Virtual-Pod-Assisted Routing and Resource Assignment in Elastic All-Optical Switched Intra-Datacenter Networks

Limei Peng, Min Chen, Kiejin Park, and Chan-Hyun Youn

***Abstract*—Service requests of intra-datacenter networks (intra-DCNs) are different from traffic demands of traditional transport networks in the following features: 1) The latter is typically generated between dedicated node pairs that only require sufficient transmission bandwidth, i.e., frequency spectrum. Intra-DCN service requests, in contrast, require IT resources, such as computational, memory and storage resources, in addition to the transmission bandwidth. 2) For a given intra-DCN service request, any intra-DCN node that can provide the required IT resources can serve as a destination node. Thus, this type of network poses an important research problem of routing and spectrum/IT resource assignment (RSIA).**

To support these features, we first develop an integer linear programming (ILP) model to address the static RSIA problem, and then propose efficient heuristic algorithms to address the dynamic RSIA issues, subject to the intra-DCNs' limited network resources. The results of the proposed ILP model and heuristic algorithms are compared with the traditional network models and algorithms. It is found that the proposed ILP model and dynamic algorithms perform much better than the traditional approaches in terms of using intra-DCN network resources and reducing the service-request blocking probabilities.

I. Introduction

Datacenters (DCs) have received increasing attention in recent years since they serve as a key element in Cloud computing services, allowing most leading information technology (IT) companies to provide both real-time access to millions of mobile users [1], [2], and bulk data transfers for distributed storage services. For instance, more than 1.35 billion people use Facebook on an ongoing basis. All these users rely on seamless and always-on site performance, which requires advanced sub-systems and infrastructures, such as datacenters. The data volume from Facebook to the Internet is huge and ever increasing as more people connect and more new products and services are developed [3], [4].

However, the largest data volume is not from Facebook to the Internet, but within/among datacenters. This is because every time a user logs into a social-media site such as Facebook, hundreds of geographically dispersed servers are called into action to complete different parts of the user's task on the fly. In other words, what happens inside/among the Facebook datacenters is several orders of magnitude larger than what goes out to the Internet. The same situation exists in the datacenters of other leading IT companies, such as Google, Twitter, LinkedIn, etc. From this perspective, the efficient construction and management of datacenters show increased significance in maintaining the guaranteed high-performance and real-time services at the back-end of these enterprise Clouds.

A. Background

A DC is connected to hundreds of thousands of servers, which provide a huge number of resources, such as computational, memory, and storage resources that are generally called IT resources. Several DCs are then interconnected with each other to form a datacenter network (DCN). A DCN plays a pivotal role to DCs since it connects all their IT resources and provides network transmission bandwidth for massive service requests to switch among DCs. In other words, DCNs provide 2-dimenational resources including both network transmission bandwidth and IT resources. Nonetheless, most of the early studies on DCNs focused on extending the network transmission bandwidth capacity and develop efficient switching technologies. Specifically, Cloud service [5]–[7] requests have exhibited tremendous growth in the past years, and the currently increasing social-multimedia requests show no sign of stopping [8]. These growing Cloud-service requests, such as text or video messages, albums, and interaction activities, show diverse attribute features [9]. The arrival rates, sizes, and attributes of these service requests are quite bursty and dynamic [10]. These facts have driven us to construct DCNs with huge transmission-bandwidth capacities as well as flexible-switching capabilities to handle the ever-increasing and bursty Cloud service requests [11]. In the past decades, great efforts have been made to develop various efficient and scalable DCN interconnection architectures, so as to satisfy the DCNs' requirements for huge transmission bandwidth and flexible switching capability [12]–[16].

To extend the DCNs' transmission-bandwidth capacity, switching technologies have evolved from pure electrical switching, to hybrid electric/optical switching, and then to all-optical switching. To improve the switching flexibility of all-optical switched DCNs, technologies have evolved from huge expensive single optical switches, which can support hundreds of ports, to all-optical network interconnections, which are composed of numerous small-and-cheap off-the-shelf optical

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switches that are interconnected using promising switching technologies, such as optical orthogonal frequency-division multiplexing (O-OFDM) [17], [18], [44].

O-OFDM technology has received tremendous attention and has been extensively explored in recent years, because of its efficiency in using the frequency spectrum. Compared to the traditional wavelength-division multiplexing (WDM) technology, which follows the ITU-T (International Telecommunication Union's Telecommunication Standardization Sector) fixed frequency-grid standard [17], and thus introduces low spectrum utilization, O-OFDM uses flexible frequency grids. It allocates bandwidth in a finer granularity and allows partial spectrum overlapping, which greatly increases the switching flexibility and, thus, can match the bursty DCN service requests very well. This type of network is called an elastic all-optical switched DCN and has attracted increasing attention in recent years.

DCNs can be divided into inter-DCN and intra-DCN, according to their communication scales. Inter-DCN consists of DC nodes along with general backbone core nodes that do not connect to any DC, and simply forms a virtual network on top of the public Internet. An intra-DCN attempts to interconnect a number of geographically adjacent pods or top-of-racks that are connecting to hundreds of thousands of servers, and thus has a much smaller communication scale than the inter-DCNs. As a result, most of existing studies on intra-DCNs have concentrated on proposing regular interconnection topologies that are scalable with huge transmission capacities and flexibly switching capabilities. Specifically, most of them adopt regular topologies, such as Fat-tree, BCube, DCell, VL2, Torus, n-Cube etc., because of their simplicity and self-similarity, which indicate good scaling capability [12]–[14], [17]–[19], [43]. For inter-DCNs, since they are physically deployed based on existing backbone networks, which is difficult to reconfigure, few efforts have been made on designing their interconnection architectures. Instead, routing and resource assignment (RRA) issues, which are similar to routing and wavelength/spectrum assignment (RWA/RSA) issues in traditional backbone networks [38], [39], have attracted great attentions in the past years. Nonetheless, such issue has not received sufficient attention for intra-DCNs and few efforts have been made so far as we know.

Service requests of intra-DCNs are quite different from the traffic demands of traditional transport networks. More specifically, traditional traffic demands are generated for dedicated source-destination (SD) node pairs, and only require sufficient transmission bandwidth [40]. In contrast, intra-DCNs require IT resources, in addition to sufficient transmission bandwidth. Another feature of intra-DCN service requests is that, for a given service request of a source node, any intra-DCN node that can provide the required IT resources can serve as a destination node. These features indicate much more flexibility and complexity in addressing the routing and resource-assignment (RRA) issues of intra-DCNs, when compared to traditional traffic-demand transport networks. In traditional elastic all-optical transport networks, RRA is actually the resource and spectrum assignment (RSA) issue in existing work. Nonetheless, for elastic all-optical switched intra-DCNs, RRA is summarized as the routing and spectrum/IT-resource assignment (RSIA) issue. Obviously, traditional RSA approaches are not appropriate for serving intra-DCN service requests. Novel RSIA strategies are required to more efficiently manage and utilize intra-DCN resources, including transmission-bandwidth resources and IT resources, by considering the advantages of O-OFDM technology.

Inter-DCN service requests also exhibit similar features since they also require both transmission bandwidth and IT resources for Cloud service request [41], [42]. However, the main difference is that since they are physically deployed on top of existing backbone networks, most of the existing studies that addressed RRA issues for inter-DCNs considered the same backbone network architecture by connecting only a few DC nodes to the backbone networks. Therefore, IT resources are only required on the sporadic interconnected DC nodes by Cloud service requests. Nonetheless, this is not the case for traditional backbone traffic demands that are also provisioned. In contrast, for intra-DCNs, since every pod/top-of-rack that are connecting to hundreds of thousands of servers provides the IT resources and all the requests are Cloud service requests, IT resource provisioning on every pod should be considered for all the service requests, which is quite different from that of the inter-DCNs.

B. Related works

After an intense wave of effort to develop efficient DCN interconnection architectures for intra-DCNs, researchers turned to work on RRA issues, especially for all-optical inter-DCNs. Existing studies on RRA issues can be classified according to whether they consider network resources (network resource-oriented), IT resources (IT resource-oriented), or both (joint network- and IT-resource oriented). Note that throughout this paper, unless otherwise specified, network resources refer to transmission bandwidth in terms of wavelength or spectrum slots.In addition, optimizations of cloud computing by using genetic algorithms have been explored by prior researches, which addressed the resource scheduling improvements [21], [22].

As an example of network-oriented work, *M. Al-Fares et al.* presented a scalable and dynamic flow-scheduling system called Hedera [23], 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, *A. Chandra et al.* discusses dynamic resource allocation for web applications running on shared datacenters [24]. 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, *L. Wang et al.* [25] 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. *X. Li et al.* [26] 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.*Qiu et al.* [27] proposed an optimization algorithm for data allocations in mobile cloud systems, which used dynamic programming to produce optimal solutions to energy-aware data allocation plan.

M. Gharbaoui et al. also considered the joint management of network and IT resources for inter-DCNs in [28]. 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. *L. Zhang et al.* investigated offline and online RSA problems for anycast requests in elastic optical inter-DCNs [29]. An integer linear programming (ILP) model was formulated for offline problems, and several heuristic algorithms that jointly consider the computing and bandwidth resources were designed for online problems.

A. Fallahpour et al. [30] presented a manycast ILP model and two heuristic algorithms to address the routing and spectrum assignment issue. The goal of the proposed model and algorithms was to minimize the overall network energy efficiency by turning off idle elements and adapting a cost function to model the energy consumption of network's components in the routing algorithm. Finally, two types of power supply for data centers, green and brown power supply, which used the above model and algorithms were studied.

C. H. Liu et al. [31]–[33] carefully studied the significant challenges when identifying the cause of congestion in a DCN down to the flow level on a physical port of a switch/router in real time with high accuracy, low computational complexity and good scalability to cope with the exploding data. The authors proposed a sketch-based algorithm, called P(d)-CU, based on the existing Conservative Update (CU) approach. It fully considers the amount of skew for different network services to aggregate traffic statistics of each service type at individual horizontally partitioned sketches. The authors also introduced a way to produce the real-time moving average of the reported results.

Further, the existing work can also be classified based on whether an anycast/manycast method is used. Anycast service-request routing entails finding a data channel that best suits both the network connectivity and IT resource requirements. Manycast service-request routing entails finding several data channels that together best suits both the network connectivity and IT resource requirements. Some studies [23]–[26] did not consider anycast or manycast routing; traditional unicast routing was used instead. Other studies [28]–[30] adopted the anycast/manycast approach, which was deemed to better match the DCN service-request features.

With the support of data centers and DCN technology, various big data analytics applications and services can be deployed. Hossain et al. proposed an algorithm using parallel clustered particle swarm optimization for big data-driven service composition [34]. The authors also proposed two other frameworks on cloud-assisted IoT for health monitoring, and on audio-visual emotion recognition using bid data, respectively [35], [36].

C. Contributions and Organization

In this paper, we concentrate on elastic all-optical switched intra-DCNs, and resort to the concept of a virtual-pod (V-pod) pool to discuss both static and dynamic routing and spectrum/IT resource assignment (RSIA) issues. We adopt anycast routing when considering jointly optimized network and IT resources for intra-DCNs. Intra-DCN service requests differ from those of traditional transport network traffic demands in the following aspects. First, the source-destination node pairs for any given traffic demand of a traditional transport network is dedicated, which indicates that a unicast method is more appropriate. However, for an intra-DCN service request from a source node, any node that can provide sufficient IT resources can be selected as its destination node. This feature drives us to apply anycast routing. Second, traditional transport network traffic demands only require the transmission bandwidth on fiber links to be satisfied. In contrast, intra-DCN service requests, in addition to the transmission bandwidth, also require the IT resources to be satisfied. This feature drives us to jointly consider both network and IT resources.

Specifically, we first address static RSIA issues for intra-DCNs by developing an integer linear programming (ILP) model based on anycast routing. Then, we propose dynamic RSIA heuristic algorithms for intra-DCNs based on the concept of node migration, which can be mapped with an anycast approach in static RSIA. The objectives of the ILP model and heuristic algorithms, respectively, are as follows. First, for given service-request matrices with unknown network and IT resources, we aim to minimize the required network-transmission bandwidth in terms of spectrum slots and the required IT resources. Second, we aim to minimize the blocking probability of service requests under the given number of network and IT resources.

The key contributions of this paper include the following:

- We introduce a regular elastic all-optical intra-DCN architecture based on O-OFDM technology, the denotation of service requests, and the concept of a virtual pod (V-pod) pool. Note that the concept of virtual pod pool has not been widely used in existing studies so far as we know.
- For a given elastic all-optical intra-DCN interconnection using the concept of a V-pod pool, we propose a static integer linear programming (ILP) model based on anycast, with the objective of minimizing the maximum number of required network and IT resources. The ILP model is proposed under the assumption of given service-request matrices, which inform the numbers of both required spectrum slots and required IT resources for each service

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2016.2612651, IEEE Access

request. The results obtained from the proposed anycast ILP model are compared with those of intra-DCNs using the unicast method.

- For V-pod pool-based elastic all-optical intra-DCNs, we assume the given amount of available network and IT resources, and develop dynamic RSIA algorithms using the concepts of full migration and partial migration to reduce the ratio of blocked service requests. The concepts of full migration and partial migration can be mapped to the anycast method used in the static ILP model, since they both use the idea of unfixed destination nodes for service requests. Simulation results are conducted, evaluated, and compared with algorithm that does not use migration methods, say no migration.

In addition, we would emphasize the differences between our work and existing studies that also consider joint network and IT resources [23]–[26], or anycast routing [28], [29]. First of all, none of them have address the joint network and IT resource assignment issue for intra-DCNs. All of them are for inter-DCNs, which indicates that only a few Cloud service requests require IT resources in a few DC nodes that are connected to traditional backbone network nodes. For example, only two DC nodes that provide IT resources are assumed to connect to the backbone networks in [29]. Our work concentrates on the joint optimization problem for intra-DCNs, in which IT resources are provided by all intra-DCN nodes. Second, since only sporadic DC nodes are distributed in inter-DCNs, anycast routing is actually only required on the sporadic distributed DC nodes, such as the two DC nodes in [29]. In our work, anycast routing is required on every intra-DCN node. Third, our work proposes the static ILP model with the objective of optimizing both network and IT resources, which have not been considered in existing studies. Existing study that also proposed anycast ILP model [29] just considered to optimize the number of required network resources, which were quite similar to RWA/RSA solutions in traditional optical transport networks. Finally, partial migration has rarely been considered in existing work.

The rest of the paper is organized as follows. In Section II, the intra-DCN architecture, representation of the intra-DCN service requests, and the concept of a V-pod pool are introduced. In Section III, an anycast-based ILP optimization model for addressing static RSIA issues is proposed. The results are evaluated and compared with that of an unicast model. Dynamic RSIA heuristic algorithms are developed by adopting the idea of node migration. Full and partial migration algorithms are proposed. In Section V, simulation results for the dynamic RSIA algorithms are investigated and analyzed. Section VI concludes the paper.

II. Intra-DCN Architecture, Service Request, and Virtual-Pod Pool

Intra-DCNs using O-OFDM-based elastic switching technology are considered in this paper. For intra-DCNs, regular topologies have been widely used, due to their advantages of simplicity and self-similarity [13], [14], [17]–[19]. In this work, we also use regular topologies, such as an n-cube [43], or torus [19], to interconnect pods for intra-DCNs. Fig. 1 shows an example of using a 3-cube to interconnect eight pods by twelve optical fiber links. Fig. 2 shows an example of using a 3-by-3 torus to interconnect nine pods by eighteen links. The switching technology among pods is based on O-OFDM technology. Each pod is supposed to connect with a large number of servers, which provide IT resources. We normalize the IT resources of the servers in each pod as IT units. Each IT unit is represented by a small grid, as shown in Figs. 1 and 2. The solid grids represent busy units and the blank ones represent unused ones.

Compared to the traditional traffic demands which only require network transmission bandwidth, intra-DCN service requests require both transmission bandwidth and IT resources. Thus, to represent the intra-DCN service requests, a 3-tuple denoted by SR (SRC, BW, IT) is used, where SR, SRC, BW, and IT represent a service request, source node of the service request, required transmission bandwidth in terms of spectrum slots, and required IT units, respectively. For example, SR (2, 50, 10) means that the service request is from source node 2, and the numbers of required spectrum slots and IT units are 50 and 10 units, respectively. In this paper, we assume the maximum transmission bandwidth capacity of a fiber link is 2000 Ghz. Each fiber link can be divided into 400 mini-grid spectrum slots with the same size of 5 Ghz. Note that for a given DCN service request, the two-dimensional network resources, e.g., spectrum slots and IT units, needed by different SD node pairs vary from case-to-case, since different destination nodes result in different routing paths, as well as different spectrum-assignment schemes. Meanwhile, different destination nodes may provide a varied number of available IT units. Thus, it is significant to select the most appropriate destination node for each request so as to minimize the total number of required DCN resources in terms of spectrum slots and IT units and, meanwhile, reduce the service-request blocking probability. Since a source node does not designate a specific destination node, any node that can provide the required number of IT units can be selected.

From this perspective, we use an uncertain/flexible parameter as the destination node rather than a fixed one, as shown in the SR representation where the destination node of each request is not preset. In other words, all the IT units of the different pods can be shared by all the service requests, so as to increase the utilization of the IT units and reduce the service-request blocking probability. To accomplish such resource sharing, we propose to use the concept of a virtual-pod (V-pod) pool, as shown in Fig. 3 [37]. More specifically, we virtually model all the pods, which are physically distributed in different locations, as a pod pool; thus, the IT units of all the pods can be shared among all the service requests. When one designated pod node cannot provide sufficient IT units for a service request, we migrate the IT unit requirements to any other destination pod that can provide sufficient IT units. Note that replacing the 3-cube in the lower layer of Fig. 3 with a 3-by-3 torus can give the same explanations on the concept of V-pod pool.

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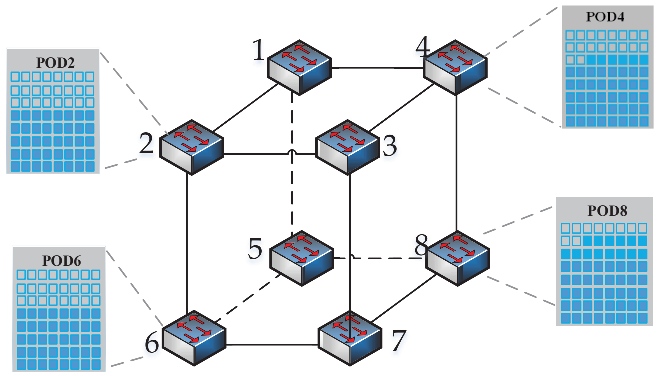

Fig. 1. A 3-Cube Elastic Intra-DCN Architecture

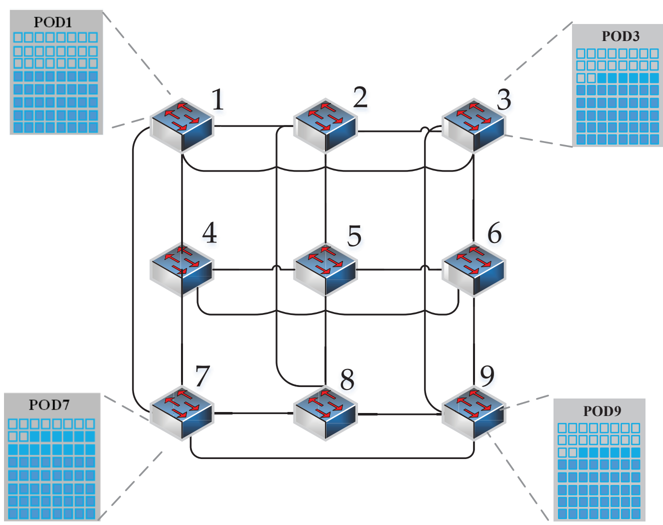

Fig. 2. A 3-by-3 Torus Elastic Intra-DCN Architecture

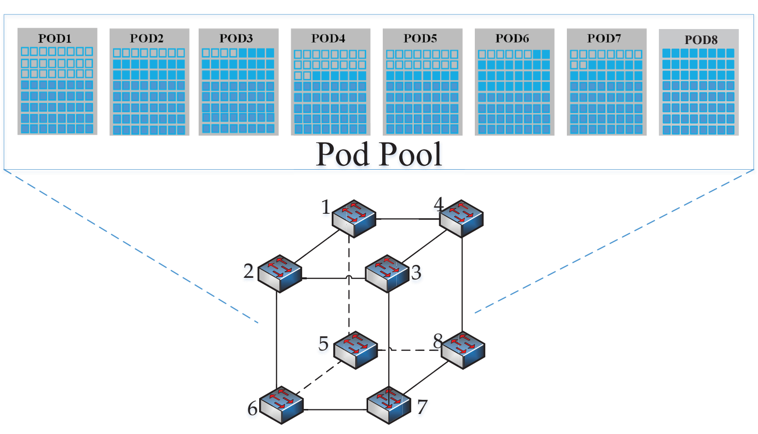

Fig. 3. An Illustrative Example of Virtual-pod Pool

III. ILP Model for Static Routing and Spectrum-Computing/Storage Assignment (RSCA)

A. *Anycast ILP Model for intra-DCN Static RSCA*

Provisioning DCN service requests with unset destination nodes is quite similar to the idea of anycast, since, for a given service request, any other node that can provide sufficient IT units is able to serve as a destination node. Therefore, we normalize the static RSIA problem to a static anycast issue for intra-DCNs, and advocate a node-arc-based ILP model to simultaneously optimize the required numbers of both spectrum slots and IT units. The ILP model proposed in this paper refers to the models in [38], [39]. Even though [29] also addressed the static-RSA issues using an ILP model, it used a link-path-based ILP model for inter-DCNs and only considered optimizing the network-transmission bandwidth.

Assume that a network topology (V, L) and service-request matrices that provide the required numbers of spectrum slots and IT units for each service request, are given as a prior. We consider a 3-cube topology with eight nodes and twelve optical fiber links, a 3-by-3 torus with nine nodes and eighteen optical fiber links, and a 3-tuple DCN service-request (SR) represented by SR (SRC, BW, IT), as introduced in the Section II. We aim to minimize the maximum number of required spectrum slots of all the fiber links, and the maximum number of required IT units of all the destination nodes that can accommodate all the intra-DCN service requests. The anycast ILP model based on a node-arc approach for the static RSIA of intra-DCNs is described as follows.

1) Sets

- V : Set of intra-DCN nodes.
- L : Set of intra-DCN links.
- R : Set of service request indices, $1, 2, \cdots, N$.
- 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 spectrum slots required by service request i.
- IT_i: Number of IT units required by service request i.
- F_{max}: Total number of required spectrum 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 spectrum 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 spectrum 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 spectrum 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

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

$$\Sigma_{m \in N} FN^i_m = 1, \forall i \in R \quad (2)$$

$$FN^i_m \leq PN^i_m, \forall i \in R, \forall m \in V \quad (3)$$

$$\Sigma_{mn \in LK_w} PL^i_{mn} = 2PN^i_w - FN^i_w, \forall i \in R, w! = SRC_i \quad (4)$$

$$PN^i_m + PN^i_n \geq 2 * PL^i_{mn}, \forall i \in R, \forall m, n \in V, \forall mn \in L \quad (5)$$

$$F \leq F_{max} \quad (6)$$

$$F \geq f_i + BW_i + G, \forall i \in R \quad (7)$$

$$F \geq \Sigma_{i \in R} PL^i_{mn} * BW_i, \forall mn \in L \quad (8)$$

$$\beta_{i,j} + \beta_{j,i} = 1, \forall i, j \in R \quad (9)$$

$$f_i + BW_i + G - f_j \leq F_{max}(1 - \beta_{i,j} + 2 - PL^i_{mn} - PL^j_{mn}), \forall i, j \in R, \forall mn \in L \quad (10)$$

$$\Sigma_i FN^i_m * IT_i \leq I, \forall i \in R, \forall m \in V \quad (11)$$

$$IT_i \leq I, \forall i \in R \quad (12)$$

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.

B. Unicast ILP Model for intra-DCN Static RSCA

To evaluate the efficiency of our proposed anycast ILP model 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 spectrum slots [39], [43], no unicast ILP model exists for addressing static RSIA issues of intra-DCNs, with the objective of minimizing the maximum numbers of both required spectrum slots and required IT units. For a fair comparison, we propose the unicast ILP model for addressing static RSIA issues of intra-DCNs based on a node-arc approach [39].

Similarly, assume that a network topology (V, L) and service request matrices that inform the required numbers of spectrum 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 optical fiber links, 3-by-3 torus topology with nine nodes and eighteen optical fiber 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 spectrum slots, and the required IT units. We aim to minimize the maximum number of required spectrum 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 [39]. Except for parameter IT_{sd}, variable I, and constraint (22), most of the rest of the sets, parameters, variables, and constraints are the same as or only slightly different from those in [39]. 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 IT 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^{sd}_{mn}: A binary value. The value is equal to 1 if the lightpath for node pair sd traverses physical link mn; zero, otherwise.
- PN^{sd}_{m}: 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 IT units among all the destination nodes of the entire intra-DCN.

4) Objective

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

5) Constraints

$$\Sigma_{mn \in LK_s} PL^{sd}_{mn} = 1, \forall sd \in SD \tag{13}$$

$$\Sigma_{mn \in LK_d} PL^{sd}_{mn} = 1, \forall sd \in SD \tag{14}$$

$$\Sigma_{mn \in LK_w} PL^{sd}_{mn} = 2PN^{sd}_{w}, \forall sd \in SD, w! = s, d \tag{15}$$

$$PN^{sd}_{m} + PN^{sd}_{n} \geq 2 * PL^{sd}_{mn}, \forall sd \in SD, \forall m, n \in V, \forall mn \in L \tag{16}$$

$$F \leq F_{max} \tag{17}$$

$$F \geq f_{sd} + BW_{sd} + G, \forall sd \in SD \tag{18}$$

$$F \geq \Sigma_{sd \in SD} PL^{sd}_{mn} * BW_{sd}, \forall mn \in L \tag{19}$$

$$\beta_{sd1,sd2} + \beta_{sd2,sd1} = 1, \forall sd \in SD \tag{20}$$

$$f_{sd1} + BW_{sd1} + G - f_{sd2} \leq F_{max}(1 - \beta_{sd1,sd2} + 2 - PL^{sd}_{mn} - PL^{sd}_{mn}), \forall sd \in SD, \forall mn \in L \tag{21}$$

$$\Sigma_{s \in V} IT_{sd} \leq I, \forall sd \in SD \tag{22}$$

Constraint (13) ensures that the lightpath for the service request between node pair sd starts from source node s. Constraint (14) ensures that the lightpath for the service request between node pair sd ends at destination node d. Constraint (15) 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 (16) 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 (17) 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 (18) 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 (19) 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 (20) and (21) 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 (22) ensures that, for any destination node, say 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.

C. Complexity Analysis

In this part, we compare the complexity of the anycast- and unicast-based ILP models in terms of the dominant numbers of variables and constraints for both 3-cube and 3-by-3 torus intra-DCN interconnections. According to the above anycast and unicast ILP models, the dominant numbers of variables and constraints of anycast-based ILP model are O($|V|.|R|$) or O($|L|.|R|$) or O($|V|^2$) and O($|V|^2.|R|.|L|$), respectively. In contrast, the dominant numbers of variables and constraints of unicast-based ILP model are O($|S|^2$) or O($|S|.|L|$) or O($|S|.|V|$) and O($|V|^2.|S|.|L|$), respectively. $|V|$, $|L|$, $|R|$, and $|S|$ represent the total numbers of nodes, links, service requests, and source-destination node pairs, respectively. The total numbers of variables and constraints obtained from Gurobi ILP solver for 3-cube and 3-by-3torus intra-DCN interconnections, respectively, are shown in Table I. The values of $|V|$, $|L|$, $|R|$, and $|S|$ are 8, 12, 12, and 28, respectively, for a 3-cube, and 9, 18, 12, and 36, respectively, for a 3-by-3 torus. From Table I, we can see that the unicast-based ILP model have similar complexity with that of anycast-based ILP model for both of a 3-Cube and a 3-by-3 torus.

TABLE I
COMPLEXITY COMPARISON FOR A 3-CUBE AND A 3-BY-3 TORUS INTRA-DCN TOPOLOGIES 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)
3-Cube	***Anycast***	428	2108
	Unicast	506	2086
3*3 Torus	***Anycast***	578	3003
	Unicast	482	2862

D. Result Analysis

In this part, we compare the results for the maximum numbers of required spectrum slots and IT units, say F and I, for the anycast and unicast ILP models of intra-DCNs, respectively. For both the anycast and unicast ILP models, we assume that the number of service requests varies as 12, 16, and 20. We consider the same 3-cube and 3-by-3 torus intra-DCN topologies and the same service-request matrices in all the simulations. The results for minimizing the maximum

TABLE II
RESULTS COMPARISON FOR ANYCAST ILP MODEL AND UNICAST ILP MODEL. SRS = 12 MEANS THE NUMBER OF SERVICE REQUESTS IS 12.

Model Name	SRs = 12		SRs = 16		SRs = 20	
	F	I	F	I	F	I
3-*Cube-Anycast*	209	76	289	76	318	96
3-*Cube-Unicast*	277	118	450	118	494	219
$3 * 3$ *Torus-Anycast*	209	76	238	76	248	81
$3 * 3$ *Torus-Unicast*	212	118	276	118	348	219

numbers of required spectrum slots and IT units for the anycast ILP model and unicast ILP model are shown in Tables II, respectively.

Observing the table, we can see that for both of the 3-cube and 3-by-3 torus interconnections, the values of F and I under the anycast ILP model are much smaller than those under the unicast ILP model for all different numbers of required service requests. Take a 3-cube for example, when the number of service requests is 20, the values of F and I under the anycast ILP model are 318 and 96, respectively, compared to the values of 494 for F and 219 for I under the unicast ILP model. Similar performance difference can be observed for a 3-by-3 torus interconnection.

When comparing 3-cube to 3-by-3 torus interconnections, it is observed that the 3-by-3 torus interconnection shows slightly better performance in aspect of requiring fewer DCN resources. This is mainly due to the fact that the average node degree (i.e., number of input/output links of a node) of a 3-by-3 torus topology is 4, which is higher than that of a 3-cube topology which is 3. This indicates that there are more provisioning selections when using a 3-by-3 torus interconnection and thus exhibits better optimization results.

As the number of service requests increases, the differences for F and I, respectively, between anycast and unicast ILP models also increase significantly. For the case of 20 service requests, the number of required IT units under the anycast model, say 96 for a 3-cube and 81 for a 3-by-3 torus is less than half of that required with the unicast model, say 219 for a 3-cube and 219 for a 3-by-3 torus. The results indicate that adopting the anycast method in intra-DCNs requires much fewer network resources, even when supporting the same number of service requests, compared to adopting the unicast method in intra-DCNs. The results are reasonable because, when using the anycast method, both the numbers of required spectrum slots and required IT units of any service request could be provisioned by simultaneously selecting an available destination node and an available lightpath in a just-fit and best-effort manner. However, for the unicast method, since the destination for each service request is fixed, either insufficient spectrum slots on a lightpath or insufficient IT units at a destination node would lead to another choice, which requires larger provisions in both spectrum slots and IT units.

The impacts of the weights of F and I in the objective formula are also evaluated for the anycast ILP model. We slightly revise the objective formula from $F + I$ to $F + \alpha I$ and $\gamma F + I$, respectively. All the sets, parameters, variables, and constraints remain the same. The number of service requests is set to 20 for all cases. Since 3-cube and 3-by-3 torus show similar trends, we only investigate for the 3-cube interconnection. We change the values of α and γ and show the results in Tables III and IV. From the results in Tables III and IV, we can see that there is almost no change in the values of the Fs and Is even though we change their weights in the objective formula. In other words, changing the weights of F and I does not further help reduce the required number of spectrum slots or IT units; however, it affects another item in the objective formula.

TABLE III
RESULTS UNDER DIFFERENT VALUES OF α, $F + \alpha I$

α	F	I
1	318	96
2	318	96
3	320	96

TABLE IV
RESULTS UNDER DIFFERENT VALUES OF γ, $\gamma F + I$

γ	F	I
2	318	96
3	318	96
4	318	97

If we increase the weight of I, i.e., increase α from 1 to 3, then F is slightly affected with a slightly increased value when α is 3, i.e., from 318 to 320. This is because I is given a higher priority with a higher weight value. However, the value for I is not further reduced. Similarly, if we increase the weight of F, i.e., increase γ from 2 to 4, then I is affected with a slightly increased value when γ is 4, i.e., from 96 to 97. This is because F is given a higher priority with a higher weight value. However, the value for F is not further reduced either. This indicates that the values of 318 for F and 96 for I, obtained when the weights for F and I are equal, are the minimum values required to serve all the service requests under all different cases, and it is impossible to further reduce these values by any means.

IV. V-POD-ASSISTED ALGORITHMS FOR DYNAMIC RSCA

Since ILP models for addressing static RSIA issues are generally restricted to evaluating intra-DCNs with limited network sizes, dynamic RSIA algorithms that can work well with larger-scale intra-DCNs are also needed. To address dynamic

RSIA issues, we were also inspired to develop algorithms according to whether the unicast method is appropriate.

When using unicast-based dynamic RSIA schemes with fixed destination nodes in intra-DCN, it is quite possible that hot pods and cold pods co-exist, since service requests are not equally distributed among all the pods. Hot pods are those with a higher load and are required to provide more IT units, while cold pods are those with a lower load and are underutilized most of the time. A high ratio of hot pods to cold pods can lead to a high blocking probability for service requests in hot pods and underutilization of DCN resources in cold pods, which will affect the overall intra-DCN performance. Therefore, addressing dynamic RSIA issues is similar to addressing static RSIA issues in that assigning flexible destination nodes for service requests can alleviate the above unbalanced hot and cold pods. Since the destination node for each request is flexible, we can schedule to equalize the use of both the overall transmission bandwidth of all fiber links and the IT resources of all DCN destination nodes, so as to balance the entire DCN-resource utilization and reduce the service-request blocking probability.

From this point of view, we propose two migration algorithms that can be matched with the anycast approach, i.e., full migration and partial migration. For a given service request, e.g., SR (0, 6, 5), we first randomly select a destination node, say node 10, for instance. The service request is then revised from SR (0, 6, 5) to SR (0-10, 6, 5). If the required five IT units cannot be satisfied by destination node 10, the entire service request will be migrated to another destination node, if any, when using full migration. For partial migration, if the originally designated destination node 10 can only provide two IT units, then only the remaining three IT units will be migrated to another destination node, if any. Similarly, no migration algorithm can be matched with the unicast approach since both of them use dedicated destination node for each service request. For the routing process of all the algorithms, we simply apply the shortest-path scheme based on the Dijkstra algorithm. In the following sections, we introduce the dynamic algorithms for full migration and partial migration.

A. Full Migration

The full migration algorithm includes various schemes to migrate from the originally designated destination nodes to other candidate destination nodes. We classify the schemes as IT first-fit (IT FF), IT best-fit (IT BF), integrated shortest-path first and IT FF (SPF+IT FF), and integrated SPF+IT BF. Their partial versions have been described in [43]. They are introduced as follows.

1) IT first-fit (IT FF) scheme. For the IT FF scheme, the migrating destination node is selected according to the number of remaining available IT units. If several candidate nodes can provide sufficient spectrum slots, then the first node that can provide a sufficient number of IT units is selected as the migrating destination node. Taking SR (0-10, 6, 5) for example, suppose the destination node 10 cannot provide the required 5 IT units; then, node migration is needed in the V-pod pool. If three candidate destination nodes, say nodes 1, 2, and 3, can provide 20, 10, and 5 IT units, respectively, and all have sufficient spectrum slots from node 0, then the first-fit node, i.e., node 1, which has the most available IT units, is selected. The service request is then revised from SR (0-10, 6, 5) to SR (0-1, 6, 5).
2) IT best-fit (IT BF) scheme. For the IT BF scheme, the migrating destination node is also selected based on the number of remaining available IT units. If several candidate nodes have sufficient transmission bandwidth from the source node, then the one that can provide the best-fit number of IT units is selected as the migrating destination node. For example, for SR (0-10, 6, 5), which is to be migrated, if three candidate destination nodes, say nodes 1, 2, and 3, can provide 20, 10, and 5 IT units, respectively, and all have sufficient spectrum slots from node 0, then node 3 is selected because it best fits the available IT units.
3) Integrated shortest-path first (SPF) and IT FF (SPF+IT FF) scheme. For the SPF+IT FF scheme, the migrating destination node is selected according to the number of hops from the source to the candidate destinations and the first-fit IT units. If several candidate nodes can provide the required numbers of transmission bandwidth and IT units, the first one that has the smallest number of hops from the source node is selected. For example, for SR (0-10, 6, 5), which is to be migrated, if three nodes, say nodes 1, 2, and 3, can provide 20, 10, and 5 IT units, respectively, and the hops from source node 0 to nodes 1, 2, and 3 are 7, 2, and 5, respectively, then node 2 will be selected as the migrating destination node.
4) Integrated SPF+IT BF scheme. For the integrated SPF + IT BF scheme, we combine the SPF and IT BF schemes. The candidate node that has the smallest number of hops from the source node and, meanwhile, can provide the best-fit number of IT units, will be selected as the migrating destination node. The flowchart of all the schemes is shown in Fig. 4.

B. Partial migration

The difference between the full migration and partial migration algorithms lies in that, when the originally designated destination node cannot provide the required number of IT units, the entire group of IT units will migrate to another destination when using full migration. However, when using partial migration, if the original designated destination node lacks 30% of the IT units, for example, only the insufficient 30% is migrated to another destination node. The original 70% of the IT units is still provisioned by the originally selected destination node. In other words, when scheduling a partial migrated service request, we first serve the number of IT units that can be provided by the originally designated destination

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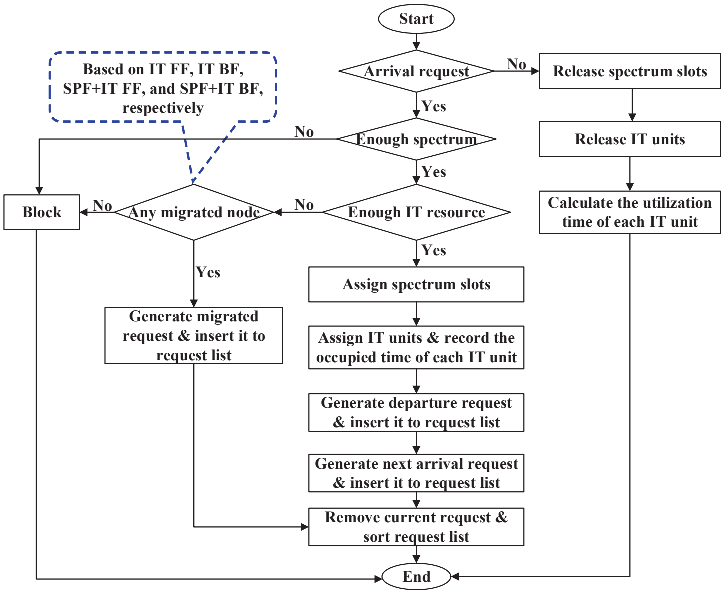

Fig. 4. Flowchart for Schemes of Full Migration

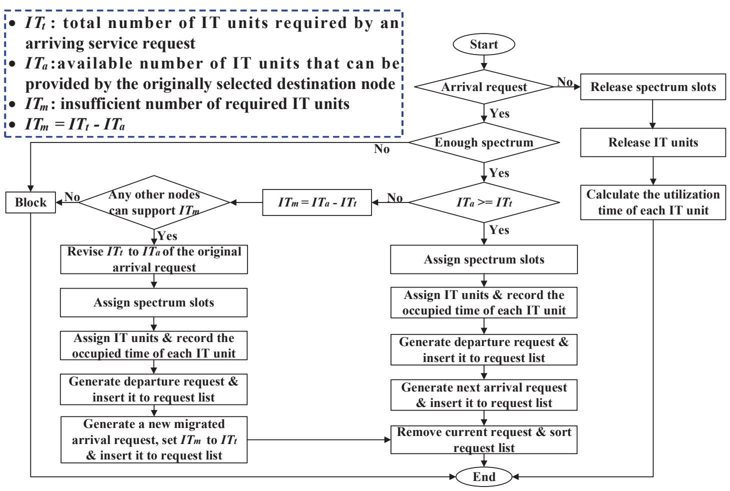

Fig. 5. Flowchart for Partial Migration

node; then, we migrate the insufficient part to another destination node. The schemes for migrating the insufficient part are the same as those for the full migration algorithm. We apply the integrated SPF+IT FF scheme to migrate the insufficient part of the IT units in the partial migration algorithm. The flowchart of the partial migration algorithms is shown in Fig. 5.

In Fig. 5, to provision an arriving service request i at destination node j, for example, IT_t denotes the total number of IT units required by the service request i that needs provisioning. IT_a denotes the available IT units that the originally designated destination node j can provide for the arriving service request i. IT_m indicates the lacking number of IT units required by service request i at node j; $IT_m = IT_t - IT_a$. If the value of IT_m is larger than 0, then this insufficient part of the required IT units should be migrated to another destination node; IT_a of the required C/S units is served by the originally designated destination node.

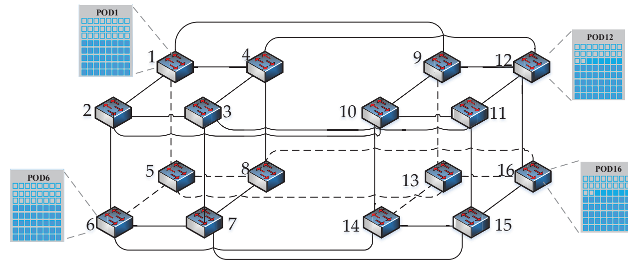

Fig. 6. A 4-Cube Intra-DCN Interconnection

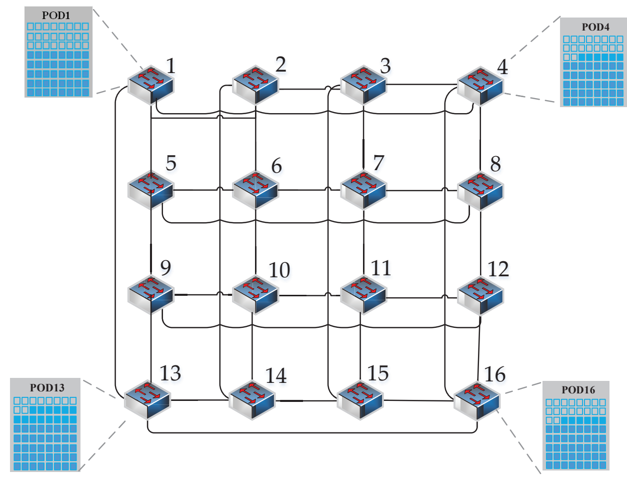

Fig. 7. A 4-by-4 Torus Intra-DCN Interconnection

V. Performance Evaluation

In this section, we evaluate and compare the simulation results for the dynamic RSIA algorithms. We assume a dynamic service-request model. Service requests are assumed to arrive in the form of a Poisson distribution, and the holding time of each service request follows an exponential distribution. A total of 10^6 service requests were generated and simulated. The network performance is evaluated in terms of service-request blocking probability and utilization of IT resources in the V-pod pool. The service-request blocking probability is defined as the ratio of the number of blocked requests to the total number of arrived requests. The utilization of IT resources is defined as (sum of occupied time of each IT unit) / ((total simulation time) * (total number of IT units)), where the amount of occupied time of each IT unit is calculated as the time duration from the moment that the IT unit is occupied to the moment that it is released.

We consider a 4-cube intra-DCN interconnection architecture consisting of 16 pod nodes and 32 optical fiber links as shown in Fig. 6 and a 4-by-4 torus intra-DCN interconnection architecture consisting of 16 pod nodes and 32 optical fiber links as shown in Fig. 7. The total available numbers of spectrum slots per fiber link and IT units per pod are assumed to be 400 and 200, respectively. The size of all spectrum slots is assumed to be 5 GHz. The average number of required spectrum slots per service request is assumed to be 3. The average number of required IT units per service request is assumed to be 2.

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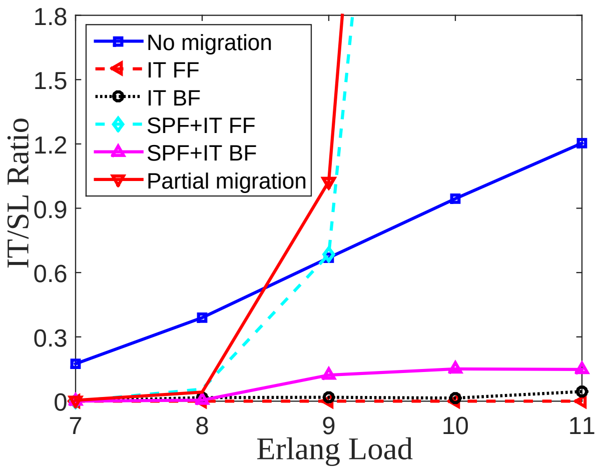

Fig. 8. Loss Ratio of IT Units to Spectrum Slots for A 4-Cube

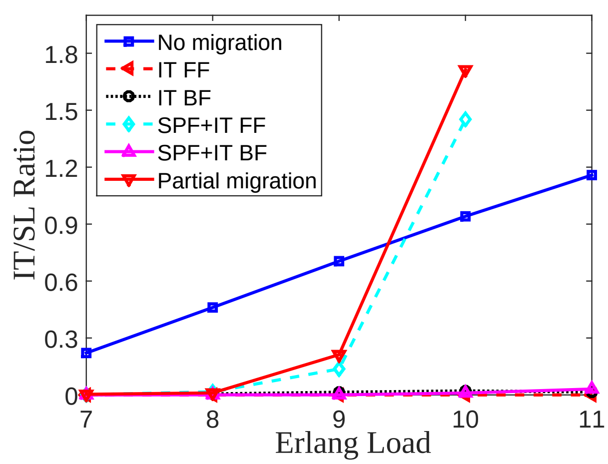

Fig. 9. Loss Ratio of IT Units to Spectrum Slots for A 4-by-4 Torus

A. Results Evaluation and Comparison between Algorithms Using Migration and Those Not Using Migration

Manipulation of the service request blocking by network resources in terms of spectrum slots or IT resources is evaluated first. Figs. 8 and 9 shows the loss ratio of IT units to spectrum slots (IT/SL loss ratio) under different network erlang loads for a 4-cube and a 4-by-4 torus, respectively. It is observed that, for most of the schemes, the IT/SL loss ratio is much less than one, which indicates that the effect of the number of required IT units is much weaker than that of the number of required spectrum slots.

For the IT BF, IT FF, and SPF+IT BF schemes, the ratios under all different erlang loads are very low. This means that the loss due to insufficient spectrum slots strongly affects the service-request blocking probability. This is because all these three schemes are biased to first solve the loss due to lacking IT units, and leave the loss due to insufficient spectrum slots to the second priority.

For the no-migration scheme, under lower erlang loads, the loss due to insufficient spectrum slots dominates the service-request blocking probability since the IT/SL value is much less than one. As the erlang load increases, the losses due to insufficient spectrum slots and IT units show similar impacts on the service-request blocking probability, since the ratio of IT/SL approaches one under higher erlang loads. Partial migration and SPF+IT FF schemes show dynamic increases in IT/SL-loss ratios from the point when the erlang load is 9. This does not mean that the loss due to lacking IT units increases dynamically, but indicates that the loss due to lacking spectrum slots is reduced significantly. This is attributed to the fact that these two strategies are prone to first reduce the service-request blocking probability due to insufficient spectrum slots.

Figs. 10 and 11 shows the request blocking probability and IT resource utilization for a 4-cube intra-DCN interconnection. The results in Fig. 10 show that the partial migration scheme performs the best in terms of the service-request blocking probability, followed by SPF+IT FF, SPF+IT BF, no migration, IT FF, and IT BF. We first compare the algorithms of no migration with full migration. It is observed that, among all the full migration schemes, IT FF and IT BF perform even worse. This can be attributed to the fact that the transmission bandwidth in terms of spectrum slots is shown to affect the service-request blocking probability more severely than the number of IT units does. In IT FF and IT BF, the provisioning of IT units is given higher priority than spectrum slots, which very likely leads to select a destination node with enough IT units but longer hops. Especially, for IT BF, source-destination (SD) pairs with more hops but best-fit IT units are very likely to be selected, which leads to a higher request-blocking probability.

In contrast to IT BF, because IT FF is less dedicated to selecting the best-fit IT units by sacrificing the transmission hops between SD pairs, it performs slightly better. Both SPF+IT FF and SPF+IT BF greatly outperform no migration, since SPF always chooses the SD pairs with fewer hops, which are easier to be satisfied with spectrum slots. In addition, they aim to simultaneously reduce losses due to insufficient IT units. Between them, SPF+IT FF outperforms SPF+IT BF significantly, which is attributed to the fact that IT FF outperforms IT BF. The partial migration algorithm based on SFP+IT FF significantly outperforms all of the full migration algorithms. This is because the service requests that need to be migrated in the partial migration algorithm require a smaller number of spectrum slots and a smaller number of IT units.

Fig. 11 shows the IT resource utilization of the entire V-pod pool. The scheme of partial migration performs the best, followed by SPF+IT FF, SPF IT+BF, no migration, IT FF, and IT BF. The results of the IT resource utilization are exactly implied by the trend of the service-request blocking probabilities in Fig. 10; i.e., lower request-blocking probability, higher IT resource utilization. Figs. 12 and 13 shows the request blocking probability and IT resource utilization for a 4-by-4 torus intra-DCN interconnection. The trends of the results in the two figures are almost the same with that of the results for a 4-cube based intra-DCN interconnection.

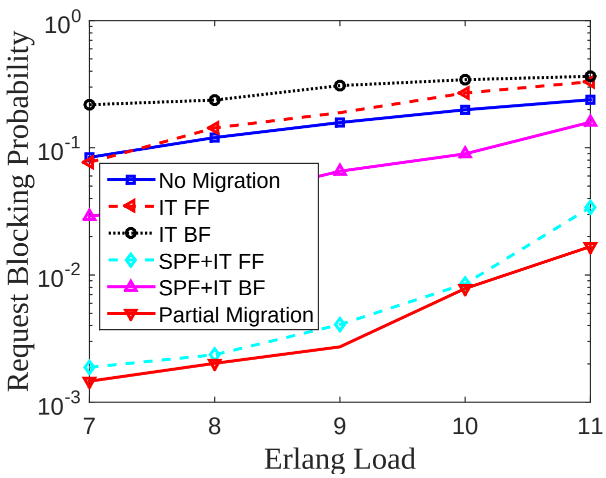

Fig. 10. Service-request Blocking Probability for A 4-Cube

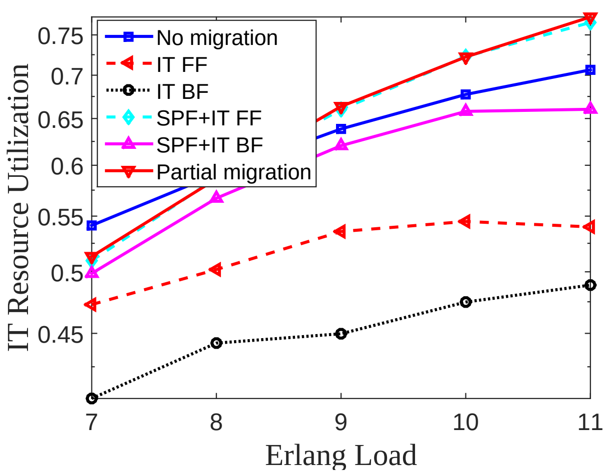

Fig. 11. IT Resource Utilization for A 4-Cube

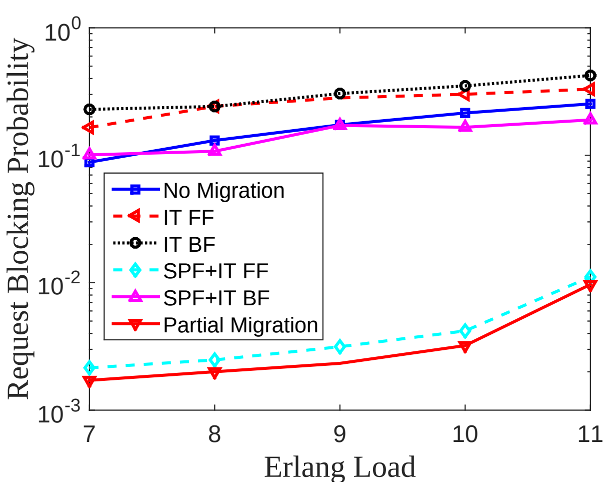

Fig. 12. Service-request Blocking Probability for A 4-by-4 Torus

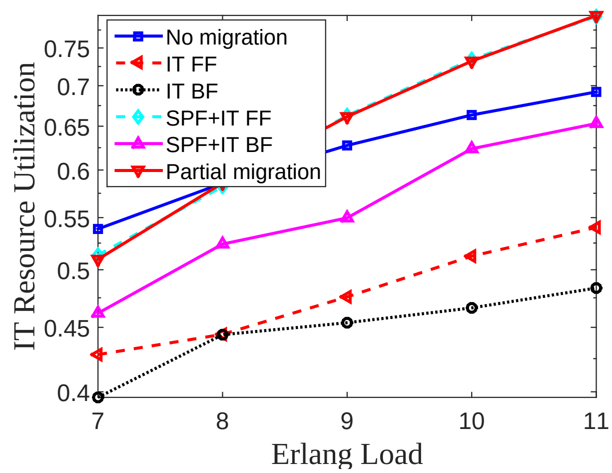

Fig. 13. IT Resource Utilization for A 4-by-4 Torus

B. Impact of Required Numbers of Spectrum Slots and IT Units on Intra-DCN Performance

In this part, we evaluate how the service requests' average numbers of spectrum slots and IT units affect the intra-DCN network performance. Since both 4-cube and 4-by-4 torus intra-DCN interconnections show similar performance trends in the IT/SL loss ratio, request blocking probability and IT resource utilization, we take 4-cube-based interconnection as an example in this investigation. SPF+IT FF full migration scheme is used. Fig. 14 shows the network performance when the number of required IT units per service request varies as 2, 3, and 4. For all three cases, the average number of required spectrum slots per service request is 3. It is observed that the service-request blocking probability increases dynamically with the increasing number of required IT units. The results are reasonable since a larger number of required IT units indicates more difficulties in successfully provisioning service requests. Nonetheless, the network performance in terms of IT resource utilization also increases with the increase in required IT units, as shown in Fig. 15. This is because even though the service-request blocking probabilities are higher for the cases with more required IT units, the size of the IT units occupied by each service request is also much larger. Since the IT resource utilization is proportional to (number of successfully served service requests)*(average number of required IT units per service request), the IT resource utilization still increases dynamically for cases with larger average numbers of required IT units per service request, even when the number of successfully served service requests is slightly reduced.

Fig. 16 shows the network performance for different numbers of required spectrum slots (SLs) per service request. The number of required spectrum slots varies as 3, 4, and 5. For all three cases, the average number of required IT units per service request is 2. It is also observed that the service-request blocking probability increases dynamically with the increasing number of required spectrum slots. The results are reasonable since more required spectrum slots indicate more difficulties in successfully provisioning the service request.

The network performance of the IT resource utilization

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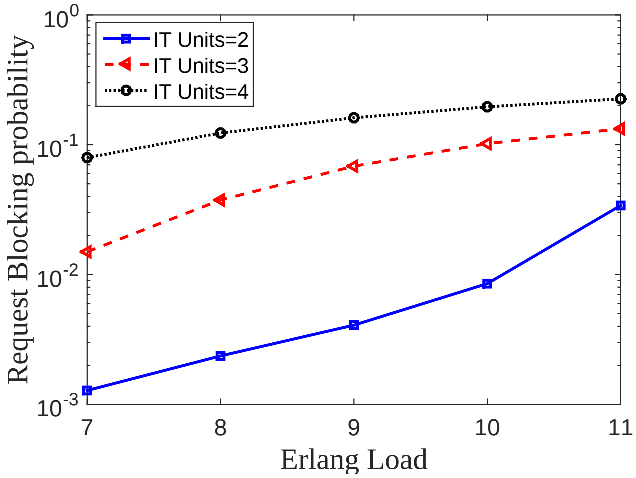

Fig. 14. Request Blocking Probability Under Different Numbers of IT Units for A 4-Cube

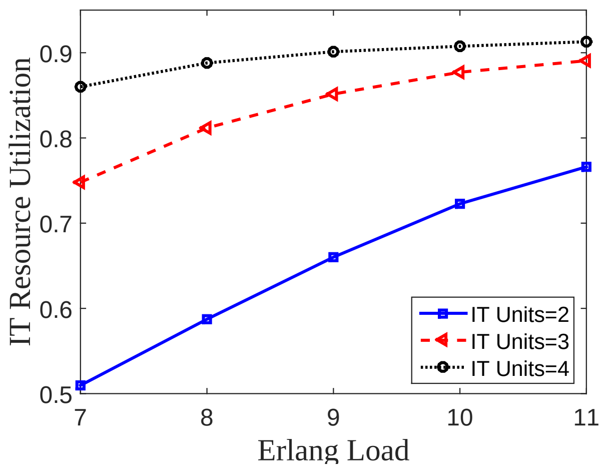

Fig. 15. IT Resource Utilization Under Different Numbers of IT Units for A 4-Cube

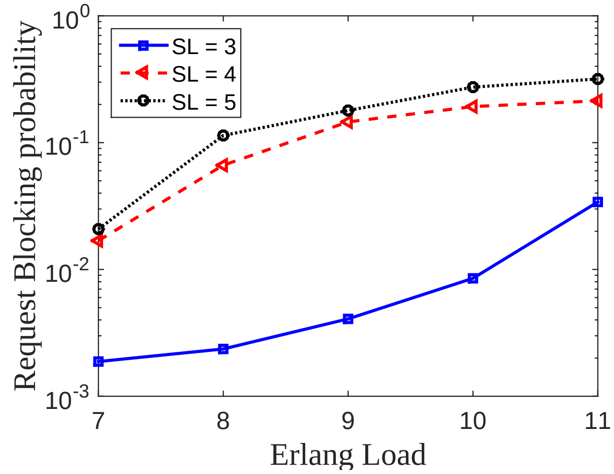

Fig. 16. Request Blocking Probability Under Different Numbers of Spectrum Slots for A 4-Cube

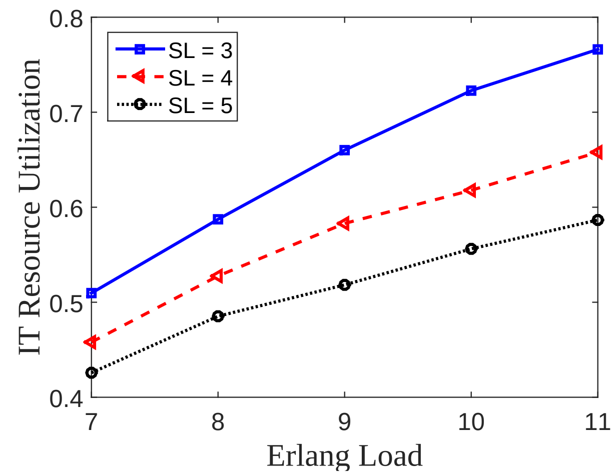

Fig. 17. IT Resource Utilization Under Different Numbers of Spectrum Slots for A 4-Cube

shows the reverse trend: It decreases with the increasing number of required SLs, as shown in Fig. 17. We note that this trend is the reverse of that for different numbers of required IT units. This is because, for cases requiring different numbers of IT units but the same number of spectrum slots per service request, the IT resource utilization is mainly affected by the average number of required IT units per service request. However, for cases requiring different numbers of spectrum slots but the same number of IT units per service request, the IT resource utilization is mainly affected by the number of successfully served service requests. Since a smaller number of required spectrum slots indicates a more successful provisioning probability, the IT resource utilization for a smaller number of required spectrum slots shows better IT resource utilization.

VI. Conclusions

In this paper, we investigated the issues of routing and spectrum/IT resource assignment (RSIA) for intra-DCNs by considering the unique features of DCN service requests and the advantage of O-OFDM technology. The concept of a virtual-pod pool was used for IT resource sharing among all the intra-DCN service requests. ILP models based on anycast were proposed for addressing static RSIA issues, and dynamic RSIA algorithms were developed based on full migration and partial migration algorithms for addressing dynamic RSIA issues. The concept of migration can be matched with the anycast method since both of them assume flexible destination-node selection for a given service request. Both the static RSIA ILP model and the dynamic RSIA algorithms showed obvious network performance improvements when compared to the cases using unicast schemes with a fixed-destination-node approach.

For the same given service-request matrices and the same network interconnection architecture, the proposed static ILP model using the anycast method showed much better performance than the model using the unicast method. Both of them aimed to minimize the maximum numbers of both required transmission bandwidth and IT resources. When given the same available network resources in terms of both transmission bandwidth and IT resources, the dynamic RSIA algorithms showed much better performance in terms of reducing the service-request blocking probability and increasing the IT resource utilization when compared to the approach using no migration.

ACKNOWLEDGEMENT

This work was supported in part by the National Research Foundation of Korea (Grant No. 2015R1C1A1A02036536), in part by the Ajou University Research Fund, in part by the Cross-Ministry Giga KOREA Project of the Ministry of Science, ICT and Future Planning, Korea [GK16P0100, Development of Tele-Experience Service SW Platform based on Giga Media], and has been performed as a collaborative research project through supercomputer development for leveraging the leadership of national supercomputing supported by KISTI. Prof. Min Chen's work was supported by the National Natural Science Foundation of China (grant No. 61572220).

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