTAL
NA-$Anycast$-$mAXSFI$	1194	290	1484	1486	356	1842	2120	477	2597
NA-$Unicast$-$maxSFI$	1201	283	1484	1483	304	1787	2048	337	2385

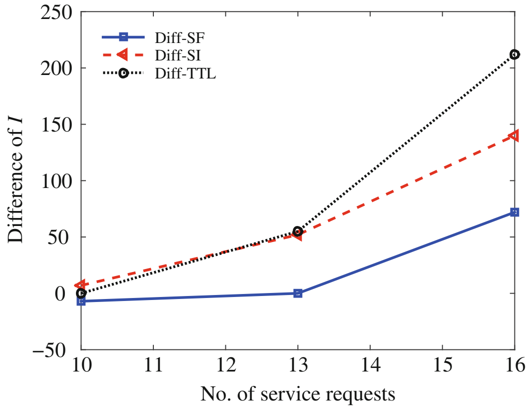

Figure 5 (Color online) Difference between anycast and unicast ILP models in terms of served spectrum frequency slots (SF), served IT units (SI), and total intra-DCN resources.

performs better than anycast ILP model. This is because in manycast ILP model, service requests that require larger numbers of frequency slots and/or IT units can be divided into smaller pieces and distributed to different destination nodes, which are relatively easy to satisfy.

4.2 Result comparisons for maximizing the number of successfully served service requests

In this part, for given number of available DCN resources and known service-request matrices of intra-DCNs, we evaluate and compare the intra-DCN service-provisioning capacity in terms of successfully serving service requests. For both ILP models with the objective of maximizing the successfully served service requests, we assume the number of service requests varies as 10, 13, and 16. The number of successfully served service requests is evaluated in terms of successfully served frequency slots and IT units, say SFs, SIs, respectively. Their results are shown in Table 2. We set the results of NA-$Unicast$-$maxSFI$ as a normalized one and show the differences of SFs (Diff-SF), SIs (Diff-SI), and total of both SFs and SIs (Diff-TTL) between it and anycast in Figure 5.

From the results shown in Table 2 and Figure 5, we can see that the maximum numbers of served service requests in terms of both served frequency slots (SFs) and served IT units (SIs) of anycast ILP model are much higher than that of the unicast ILP model. When the number of service requests is relatively smaller, say 10, the difference between served frequency slots is not obvious. Under ten given service requests, the number of served frequency slots of unicast ILP model is even slightly higher than that of anycast ILP model, say 1201 versus 1194. However, for served IT units (SIs), anycast ILP model shows better performance even under ten given served requests, say 290 versus 283. For the total value of both SFs and SIs, anycast almost outperforms unicast. As the number of service requests increase, the differences of SFs (Diff-SF), SIs (Diff-SI) and total (Diff-TTL) between anycast and unicast ILP models grows dynamically as shown in Figure 5. The results indicates that anycast ILP model can perform much better than unicast ILP model in successfully provisioning service requests even under the same intra-DCN environment.

4.3 Complexity comparison

In this part, we compare the complexity of the proposed ILP models in terms of the dominant numbers of variables and constraints. Their results are analyzed and compared in Table 3. The results of the

Table 3 Complexity comparison

Model name	Dominant number of variables	Dominant number of constraints
NA-Anycast-minFI	$O(\|V\|.\|R\|)$ or $O(\|L\|.\|R\|)$ or $O(\|V\|^2)$	$O(\|V\|^2.\|L\|.\|R\|)$
LP-Anycast-minFI	$O(\|R\|^2)$ or $O(\|P\|.\|R\|)$	$O(\|V\|.\|P\|.\|R\|)$
NA-Manycast-minFI	$O(\|R\|^2.\|M\|^2)$ or $O(\|R\|.\|M\|.\|V\|)$	$O(\|V\|^2.\|M\|.\|L\|.\|R\|)$
NA-Unicast-minFI	$O(\|S\|^2)$ or $O(\|S\|.\|L\|)$ or $O(\|S\|.\|V\|)$	$O(\|V\|^2.\|S\|.\|L\|)$
NA-Anycast-mAXSFI	$O(\|V\|.\|R\|)$ or $O(\|L\|.\|R\|)$ or $O(\|V\|^2)$	$O(\|V\|^2.\|L\|.\|R\|)$
NA-Unicast-maxSFI	$O(\|S\|^2)$ or $O(\|S\|.\|L\|)$ or $O(\|S\|.\|V\|)$	$O(\|V\|^2.\|S\|.\|L\|)$

Table 4 Complexity comparison for A 3-cube intra-DCN based on the actual numbers of variables and constraints given by Gurobi ILP solver. No. of service requests = 12

Model name	Rows (variables)	Columns (constraints)
NA-Anycast-minFI	428	2108
LP-Anycast-minFI	326	2146
NA-Manycast-minFI	2378	17528
NA-Unicast-minFI	398	1980
NA-Anycast-mAXSFI	506	2086
NA-Unicast-maxSFI	422	1985

dominant numbers of variables and constraints varied based on whether a model uses anycast, manycast, or unicast and whether node-arc or link-path based methods is used. In Table 3, $|V|$, $|L|$, $|R|$, $|P|$, $|S|$, and $|M|$ represent the total numbers of nodes, links, service requests, paths, source-destination pairs, and the maximum destination nodes that can be selected by a manycast service request.

The total numbers of variables and constraints given by the Gurobi ILP solver when solving the six ILP models for a 3-cube network are given in Table 4. The number of service requests under for all the ILP models are 12. For $|P|$, since the K-shortest path algorithm is used, it varies according to the number of K. In our model, we set K to 1 which means that there is only one path from each source node to each candidate destination node. Therefore, the values of $|V|$, $|L|$, $|R|$, $|P|$, $|S|$, and $|M|$ are 8, 12, 12, 56, 28, and 2, respectively. From the results we can see that even though manycast can perform the best in minimizing the maximum number of required DCN resources, it suffers from the highest complexity than all the other ILP models. The number of columns of manycast ILP model is almost ten times higher than the other ILP models. Except it, all the other ILP models show similar complexity.

5 Conclusion

In this paper, we addressed the static routing, spectrum and IT resource assignments (RSIA) issues for intra-DCNs by proposing different ILP models. First, for given service-request matrices but unknown intra-DCN resources, we proposed node-arc and link-path based ILP models using anycast routing to minimize the maximum numbers of network and IT resources. Then, we proposed node-arc based manycast ILP model with the same objective. Results show that manycast ILP model performs the best in requiring the least number of DCN resources to accommodate the same number of service requests. Nonetheless, it suffers from the highest complexity. Second, for given number of network and IT resources as well as given service-request matrices, we proposed node-arc based anycast ILP model to maximize the total number of successfully served service requests. The results were compared to the unicast ILP model and it showed that anycast ILP model can perform better in successfully serving service requests even under the same intra-DCN environment.

Acknowledgements This work was supported in part by National Research Foundation of Korea (Grant No. 2015R1C1A1A02036536), in part by Ajou University Research Fund, and in part by MSIP (Ministry of Science, ICT and Future Planning), Korea, under ITRC (Information Technology Research Center) Support Program

(IITP-2016-H8501-16-1015) supervised by the IITP (Institute for Information & communications Technology Promotion).

Conflict of interest The authors declare that they have no conflict of interest.

References

1 Farrington N, Andreyev A. Facebook's data center network architecture. In: Proceedings of IEEE Optical Interconnects Conference, Santa Fe, 2013. 49–50

2 Greenberg A, Hamilton J R, Jain N, et al. VL2: a scalable and flexible data center network. In: Proceedings of the ACM SIGCOMM 2009 Conference on Data Communication. New York: ACM, 2009. 51–62

3 Al-Fares M, Loukissas A, Vahdat A. A scalable, commodity data center network architecture. In: Proceedings of the ACM SIGCOMM 2008 Conference on Data Communication. New York: ACM, 2008. 63–74

4 Peng L M, Shen G X. Virtual-pod-assisted resource assignment in elastic all-optical switching intra-datacenter networks. In: Proceedings of the Asia Communications and Photonics Conference, Hong Kong, 2015. AM1H.4

5 Peng L M, Youn C-H, Tang W, et al. A novel approach to optical switching for intra-datacenter networking. IEEE/OSA J Lightw Technol, 2012, 30: 252–266

6 Shen G X, Guo H, Bose S K. Survivable elastic optical networks: survey and perspective. Photon Netw Commun, 2015, 31: 71–87

7 Shen G X, Zukerman M. Spectrum-efficient and agile O-OFDM optical transport networks: architecture, design, and operation. IEEE Commun Mag, 2012, 50: 82–89

8 Wei Y, Shen G X, Bose S. Span-restorable elastic optical networks under different spectrum conversion capabilities. IEEE Trans Reliab, 2014, 63: 401–411

9 Chandra A, Gong W B, Shenoy P. Dynamic resource allocation for shared data centers using online measurements. In: Proceedings of the 2003 ACM SIGMETRICS International Conference on Measurement and Modeling of Computer Systems. New York: ACM, 2003. 300–301

10 Al-Fares M, Radhakrishnan S, Raghavan B, et al. Hedera: dynamic flow scheduling for data center networks. In: Proceedings of the 7th USENIX Conference on Networked Systems Design and Implementation, San Jose, 2010. 19

11 Wang L, Zhang F, Vasilakos A, et al. Joint virtual machine assignment and traffic engineering for green data center networks. ACM SIGMETRICS Perform Eval Rev, 2013, 41: 107–112

12 Gharbaoui M, Martini B, Cerroni W, et al. Network resource allocation in data center interconnection with anycast service provisioning. In: Proceedings of the 2012 IEEE Global Communications Conference (GLOBECOM), Anaheim, 2012. 2511–2516

13 Li X, Wang H, Ding B, et al. Resource allocation with multi-factor node ranking in data center networks. ACM J Future Gener Comput Syst, 2014, 32: 1–12

14 Cai A L, Shen G X, Peng L M, et al. Novel node-arc model and multi-iteration heuristic for static routing and spectrum assignment in elastic optical networks. IEEE/OSA J Lightw Technol, 2013, 31: 3402–3413

15 Christodoulopoulos K, Tomkos I, Varvarigos E. Spectrally/bitrate flexible optical network planning. In: Proceedings of the 36th European Conference and Exhibition on Optical Communication (ECOC), Torino, 2010. 1–3