Orchestrating Multicast-Oriented NFV Trees in Inter-DC Elastic Optical Networks

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***Abstract*—It is known that by incorporating network function virtualization (NFV) in inter-datacenter (inter-DC) networks, we can use the network resources more intelligently to deploy new services faster. This paper considers an inter-DC elastic optical network (IDC-EON) and studies how to orchestrate the multicast-oriented NFV trees (M-NFV-Ts) in it efficiently. We first consider an offline scenario in which all the M-NFV-Ts are known and need to be served in the network. A mixed integer linear programming (MILP) model is formulated to solve the problem exactly, and we also propose a heuristic based on path-intersection (PI) to reduce the time complexity. With extensive simulations, we show that the proposed heuristic can approximate the MILP's performance on low-cost M-NFV-T provisioning but only requires much shorter running time. Next, the online scenario where the M-NFV-Ts can come and leave on-the-fly is addressed, and we leverage PI to design two online algorithms for orchestrating dynamic M-NFV-Ts in IDC-EONs, *i.e.*, with either the batch (B-PI) or sequential (S-PI) scheme. Simulation results indicate that compared with S-PI, B-PI can reduce blocking probability effectively.**

***Index Terms*—Network function virtualization (NFV), Multicast, Elastic optical networks (EONs), Inter-datacenter networks.**

I. Introduction

Recently, with the rise of cloud computing and big data, the inter-datacenter (inter-DC) networks that inter-connect geographically distributed DCs have been deployed rapidly. Due to the dynamic nature of cloud-based applications, the traffic in such networks usually exhibit the co-existence of huge peak throughput and high burstiness [1]. It is known that with the tremendous bandwidth in fibers, optical networking provides inter-DC networks a viable and reliable infrastructure to support high-speed traffic economically [2]. Meanwhile, thanks to the technical advances on flexible-grid elastic optical networks (EONs) [3], agile bandwidth management can be realized in the optical layer and hence traffic demands with various bandwidth requirements can be provisioned more efficiently. Therefore, EON has become a promising physical infrastructure to realize future inter-DC networks [1, 4].

On the other hand, network function virtualization (NFV) has recently become an attractive topic. Basically, NFV enables network operators to realize virtualized network functions (vNFs) with generic network resources (*i.e.*, bandwidth, CPU cycles and memory space), for replacing the special-purpose network elements that are expensive and difficult to maintain and upgrade [5]. Hence, by incorporating NFV in inter-DC networks, we can use the network resources in a more intelligent manner, and deploy new services faster [6]. Note that, to support point-to-multiple-point communications (*e.g.*, DC backup and migration) efficiently, multicast sessions need to be established in inter-DC networks, while the multicast sessions can realize more functionalities by leveraging NFV trees. For instance, in a multicast-based DC backup, vNFs for data encryption can be placed on certain branches to address the differentiated trust-levels on destination DCs. Therefore, it would be relevant to study how to realize multicast NFV trees (M-NFV-Ts) efficiently in Inter-DC EONs (IDC-EONs).

Basically, to provision an M-NFV-T in an IDC-EON, we need to determine both the vNF placement and the routing and spectrum assignment (RSA) on the multicast tree to connect the source, vNFs and destinations. To the best of our knowledge, this problem has not been addressed in literature before. Note that, even though they look similar at first glance, the problem is fundamentally different from the multicast-capable routing and spectrum assignment (RSA) [7] and the multicast-oriented virtual network embedding (VNE) [8]. Multicast-capable RSA considers how to allocate bandwidth resources (*i.e.*, frequency slots (FS')) to support multicast sessions in EONs, while the DC-related IT resource allocation is not involved. Multicast-oriented VNE needs to embed virtual networks (VNs) for multicast services in a substrate EON. Although this does include the joint allocation of spectrum and IT resources, the topologies of VNs are known in advance. In our problem, the actual topology used to serve an M-NFV-T changes with the vNF placement. Moreover, NFV allows the same vNF on a DC to be shared by different M-NFV-Ts.

In this paper, we study how to realize efficient network orchestration in IDC-EONs. We first formulate a mixed integer linear programming (MILP) model to solve the problem exactly. Then, a heuristic algorithm based on path-intersection is proposed to reduce the time complexity. Finally, we consider M-NFV-Ts in dynamic IDC-EONs and design two online algorithms. The rest of the paper is organized as follows. Section II surveys the related work briefly. We describe the network model and define the problem of orchestrating M-NFV-Ts in IDC-EONs in Section III. The MILP model is formulated in Section IV, while the time-efficient heuristic is proposed and evaluated in Section V. In Section VI, we consider the online version of the problem. Finally, Section VII summarizes the paper.

II. Related Work

Since its inception, NFV has attracted a fair amount of interests from both academia and industry, and white papers have already been published online to stimulate the standardization activities [5, 9]. Moens *et al.* studied the vNF placement problem for a hybrid network environment in which physical network elements and vNFs can co-exist, and formulated an ILP model to solve it [10]. However, due to its complexity, the ILP model could only work in the offline manner. The placement of NFV chains in packet networks has been studied in [11], but only the unicast-oriented NFV chains were considered. The authors of [12] developed an approach to solve the routing problem for M-NFV-Ts in packet networks, under the assumption that the possible locations for vNFs are pre-determined. All the aforementioned investigations were not conducted under an optical networking background. Xia *et al.* addressed the vNF placement for NFV chaining in optical DCs in [13], and developed a binary integer programming model to minimize the optical-to-electrical-to-optical (O/E/O) conversions. Nevertheless, they considered neither the multicast-oriented NFV nor the bandwidth allocation in the optical layer. Note that, in optical DCs, the service provisioning scheme will be sub-optimal if we do not consider the allocations of bandwidth and IT resources jointly [14].

III. Problem Formulation

We model the IDC-EON as a directed graph $G(V, E)$, where V and E denote the sets of DC nodes and fiber links, respectively. Each DC node equips a bandwidth-variable optical switch for external communications. The IT resource capacity on DC $v \in V$ is denoted as C_v. We assume that a few types of vNFs can be instantiated on each DC in the IDC-EON, while Γ represents the set of vNF types. There are F FS' on each link $e \in E$.

An M-NFV-T request is denoted as $MR^i = \{s^i, D^i, T^i, b^i\}$, where i is its index, s^i is the source, D^i is the destination set, T^i is the set of requested vNFs, and b^i is the bandwidth requirement. Moreover, the data-flow to each destination of MR^i should be processed by a vNF. We define the j-th destination of MR^i as $d^{i,j} \in D^i$, and its requested vNF is $t^{i,j} \in T^i$. For $d^{i,j}$, its vNF can be realized on one of the DCs in set $N^{i,j}$. Here, we consider two kinds of vNFs, *i.e.*, the location-restricted and location-independent ones. A location-restricted vNF can only be provisioned on a designated DC, *i.e.*, $|N^{i,j}| = 1$, while a location-independent one can be placed on any DC node except the source node that the data-flow traverses, *i.e.*, $|N^{i,j}| = |V| - 1$. Since both spectrum and IT resources need to be allocated for realizing MR^i, we price the usage of an FS on a link as w_s and assume that the IT resources used by the vNFs to process per bit-rate traffic cost w_c. We also assume that instantiating a vNF on a DC incurs a deployment cost of w_v. Therefore, in order to realize M-NFV-Ts in an IDC-EON efficiently, we need to minimize the total cost from spectrum utilization, IT resource consumption, and vNF deployments.

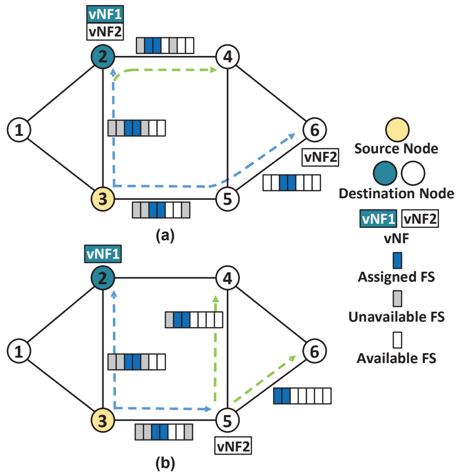

Fig. 1. Examples on realizing an M-NFV-T in IDC-EON.

Fig. 1 illustrates two examples on provisioning an M-NFV-T request. We assume that the M-NFV-T request has the source as *Node* 3, and its destinations are *Nodes* 2, 4 and 6, with the requested vNFs as *vNF1*, *vNF2* and *vNF2*, respectively. In Fig. 1(a), *vNF1* is provisioned on *Node* 2, and two instances of *vNF2* are realized on *Nodes* 2 and 6. Hence, the all-optical light-tree is from *Node* 3 to *Nodes* 2 and 6, on whose branches the FS assignments are the same. There is an O/E/O conversion on *Node* 2 for *vNF2* to process the data-flow for *Node* 4, and thus the FS assignment on *Link* 2-4 can be different from that on the light-tree. For this case, we instantiate three vNFs. For the case in Fig. 1(b), *vNF1* is provisioned on *Node* 2 and *vNF2* is realized on *Node* 5. Hence, only two vNFs are instantiated. Due to the less deployed vNFs, Fig.1 (b) also consumes less IT resources than Fig. 1(a). Comparing the two cases in Fig. 1, we can see that the one in Fig. 1(b) is more cost-effective. This explains why we need to optimize the vNF placement and multicast RSA jointly for orchestrating M-NFV-Ts efficiently in an IDC-EON. Moreover, as we allow different M-NFV-Ts to share the same vNF on a DC, the situation can become even more sophisticated when multiple M-NFV-Ts need to be accommodated in the network.

IV. MILP Formulation

In this section, we formulate an MILP model to solve the problem of orchestrating M-NFV-Ts efficiently in IDC-EONs.

Notations:

- $G(V, E)$: the physical topology of the IDC-EON.
- Γ: the possible vNF types in the IDC-EON.
- $\{MR^i | i \in I\}$: the set of M-NFV-Ts.
- s^i: the source node of MR^i.
- D^i: the destination node set of MR^i.
- T^i: the set of requested vNF types of MR^i.
- b^i: the bandwidth requirement of MR^i.
- $d^{i,j}$: the j-th destination of MR^i, $d^{i,j} \in D^i$ and $j \in J^i$.
- $t^{i,j}$: the requested vNF type of $d^{i,j}$, $t^{i,j} \in T^i$.
- $N^{i,j}$: the set of DCs where $t^{i,j}$ can be provisioned.

- F: the number of FS' on each fiber link.
- C_v: the IT resource capacity of DC $v \in V$.
- $P_{u,v}$: the set of K shortest paths from u to v, $u, v \in V$.
- $G_p^{i,j}$: the set of available FS-blocks for $d^{i,j}$ on ingress path p, where $p \in P_{s^i,v}$ and $v \in N^{i,j}$. Each FS-block contains $\left\lceil \frac{b^i}{B_w} \right\rceil$ FS', where B_w is an FS' bandwidth.
- $\widetilde{G}_p^{i,j}$: the set of available FS-blocks for $d^{i,j}$ on egress path p, where $p \in P_{v,d^{i,j}}$ and $v \in N^{i,j}$.
- $L_v^{i,j}$: the set of feasible ingress RSA solutions for $d^{i,j}$ if deploying the vNF on node v. Each element is $l = (p, g) \in L_v^{i,j}$, where $p \in P_{s^i,v}$ and $g \in G_p^{i,j}$.
- $\widetilde{L}_v^{i,j}$: the set of feasible egress RSA solutions for $d^{i,j}$ if deploying the vNF on node v. Each element is $l = (p, g) \in \widetilde{L}_v^{i,j}$, where $p \in P_{v,d^{i,j}}$ and $g \in \widetilde{G}_p^{i,j}$.
- $L^{i,j}$: the set of feasible ingress RSA solutions for $d^{i,j}$, and $L^{i,j} = \bigcup\limits_{v \in N^{i,j}} L_v^{i,j}$.
- w_s: the cost of using an FS per link.
- w_c: the cost of DC IT resource consumption for processing per bit-rate traffic.
- w_v: the cost of deploying a vNF on a DC.

Variables:

- $x_v^{i,j}$: boolean variable that equals 1 if $d^{i,j}$ chooses DC v as its vNF node, and 0 otherwise.
- $y_l^{i,j}$: boolean variable that equals 1 if $d^{i,j}$ chooses ingress RSA solution l, and 0 otherwise.
- $\widetilde{y}_l^{i,j}$: boolean variable that equals 1 if $d^{i,j}$ chooses egress RSA solution l, and 0 otherwise.
- $h_{v,t}^i$: boolean variable that equals 1 if MR^i deploys a t type vNF on DC v, and 0 otherwise.
- $h_{v,t}$: boolean variable that equals 1 if a t type vNF is deployed on DC v, and 0 otherwise.
- $z_{e,f}^i$: boolean variable that equals 1 if the f-th FS on link $e \in E$ is used by any ingress path $p \in P_{s^i,v}$ for MR^i, and 0 otherwise.
- $z_{e,f}$: boolean variable that equals 1 if the f-th FS on link $e \in E$ is used, and 0 otherwise.
- η_s: the total cost of spectrum utilization.
- η_c: the total cost of DC IT resource consumption.
- η_v: the total cost of vNF deployments.
- η: the total cost including η_s, η_c and η_v.

Objective:

The optimization objective is to minimize the total cost from spectrum utilization, IT resource consumption, and vNF deployments for realizing the M-NFV-Ts, *i.e.*, $\{MR^i | i \in I\}$.

$$Minimize \quad \eta = \eta_s + \eta_c + \eta_v. \tag{1}$$

Constraints:

1) *vNF Placement Constraints:*

$$\sum_{v \in N^{i,j}} x_v^{i,j} = 1, \quad \forall i \in I, j \in J^i. \tag{2}$$

Eq. (2) ensures that the requested vNF for each destination is deployed on one and only one DC.

$$h_{v,t^{i,j}}^i \geq x_v^{i,j}, \quad \forall i, j, \ \forall v \in N^{i,j}. \tag{3}$$

Eq. (3) indicates whether DC $v \in N^{i,j}$ has a $t^{i,j}$ type vNF.

$$h_{v,t} \geq h_{v,t}^i, \quad \forall i, \ \forall v \in V, \ \forall t \in \Gamma. \tag{4}$$

Eq. (4) indicates whether a t vNF is deployed on DC $v \in V$.

2) *RSA Solution Selection Constraints:*

$$\sum_{l \in L_v^{i,j}} y_l^{i,j} = x_v^{i,j}, \quad \forall i, j, \ \forall v \in N^{i,j}, \tag{5}$$

$$\sum_{l \in \widetilde{L}_v^{i,j}} \widetilde{y}_l^{i,j} = x_v^{i,j}, \quad \forall i, j, \ \{v : v \in N^{i,j}, v \neq d^{i,j}\}. \tag{6}$$

Eqs. (5) and (6) ensure that for each M-NFV-T, only one feasible RSA solution is chosen.

$$\begin{gathered} y_{l_j}^{i,j} = y_{l_k}^{i,k}, \forall i, \ \{j, k : j, k \in J^i, j \neq k\}, \\ \{l_j, l_k : l_j = (p_j, g_j) \in L^{i,j}, l_k = (p_k, g_k) \in L^{i,k}, g_j = g_k\}. \end{gathered} \tag{7}$$

Eq. (7) ensures that the FS' assigned on each link on a light-tree for MR^i satisfy the spectrum continuity constraint.

$$\sum_{i \in I} z_{e,f}^i + \sum_{i,j} \sum_{v \in N^{i,j}} \sum_{\substack{l \in \{l : l = (p,g) \in \\ \widetilde{L}_v^{i,j}, e \in p, f \in g\}}} \widetilde{y}_l^{i,j} \leq z_{e,f}, \ \forall e \in E, f \in [1, F], \tag{8}$$

$$z_{e,f}^i \geq y_l^{i,j}, \ \forall i, j, \ \forall l = (p, g) \in L^{i,j}, \ \forall e \in p, f \in g. \tag{9}$$

The first item in Eq. (8) represents the FS' used on the ingress paths $\{p : p \in P_{s^i,v}, \ \forall i \in I, v \in N^{i,j}\}$, while the second item is for the FS' used on the egress paths $\{p : p \in P_{v,d^{i,j}}, \ \forall i \in I, v \in N^{i,j}\}$. Hence, Eqs. (8) and (9) ensure that the spectrum assignments satisfy the spectrum non-overlapping constraint.

3) *Cost Calculation*:

$$\eta_s = w_s \cdot \sum_{e \in E} \sum_{f \in [1,F]} z_{e,f}, \tag{10}$$

$$\eta_c = w_c \cdot \sum_{i \in I} \sum_{v \in V} \sum_{t \in \Gamma} h_{v,t}^i \cdot b^i, \tag{11}$$

$$\eta_v = w_v \cdot \sum_{v \in V} \sum_{t \in \Gamma} h_{v,t}. \tag{12}$$

Eqs. (10)-(12) calculate the costs from spectrum utilization, IT resource consumption, and vNF deployments, respectively.

V. Offline Heuristic Algorithm

A. Algorithm Description

Since solving the MILP model mentioned above could be time-consuming, especially for large-scale IDC-EONs, we first propose a time-efficient heuristic algorithm to address the offline version of the problem, *i.e.*, all the M-NFV-Ts are given and we try to serve them in an IDC-EON with the smallest total cost. The proposed algorithm is based on path-intersection and jointly considers the vNF placement and the multicast RSA to connect the source, vNFs and destinations together for each M-NFV-T.

We first define the concepts of destination cluster and path-intersection node set to assist the vNF placement.

Definition 1: Given a set of M-NFV-Ts $\{MR^i\}$, the **destination cluster** c^t includes all the destinations that request a t type vNF, where $t \in \Gamma$.

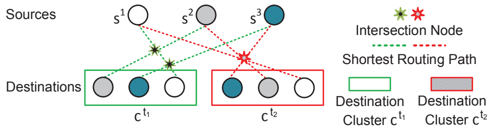

Fig. 2. Example on destination clusters and path-intersection node sets.

***Definition** 2:* With a destination cluster c^t, we can calculate K-shortest paths to connect a destination in the cluster to its designated source. Then, the **path-intersection node set** $P(t)$ includes all the intersection nodes of these paths. Then, from the perspective of reducing the vNF deployment cost, we should try to use the DCs in $P(t)$ to place the t type vNFs.

Fig. 2 shows an intuitive example on how to get the path-intersection node set. There are three M-NFV-Ts in the IDC-EON, and we denote their sources as s^1, s^2, and s^3. Each M-NFV-T consists of two destinations, and the requested vNF types are t_1 and t_2. Hence, we have two destination clusters, *i.e.*, each destination in *Cluster* c^{t_1} requests for a t_1 vNF, while those in *Cluster* c^{t_2} need t_2 vNFs. Then, we calculate $K = 1$ shortest path for each source-destination pair, and 6 paths can be obtained. For destinations in *Cluster* c^{t_1}, their paths have two intersections (marked as green stars in Fig. 2), which are all included in $P(t_1)$. Similarly, $P(t_2)$ can be obtained.

Algorithm 1 leverages the path-intersection node set to orchestrate M-NFV-Ts efficiently in IDC-EONs. *Lines* 1-5 show the procedure to obtain the destination clusters for the M-NFV-Ts. Then, for each destination cluster, if the requested vNF is location-independent, *Lines* 6-10 calculate its path-intersection node set $P(t)$. The for-loop that covers *Lines* 11-33 deploys the M-NFV-Ts with vNF placement and multicast RSA and allocate the IT and spectrum resources accordingly.

Firstly, for those that request location-restricted vNFs, *Lines* 13-14 just select their designated DCs as there is no room for vNF placement optimization. On the other hand, for location-independent vNFs, we consider the IT and spectrum resource allocation jointly to determine the vNF placement. Specifically, for each DC $v \in P(t)$, we define $\mathcal{V}(v)$ to estimate the additional cost if it is chosen as the vNF node of $d_{i,j}$.

$$\mathcal{V}(v) = w_s \cdot \lceil \frac{b^i}{B_w} \rceil \cdot H_{s^i,v,d^{i,j}} + w_c \cdot b^i \cdot (1 - h^i_{v,t}) + w_v \cdot (1 - h_{v,t}), \tag{13}$$

where the definitions of w_s, b^i, B_w, w_c, $h^i_{v,t}$, w_v, and $h_{v,t}$ have already been provided in Section IV, and $H_{s^i,v,d^{i,j}}$ stands for the hop-count of the data-transfer $s^i \to v \to d^{i,j}$, which consists of two shortest path segments (*i.e.*, for $s^i \to v$ and $v \to d^{i,j}$). Basically, the term $w_c \cdot b^i \cdot (1 - h^i_{v,t})$ in Eq. (13) means that if MR^i has already deployed a t type vNF on DC v, we can save the cost on IT resource consumption if we reuse it for $d^{i,j}$, as explained in the examples in Fig. 1. The last term $w_v \cdot (1 - h_{v,t})$ can be understood as that if any M-NFV-T has deployed a t type vNF on DC v, the cost on vNF deployment can be saved. Then, *Lines* 16-19 calculate $\mathcal{V}(v)$ for each DC $v \in P(t)$, and select the one with the minimum $\mathcal{V}(v)$ as the vNF node of $d^{i,j}$. The vNF deployment is achieved with *Lines* 21-23.

After *Line* 24, we have accomplished the vNF placement

Algorithm 1: Path-Intersection based Algorithm (PI)

1 **for** *each* $i \in I$ *and* $j \in J^i$ **do**
2   **if** $t^{i,j} = t$ **then**
3   insert $d^{i,j}$ into *Cluster* c^t;
4   **end**
5 **end**
6 **for** *each vNF type* $t \in \Gamma$ **do**
7   **if** t *is location-independent* **then**
8   calculate path-intersection node set $P(t)$;
9   **end**
10 **end**
11 **for** *each* $i \in I$ **do**
12   **for** *each* $j \in J^i$ **do**
13   **if** $t^{i,j}$ *is location-restricted* **then**
14   choose DC $v^{i,j}$ in $N^{i,j}$ for vNF placement;
15   **else**
16   **for** *each* $v \in P(t)$ **do**
17   calculate $\mathcal{V}(v)$ with Eq. (13);
18   **end**
19   choose DC $v^{i,j} \in P(t)$ with minimum $\mathcal{V}(v)$ for vNF placement;
20   **end**
21   **if** *there does not exist a* $t^{i,j}$ *type vNF on the selected DC* $v^{i,j}$ **then**
22   instantiate a $t^{i,j}$ type vNF on DC $v^{i,j}$;
23   **end**
24   **end**
25   calculate an MST for MR^i from s^i to $\{v^{i,j} : \forall j\}$;
26   assign FS' for all-optical multicast with first-fit;
27   **for** *each* $j \in J^i$ **do**
28   **if** $v^{i,j} \neq d^{i,j}$ **then**
29   check the K-shortest paths from $v^{i,j}$ to $d^{i,j}$ to choose the one with minimum FMA cost;
30   assign FS' on the selected paths with first-fit;
31   **end**
32   **end**
33 **end**

for MR^i, and then should set up the optical connections for the data-transfers among the source, vNFs and destinations. We first calculate a minimum spanning tree (MST) to cover the connections from the source to vNFs, as in *Line* 25. Spectrum assignments are performed while guaranteeing all-optical multicast as shown in *Line* 26. Then, for the connections from vNFs to the corresponding destinations, unicast lightpaths are established as O/E/O conversions will be conducted in the DCs anyway. *Lines* 27-32 show the procedure for setting up the lightpaths. Note that, in *Line* 29, we use the fragmentation-aware scheme (FMA) in [15] to select the routing paths due to its effectiveness.

Complexity analysis: Since the K-shortest paths between each node pair can be pre-calculated, the computational complexity of the proposed offline heuristic is $O((|V|^2 + F \cdot |E|) \cdot |I| + |\Gamma|)$, where $|\cdot|$ gets the size of a set.

B. Performance Evaluation

We use numerical simulations to evaluate the performance of the proposed algorithm. Here, to provide benchmarks for the evaluation, we consider two simple offline heuristics.

- **Shortest-Path-Constrained Placement (SPC):** The M-NFV-Ts are still served sequentially as in PI, but the DCs for location-independent vNFs are only chosen from the nodes on the shortest path from source to destination.
- **Random Placement (RP):** the DCs for location-independent vNFs are chosen randomly from the nodes in the topology.

The algorithms, *i.e.*, the MILP, PI, SPC and RP, are evaluated with two IDC-EONs, which have the six-node and NSFNET topologies in [7]. In the six-node topology, there are $F = 10$ FS' on each fiber link with $B_w = 12.5$ Gb/s, and the IT resource capacity of a DC is $C_v = 200$ units. We assume that there are $|\Gamma| = 4$ types of vNFs, among which *vNF1* is location-restricted and the other three are location-independent. The distribution of the vNFs is [*vNF1* : *vNF2* : *vNF3* : *vNF4*] = $[1:3:3:3]$, and the bit-rates of the M-NFV-Ts are uniformly distributed within $[10, 40]$ Gb/s. We define $w_s = \frac{1}{(F \cdot |E|)}$, $w_v = \frac{1}{(|\Gamma| \cdot |V|)}$, and $w_c = \frac{1}{(C_v \cdot |V|)}$, to normalize the costs.

Table I shows the results from the four algorithms with the six-node topology. The total cost η is calculated with Eq. (1) and we obtain the results in Table I. As expected, the MILP provides the smallest overall cost among the four algorithms, but its running time is also the longest. For the three heuristics, PI provides the smallest cost for M-NFV-T provisioning, and its results range within $[1.00, 1.19]$ times of those from the MILP. Meanwhile, the running time of PI is much shorter than that of the MILP, and is comparable to those of the two benchmarks. These results verify the effectiveness and efficiency of PI. Basically, since PI adopts the strategy to place vNFs on the path-intersection nodes, it can reduce the costs from spectrum, IT resource consumption and vNF deployments.

TABLE I
RESULTS ON AVERAGE TOTAL COST OF M-NFV-TS AND RUNNING TIME (IN SECONDS) IN SIX-NODE TOPOLOGY

$\lvert I\rvert$	$\lvert J^i\rvert$	MILP		PI		SPC		RP	
		η	Time	η	Time	η	Time	η	Time
2	2	0.16	8.00	0.16	0.09	0.21	0.06	0.26	0.06
	3	0.21	12.80	0.24	0.07	0.27	0.05	0.37	0.08
	4	0.22	54.20	0.24	0.14	0.34	0.10	0.45	0.09
6	2	0.34	56.60	0.37	0.11	0.51	0.09	0.65	0.10
	3	0.40	158.60	0.46	0.19	0.66	0.13	0.88	0.14
	4	0.47	511.60	0.56	0.24	0.80	0.22	1.05	0.21
10	2	0.48	205.20	0.55	0.21	0.73	0.13	0.96	0.16
	3	-	-	0.74	0.31	1.02	0.23	1.27	0.25
	4	-	-	0.86	0.46	1.12	0.37	1.50	0.34

As the MILP has scalability issues with large-scale networks, we evaluate the heuristics in NSFNET to further verify their performance. In the NSFNET topology, each fiber link can accommodate $F = 200$ FS' and the IT resource capacity of each DC is $C_v = 1000$ units. The average number of destinations in an M-NFV-T is 3. Fig. 3 plots the total costs from the algorithms, which still indicate that PI provisions the M-NFV-Ts with the smallest costs. This proves that PI also works well with large-scale networks. The results on the number of deployed vNFs in the network in Fig. 4 verify our analysis above, as PI deploys the smallest number of vNFs. More specifically, the advantage of PI comes from the fact that it adopts the strategy to place vNFs on the path-intersection nodes and can reuse vNFs in a more intelligent way than the benchmarks.

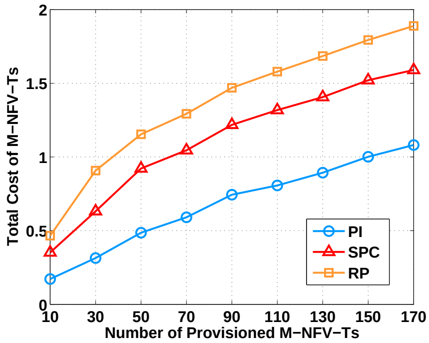

Fig. 3. Total cost of M-NFV-Ts from offline algorithms in NSFNET topology.

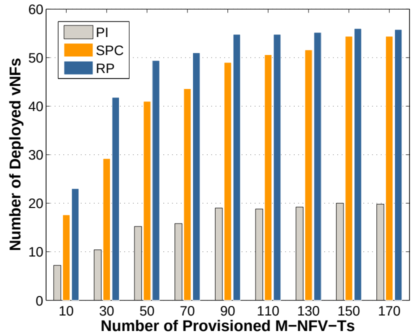

Fig. 4. Number of deployed vNFs from offline algorithms in NSFNET topology.

VI. ONLINE HEURISTIC ALGORITHMS

In this section, we consider the situation in which the M-NFV-Ts can be requested dynamically, *i.e.*, they can come and leave on-the-fly. For this scenario, we need to develop online algorithms to provision them efficiently.

A. Algorithm Description

Basically, in each provision period, the pending M-NFV-Ts can be served with one of the two schemes, *i.e.*, the batch scheme that provisions them simultaneously with joint considerations, and the sequential scheme that provisions them one by one. Since we have already verified the effectiveness of PI in the offline scenario, we can leverage it to design the online heuristics. Here, for a provision period, we denote the pending M-NFV-T set as $\mathbf{R}$, but the set of in-service M-NFV-Ts is represented as $\widetilde{\mathbf{R}}$. Then, the batch and sequential schemes (*i.e.*, B-PI and S-PI) can use the overall procedure

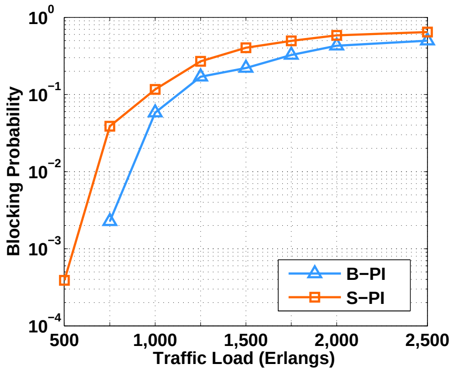

Fig. 5. Results on blocking probability in a dynamic IDC-EON.

in *Algorithm* 1, with the differences on how to calculate the path-intersection node set $P(t)$ for t type vNFs. Specifically, to serve a pending M-NFV-T $MR^i \in \mathbf{R}$, B-PI obtains the path-intersection node sets by checking all the M-NFV-Ts in $\mathbf{R} \bigcup \widetilde{\mathbf{R}}$, while S-PI only considers the M-NFV-Ts in $\{MR^i\} \bigcup \widetilde{\mathbf{R}}$. Note that, for S-PI, the in-service M-NFV-T set $\widetilde{\mathbf{R}}$ is maintained dynamically, *i.e.*, when a pending M-NFV-T is provisioned successfully, it is moved from $\mathbf{R}$ to $\widetilde{\mathbf{R}}$. We should point out that since the path-intersection node sets can be stored and updated in each provision period, the computational complexity of obtaining them can be maintained to satisfy the requirement of online provisioning. Apparently, B-PI has higher computational complexity than S-PI. Finally, we should explain how to handle the vNFs on DC in a dynamic IDC-EON. Basically, when an M-NFV-T expires, we release all the spectrum and IT resources allocated to it, but a vNF is torn down only when all the M-NFV-Ts that use it have expired.

B. Performance Evaluation

We use the IDC-EON with the NSFNET topology to evaluate the performance of B-PI and S-PI. Each fiber link accommodates $F = 358$ FS', and the IT resource capacity of each DC is $C_v = 10000$ units. We assume that there are $|\Gamma| = 4$ types of vNFs, among which *vNF1* is location-restricted and the other three are location-independent. The distribution of the vNFs is [*vNF1* : *vNF2* : *vNF3* : *vNF4*] = $[0.001 : 0.333 : 0.333 : 0.333]$, and the bit-rates of the M-NFV-Ts are still uniformly distributed within $[10, 40]$ Gb/s. The dynamic M-NFV-Ts are generated with the Poisson traffic model. In the dynamic IDC-EON, an M-NFV-T can be blocked due to resource insufficiency in the network. Fig. 5 shows the results on blocking probability. We can see that B-PI provides lower blocking probabilities than S-PI for all the traffic loads. This is achieved with the additional computational complexity that B-PI requires. Basically, B-PI acquires a more comprehensive view on the IDC-EON in each service provisioning, by considering all the pending M-NFV-Ts together in the calculation of path-intersection node sets.

VII. CONCLUSION

In this paper, we studied how to optimize vNF placement and multicast RSA jointly for orchestrating M-NFV-Ts efficiently in IDC-EONs. We first considered an offline scenario in which all the M-NFV-Ts are known and need to be served in the network. An MILP model was formulated to solve the problem exactly, and then, we proposed a heuristic based on path-intersection (PI) to reduce the time complexity. With extensive numerical simulations, we showed that the proposed heuristic could approximate the MILP's performance on low-cost M-NFV-T provisioning but only required much shorter running time. Next, the online scenario where the M-NFV-Ts could come and leave on-the-fly was addressed, and we leveraged PI to design two online algorithms for orchestrating dynamic M-NFV-Ts in IDC-EONs. Simulation results indicated that compared with the sequential scheme, the batch-based M-NFV-T provisioning could reduce blocking probability effectively.

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