Orchestrating Tree-Type VNF Forwarding Graphs in Inter-DC Elastic Optical Networks

Menglu Zeng, Wenjian Fang, and Zuqing Zhu, *Senior Member, IEEE*

***Abstract*—It is known that by incorporating network function virtualization (NFV) in inter-datacenter (inter-DC) networks, service providers can use their network resources more efficiently and adaptively and expedite the deployment of new services. This paper studies the provisioning algorithms to realize tree-type virtual network function forwarding graphs (VNF-FGs), i.e., multicast NFV trees (M-NFV-Ts), in inter-DC elastic optical networks (IDC-EONs) cost-effectively. Specifically, we try to optimize the VNF placement and multicast routing and spectrum assignment jointly for orchestrating M-NFV-Ts in an IDC-EON with the lowest cost. Our study addresses both static network planning and dynamic network provisioning. For network planning, we first formulate a mixed integer linear programming (MILP) model to solve the problem exactly, and then propose three heuristic algorithms, namely, auxiliary frequency slot matrix (AFM)-MILP, AFM-GS, and RB. Extensive simulations show that AFM-MILP and AFM-GS can approximate the MILP's performance on low-cost M-NFV-T provisioning with much shorter running time. For network provisioning, we design two additional online algorithms based on AFM-GS and RB to serve M-NFV-Ts in a dynamic IDC-EON, with the consideration of spectrumfragmentation.**

***Index Terms*—Elastic, inter-datacenter (inter-DC) networks, multicast, network function virtualization (NFV), optical networks (EONs), virtual network function forwarding graph (VNF-FG).**

I. Introduction

DUE to the exponential growth of the demands for real-time, on-demand, inexpensive, and diverse services, service providers (SPs) are eagerly looking for new technologies to make their service delivery infrastructure more flexible, programmable and cost-effective. Here, one major challenge is how to make the deployment of network functions timely, inexpensive, and easy tomaintain and upgrade. Recently, network function virtualization (NFV) [1] has emerged and been considered as a promising approach to settle this challenge and overcome the drawbacks of traditional bespoken network functions. Specifically, NFV leverages standard IT virtualization technologies to consolidate many types of virtualized network functions (VNFs) onto general-purpose servers, switches and storage, which could be easily located in a variety of NFV infrastructure points-of-presence, including dater-centers (DCs) [1].

Therefore, by incorporating NFV in inter-DC networks, SPs can use their network resources in a more intelligent manner, and expedite the deployment of new services [2]. One main advantage of NFV is that VNFs can be organized into reconfigurable graphs (i.e., VNF forwarding graphs (VNF-FGs)) to realize network services elastically [3]. Basically, in addition to the well-known VNF service chains [4], VNF-FGs may, and often will take the tree topologies and have branches [5]. The rationale behind this is that many network services, e.g., DC backup and migration, require point-to-multiple-point communications, and thus incorporating tree-type VNF-FGs leads to application-aware service composition in inter-DC networks. For instance, in a multicast-based DC backup, VNFs for data encryption can be deployed on certain branches to address the differentiated trust-levels of the destination DCs.

Previous studies have considered the NFV schemes to steer traffic in packet domains [6]–[8]. Note that, the capacity and elasticity of underlying infrastructure can affect the efficiency of VNF-FG provisioning in inter-DC networks significantly. Due to the dynamic nature of data-/bandwidth-intensive services (e.g., Big Data synthesis), the traffic flowing through VNF-FGs can exhibit high throughput and high burstiness [9]. Meanwhile, with the tremendous bandwidth in fibers, optical networking provides inter-DC networks a viable and reliable infrastructure to support high-throughput traffic economically [10]. Moreover, thanks to the technical advances on flexible-grid elastic optical networks (EONs) [9], agile bandwidth management can be achieved directly in the optical layer and thus demands for various bandwidths can be provisioned more efficiently [11]. Hence, realizing VNF-FGs in optical domains has several advantages [2], and is especially beneficial when the underlying infrastructure is an inter-DC EON (IDC-EON) to connect geographically distributed DCs [9], [12]–[14].

Basically, we need to allocate both the spectrum and IT resources in IDC-EONs jointly to provision VNF-FGs efficiently. However, this will make the control plane operation more complex. Hence, although with the network orchestration enabled by software-defined networking (SDN) [15], [16], the control plane for performing joint allocation of optical and cloud resources can be realized [17], the actual VNF-FG provisioning algorithm should be carefully designed to improve time-efficiency. Hence, it would be relevant to study the provisioning algorithm to realize tree-type VNF-FGs, i.e., multicast NFV trees (M-NFV-Ts), efficiently in IDC-EONs. Nevertheless, to the best of our knowledge, this problem has not been studied in literature before.

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The authors are with the School of Information Science and Technology, University of Science and Technology of China, Hefei, Anhui 230027, China (e-mail: mlzeng@mail.ustc.edu.cn; fwj@mail.ustc.edu.cn; zqzhu@ieee.org).

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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 do this efficiently, the essential difficulty is to minimize the number of deployed VNFs in the DCs and optimize the utilization of spectrum resources in the EON simultaneously. Basically, these two objectives are correlated and cannot be addressed independently. For example, if we only deploy a small number of VNFs to promote VNF reuse among different branches of an M-NFV-T, the routing paths among the VNFs might not be the shortest any more and thus the spectrum utilization would increase. Moreover, if we allow multiple M-NFV-Ts to share the same VNF, the situation can become even more sophisticated.

In this paper, we study how to optimize the VNF placement and multicast RSA jointly for orchestrating M-NFV-Ts in an IDC-EON with the lowest cost. Specifically, we consider three types of costs that associate with provisioning M-NFV-Ts, i.e., the cost of spectrum usage on fiber links, the cost of IT resource consumption by the deployed VNFs, and the cost of instantiating VNFs in the DCs. Our study addresses the scenarios of both static network planning and dynamic network provisioning. For network planning, we first formulate a mixed integer linear programming (MILP) model to solve the problem exactly, and then propose three heuristic algorithms. For network provisioning, we design two additional online provisioning algorithms to serve M-NFV-Ts in a dynamic IDC-EON. In summary, our main contributions are as follows.

1) We formulate an MILP model to solve the problem of orchestrating M-NFV-Ts in IDC-EONs exactly, i.e., optimizing the VNF placement and multicast RSA jointly.
2) We propose a rendezvous-based heuristic that reduces the spectrum resources used for orchestrating M-NFV-Ts and avoids instantiating redundant VNFs at the same time.
3) We investigate the underlying principle of orchestrating M-NFV-Ts in IDC-EONs and design an auxiliary frequency slot matrix (AFM) model to assist the optimization of the provisioning schemes of M-NFV-Ts. We also prove that although the optimization is still $\mathcal{NP}$-hard with the AFM model, the complexity gets reduced significantly due to much less variables and constraints.
4) We also propose a greedy-search based heuristic based on the AFM model and verify that it can provide reasonably good solutions for both static network planning and dynamic network provisioning.

The rest of the paper is organized as follows. Section II reviews the related work briefly. We describe the network model and define the problem of orchestrating M-NFV-Ts in IDC-EONs in Section III. For network planning, the MILP model is formulated in Section IV, while the heuristic algorithms are designed in Section V. Section VI evaluates the algorithms' performance for network planning with extensive simulations. In Section VII, we consider network provisioning. Finally, Section VIII summarizes the paper.

II. Related Work

Right after being sketched, NFV has been promoted by both academia and industry, and related technical documents have mushroomed over the Internet to stimulate the research and development activities [1], [3], [4]. The overview of NFV can be found in [18], which explained the requirements and architectural framework of NFV, presented several use cases, and discussed the challenges and future research directions. In [6], the authors designed and demonstrated a high-performance NFV platform named as ClickOS, but the problem of VNF placement was not addressed. The work in [7] studied the problem of VNF placement and proposed several approximation algorithms to solve it. However, the study did not take resource constraints into consideration. Clayman *et al.* [8] proposed to leverage an orchestrator to realize the automatic placement of VNFs in DCs. However, their placement engine only used relatively simple schemes to load-balance the IT resource usage, but did not consider the joint optimization of IT and bandwidth resource allocations.

The VNF placement in a hybrid network environment, where hardware network functions and VNFs co-existed, was studied in [19], and an integer linear programming (ILP) model was formulated to solve it. The placement of VNFs in packet domains has been addressed in [20], [21], and mixed integer programming models were designed to solve the problem of NFV chaining for end-to-end service provisioning. Nevertheless, due to their complexity, the ILP and mixed integer programming models could only be applied for offline planning. Time-efficient heuristics were proposed in [22]–[24] to solve the online NFV chaining problem. In [25], an algorithm for traffic-aware VNF chaining was designed and implemented in the SDN controller based on Floodlight. However, all the studies in [20]–[25] only considered the unicast-oriented VNF chains, which is much simpler than tree-type VNF-FGs. The authors of [26] developed an approach to solve the routing problem for tree-type VNF-FGs in packet domains, under an impractical assumption that the VNFs were pre-allocated.

Xia *et al.* [27] studied the VNF placement in inter-DC optical networks, and formulated a binary integer programming model to minimize the usage of optical-to-electrical-to-optical (O/E/O) converters. Nevertheless, they considered neither tree-type VNF-FGs nor spectrum allocation in the optical layer. Note that, it is known that the network orchestration in inter-DC optical networks would not be optimal if the spectrum and IT resource allocations were not considered jointly [28]. Meanwhile, we hope to point out that although at first glance, this problem looks similar to two other multicast related problems that have already been studied for EONs, i.e., the multicast-capable service provisioning in [29]–[32] and the multicast-oriented virtual network embedding (VNE) in [33], they are fundamentally different. Multicast-capable provisioning only considers how to allocate spectrum 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 tries to set up virtual networks for multicast services in a substrate EON. Even though this does include the joint allocation of spectrum

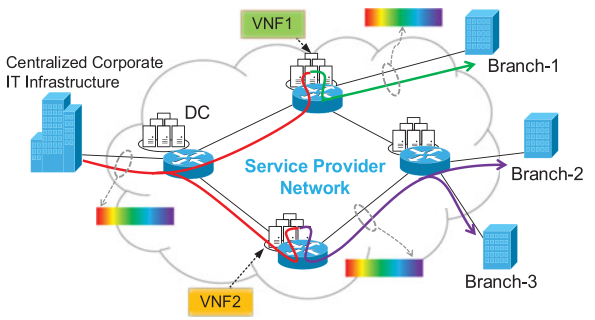


Fig. 1. Example of orchestrating an M-NFV-T in an IDC-EON for virtualized enterprise services.

and IT resources, the virtual networks' topologies are known in advance. In our problem, the actual VNF-FG topology for carrying 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.

III. Problem Description

A. Orchestrating Tree-Type VNF-FGs in IDC-EONs

Fig. 1 shows an example on orchestrating a tree-type VNF-FG (i.e., an M-NFV-T) in an IDC-EON, where we consider the use case for realizing virtualized enterprise services. Here, the company's enterprise network consists of several headquarter facilities, which are a centralized corporate IT infrastructure and a few geographically distributed branches. Note that, as the company does not own a backbone IDC-EON, it has to subscribe NFV services from the SP that manages the spectrum and IT resources [3]. The virtualized enterprise services are realized with an M-NFV-T that includes *VNF1* (e.g., for data leakage prevention) and *VNF2* (e.g., for wide-area network optimization). Hence, with multicast, the corporate traffic is steered through *VNF1* or *VNF2* on its way from the centralized corporate IT infrastructure to the three branches, and *VNF2* is shared by *Branch-2* and *Branch-3*. Note that, the VNFs can be either location-restricted or location-independent ones. For example, as *VNF1* is for data leakage prevention and has to be instantiated on secure and trusted DCs [3], it is a location-restricted VNF. While a location-independent VNF as *VNF2* can be deployed on any DCs in the SP's network.

All the links in the network use optical connections and the traffic will experience O/E/O conversions when it needs to be processed by the VNFs in DCs. Therefore, as shown in Fig. 1, all-optical multicasting is used from the centralized corporate IT infrastructure to the VNFs, and then we build lightpath(s) and/or light-tree(s) to connect the VNFs to the branches. Note that, the arrowed lines with different colors in Fig. 1 represent the optical transmission paths of the traffic, which use different spectra from the centralized corporate IT infrastructure to the VNFs, and from the VNFs to the corresponding branches. Since the VNFs are instantiated with the generic IT resources in the DCs and the optical connections are set up with the flexible bandwidth allocation in the EON, the SP can deploy, configure, scale and manage the M-NFV-T easily and timely to satisfy the quality-of-service requirements of the enterprise services. Specifically, to maximize the cost-effectiveness of its NFV services, the SP should carefully plan and adjust the network resources allocated to realize the VNF-FG.

B. Network Model

We model the IDC-EON as a directed graph $G(V,E)$, where V and E are the sets of DC nodes and fiber links, respectively. Each DC node consists of both a DC as the IT resource pool and a bandwidth-variable optical switch for in-/out-bound communications. The IT resource capacity of the DC on node $v \in V$ is C_v. On each DC in the IDC-EON, we can instantiate several types of VNFs, and Γ represents the set of all the VNF types. There are F FS' on each fiber link $e \in E$.

An M-NFV-T request from the clients has the formula of $MR^i = \{s^i, D^i, T^i, b^i\}$, 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. We assume that the traffic sent to each destination of MR^i should be processed by a VNF. The j-th destination of MR^i is denoted as $d^{i,j} \in D^i$, which requests for a $t^{i,j} \in T^i$ type of VNF to process the traffic targeting to it. For $d^{i,j}$, its VNF can be instantiated/reused on one of the DCs in set $N^{i,j}$. Here, we assume that a location-restricted VNF can only be instantiated on a designated DC, i.e., $|N^{i,j}| = 1$, while a location-independent one can be deployed on any DC node except for s^i, i.e., $|N^{i,j}| = |V| - 1$. Note that, we exclude s^i from the possible locations of a location-independent VNF to ensure that all-optical multicasting is used for the M-NFV-T. Since MR^i needs both spectrum and IT resources, we assume that the SP prices 1) the usage of an FS on a fiber as w_s, 2) the IT resources used by a VNF to process per bit-rate traffic as w_c, and 3) the cost of instantiating a VNF on a DC as w_v. Hence, to realize M-NFV-Ts in the IDC-EON cost-effectively, the SP needs to minimize the total cost from the spectrum utilization, IT resource consumption, and VNF deployment.

IV. MILP Formulation

We first formulate an MILP model to solve the problem of orchestrating M-NFV-Ts cost-effectively in an IDC-EON exactly for static network planning. Note that, similar to the studies in [28], we precalculate all the feasible RSA solutions for each request as the MILP's inputs. Specifically, for each request MR^i, we determine its spectrum requirement as $n^i = \lceil \frac{b^i}{B_w} \rceil$ FS', where B_w is the capacity of an FS in terms of bit-rate. Then, we find all the feasible FS-blocks with a size of n^i FS' on the K shortest paths between each node pair in the topology, and store them as the MILP's input.

Notations:

$G(V,E)$:	the IDC-EON's physical topology.
Γ:	the set of VNF types in the IDC-EON.
$\{MR^i = \{s^i, D^i, T^i, b^i\} : i \in I\}$:	the set of M-NFV-Ts, where I is their index set.

s^i: the source of request MR^i.
D^i: the destination set of MR^i.
$d^{i,j}$: the jth destination of MR^i, where $d^{i,j} \in D^i$, $j \in J^i$, and J^i is the index set of destinations in D^i.
T^i: the set of requested VNF types of MR^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 instantiated.
b^i: the bandwidth requirement of MR^i.
F: the number of FS' on each fiber link.
C_v: the IT resource capacity of the DC on node $v \in V$.
$P_{u,v}$: 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 $p \in P_{s^i,v}$, $v \in N^{i,j}$, and each FS-block contains $n^i = \lceil \frac{b^i}{B_w} \rceil$ FS'.
$\widetilde{G}_p^{i,j}$: 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 instantiating its requested VNF on node v. Each element $l = (p, g) \in L_v^{i,j}$ has $p \in P_{s^i,v}$ and $g \in G_p^{i,j}$.
$\widetilde{L}_v^{i,j}$: the set of feasible egress RSA solutions for $d^{i,j}$ if instantiating its requested VNF on node v. Each element $l = (p, g) \in \widetilde{L}_v^{i,j}$ has $p \in P_{v,d^{i,j}}$ and $g \in \widetilde{G}_p^{i,j}$.
$L^{i,j}$: the set of feasible ingress RSA solutions for $d^{i,j}$, and $L^{i,j} = \bigcup_{v \in N^{i,j}} L_v^{i,j}$.
w_s: the cost of using an FS on a fiber link.
w_c: the cost of DC IT resource consumption for processing per bit-rate traffic.
w_v: the cost of instantiating a VNF on a DC.

Variables:

$x_v^{i,j}$: the boolean variable that equals 1 if $d^{i,j}$ has its requested VNF on DC v, and 0 otherwise.
$y_l^{i,j}$: the boolean variable that equals 1 if $d^{i,j}$ uses ingress RSA solution l, and 0 otherwise.
$\widetilde{y}_l^{i,j}$: the boolean variable that equals 1 if $d^{i,j}$ uses egress RSA solution l, and 0 otherwise.
$h_{v,t}^i$: the boolean variable that equals 1 if MR^i instantiates/reuses a t type VNF on DC v, and 0 otherwise.
$h_{v,t}$: the boolean variable that equals 1 if a t type VNF is instantiated on DC v, and 0 otherwise.
$z_{e,f}^i$: the 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.
$z_{e,f}^{i,v,t}$: the boolean variable that equals 1 if for MR^i, any egress path $p \in P_{v,d^{i,j}}$, $j \in J^i$ uses the f-th FS on link e and $d^{i,j}$ has its requested t type VNF on DC v, and 0 otherwise.
$z_{e,f}$: the 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 on fiber links.
η_c: the total cost of IT resource consumption in DCs.
η_v: the total cost of VNF deployment.
η: the SP's overall cost for orchestrating the M-NFV-Ts.

Objective:

The optimization objective is to minimize the SP's overall cost for orchestrating the M-NFV-Ts (i.e., $\{MR^i : i \in I\}$) in the IDC-EON.

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

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 of each destination is instantiated/reused on one and only one DC. Basically, to process the multicast traffic targeting to each destination of an M-NFV-T, the SP either instantiates a new VNF for it or reuses an already deployed VNF.

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

Eq. (3) indicates whether MR^i instantiates/reuses a $t^{i,j}$ type VNF on DC $v \in N^{i,j}$.

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

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

$$\sum_i \sum_t h_{v,t}^i \cdot b^i \leq C_v, \forall v \in V. \tag{5}$$

Eq. (5) ensures that the IT resource capacity constraint is satisfied. Here, we assume that if multiple destinations in an M-NFV-T share one VNF, that VNF only needs to process the traffic once with one copy of the required IT resources.

2) *RSA Solution Selection Constraints:*

$$\sum_{l \in L_v^{i,j}} y_l^{i,j} = x_v^{i,j}, \quad \forall i, j, \; \forall v \in N^{i,j} \tag{6}$$

$$\sum_{l \in \widetilde{L}_v^{i,j}} \widetilde{y}_l^{i,j} = \begin{cases} x_v^{i,j}, & v \neq d^{i,j}, \\ 0, & v = d^{i,j}, \end{cases} \quad \forall i, j, \; \forall v \in N^{i,j}. \tag{7}$$

Eqs. (6) and (7) ensure that for each M-NFV-T, one and only one RSA solution is chosen on the selected ingress and egress paths (i.e., $s^i \rightarrow$VNF and VNF$\rightarrow d^{i,j}$) of each destination

$$\begin{aligned} y_{l_j}^{i,j} &= y_{l_k}^{i,k}, \forall i, \; \{j, k : j, k \in J^i, j \neq k\} \\ \{l_j, l_k : l_j &= (p_j, g_j) \in L^{i,j}, \\ l_k &= (p_k, g_k) \in L^{i,k}, g_j = g_k\}. \end{aligned} \tag{8}$$

Eq. (8) ensures that the FS' assigned on each link of the all-optical light-tree that connects s^i and VNF nodes $\{v : \forall x_v^{i,j} = 1\}$ for MR^i satisfy the spectrum continuity constraint

$$\widetilde{y}_{l_j}^{i,j} = \widetilde{y}_{l_k}^{i,k}, \tag{9}$$

if we have

$$\begin{aligned}&x_v^{i,j}=1,\ x_v^{i,k}=1,\\&\forall i\in I\,\forall v\in V,\ \{j,k:j,k\in J^i,j\neq k,t^{i,j}=t^{i,k}\},\\&\{l_j,l_k:l_j=(p_j,g_j)\in\widetilde{L}_v^{i,j},\\&l_k=(p_k,g_k)\in\widetilde{L}_v^{i,k},g_j=g_k\}.\end{aligned}\tag{10}$$

Eqs. (9) and (10) ensure that, if multiple destinations in an M-NFV-T share a same VNF, the multicast traffic is sent from the VNF node to these destinations using an all-optical light-tree on which the spectrum assignment should satisfy the spectrum continuity constraint. We can transform the constraints into

$$\begin{aligned}&\left|\widetilde{y}_{l_j}^{i,j}-\widetilde{y}_{l_k}^{i,k}\right|\leq 2-(x_v^{i,j}+x_v^{i,k})\\&\forall i\in I,\forall v\in V,\ \{j,k:j,k\in J^i,j\neq k,t^{i,j}=t^{i,k}\}\\&\{l_j,l_k:l_j=(p_j,g_j)\in\widetilde{L}_v^{i,j},\\&l_k=(p_k,g_k)\in\widetilde{L}_v^{i,k},g_j=g_k\}\end{aligned}\tag{11}$$

where (11) is not linear, but can be linearized as

$$\begin{cases}\widetilde{y}_{l_j}^{i,j}-\widetilde{y}_{l_k}^{i,k}\geq(x_v^{i,j}+x_v^{i,k})-2\\\widetilde{y}_{l_j}^{i,j}-\widetilde{y}_{l_k}^{i,k}\leq 2-(x_v^{i,j}+x_v^{i,k}).\end{cases}\tag{12}$$

Finally, we get (12) as the linear equation to represent the constraints in (9) and (10).

$$\sum_i z_{e,f}^i+\sum_i\sum_v\sum_t z_{e,f}^{i,v,t}\leq z_{e,f}\ \forall e\in E,\forall f\in[1,F]\tag{13}$$

$$z_{e,f}^i\geq y_l^{i,j},\ \forall i,j,\ \forall l=(p,g)\in L^{i,j}\ \forall e\in p,f\in g\tag{14}$$

$$\begin{aligned}&z_{e,f}^{i,v,t}\geq\widetilde{y}_l^{i,j}\ \forall i,j,v,t\ \forall l=(p,g)\in\widetilde{L}_v^{i,j}\\&\forall e\in p,f\in g,t^{i,j}=t.\end{aligned}\tag{15}$$

The first item in (13) represents the total FS usage on all 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 total FS usage on all the egress paths $\{p:p\in P_{v,d^{i,j}},\ \forall i\in I,v\in N^{i,j}\}$. Hence, Eqs. (13)–(15) ensure that the spectrum assignments on all the paths satisfy the spectrum non-overlapping constraint.

3) *Cost Related Constraints:*

$$\eta_s=\ w_s\cdot\sum_{e\in E}\sum_{f\in[1,F]}z_{e,f}\tag{16}$$

$$\eta_c=\ w_c\cdot\sum_{i\in I}\sum_{v\in V}\sum_{t\in\Gamma}h_{v,t}^i\cdot b^i\tag{17}$$

$$\eta_v=\ w_v\cdot\sum_{v\in V}\sum_{t\in\Gamma}h_{v,t}.\tag{18}$$

Eqs. (16)–(18) obtain the three cost components, i.e., from the spectrum utilization, the IT resource utilization, and the VNF deployment, respectively.

Note that, in the worst case, if we only consider the most dominating term, the MILP needs to determine the values of approximately $(F\cdot|I|\cdot|V|\cdot|E|\cdot|\Gamma|)$ variables according to nearly $(K\cdot F\cdot|I|\cdot|J|\cdot|V|\cdot|E|\cdot|\Gamma|)$ constraints, where $|J|=\max_{i\in I}(|J^i|)$. This yields a relatively large problem scale and makes the problem solving time consuming, especially for large-scale IDC-EONs. In the next section, we will propose a few methods to reduce this time complexity.

Algorithm 1: Overall Procedure for Orchestrating M-NFV-Ts in an IDC-EON

for *each* $i\in I$ *and* $j\in J^i$ **do**
  if $t^{i,j}=t$ **then**
    insert $d^{i,j}$ into *Cluster* c^t;
  end
end
for *each* $t\in\Gamma$ **do**
  if $c^t\neq\emptyset$ **then**
    if t *is location-restricted* **then**
      for *each* $d^{i,j}\in c^t$ **do**
        choose the DC in $N^{i,j}$ to place a VNF;
        allocate IT resources accordingly;
      end
    else
      orchestrate the VNF(s) of all $d^{i,j}\in c^t$;
    end
  end
end
for *each* $i\in I$ **do**
  build an MST from s^i to the VNF nodes $\{v^{i,j}:\forall j\}$;
  assign FS' on the MST to realize optical multicast;
  for *each subset of destinations that share a same VNF on node* v **do**
    build an MST from v to the destinations;
    assign FS' to realize optical multicast;
  end
end

V. Heuristic Algorithms for Network Planning

In this section, we design three algorithms to address the network planning for orchestrating M-NFV-Ts in the IDC-EON in a more time-efficient manner than the MILP. Since we still need to jointly consider the VNF placement and the multicast RSA to connect the source, VNFs and destinations for each M-NFV-T, we first define the concept of destination cluster to assist the VNF orchestration.

Definition 1: Given a set of M-NFV-Ts, the **destination cluster** c^t includes all the destinations that request for a t type VNF, where $t\in\Gamma$. Classifying the destinations into clusters helps us to improve the sharing ratio of VNFs in VNF placement, and also reduces the complexity of the problem as different destination clusters can be handled independently when orchestrating the M-NFV-Ts.

Since the M-NFV-Ts can only be provisioned in the IDC-EON after all the VNF nodes having been determined, we try to solve the problem in two steps. Firslty, we determine the VNF placement in a way such that the potential spectrum and IT resource utilizations are considered jointly. Secondly, we carefully design the multicast RSA schemes to connect the sources, VNFs, and destinations for each M-NFV-T to minimize the spectrum utilization. *Algorithm* 1 shows the overall procedure. *Lines* 1–5 obtain the destination clusters of the M-NFV-Ts. Then, for each destination cluster, if the requested VNF is location-restricted, *Lines* 9–12 just select their designated DCs and allocate IT resources accordingly to process the traffic of these destinations. On the other hand, for location-independent VNFs, *Line* 14 leverages an algorithm that considers the spectrum and IT resource allocation jointly to determine the VNF placement. In the following parts of this section, we will introduce three such algorithms for the VNF placement, which are the rendezvous-based algorithm (RB), the auxiliary FS-matrix based MILP (AFM-MILP), and the AFM-based greedy search algorithm (AFM-GS). *Lines* 18–25 show the procedure for setting up the multicast light-trees[1] to realize the data-transfers among the sources, VNFs and destinations of the M-NFV-Ts, i.e., performing multicast RSA. Here, for each M-NFV-T, we first calculate a minimum spanning tree (MST) to cover the source and VNFs, as shown in *Line* 19. Then, spectrum assignment is performed in *Line* 20 to realize all-optical multicast accordingly. Note that, the light-tree only spans to the VNF nodes as the traffic will experience O/E/O conversions when being processed by the VNFs. To set up the connections from the VNFs to their corresponding destinations, *Lines* 21–24 calculate an MST to cover each VNF node and the subset of destinations that share it. In this work, we assign FS' with the first-fit scheme, if not specified.

A. *Rendezvous-Based (RB) Heuristic Algorithm*

We define concepts of rendezvous destinations and rendezvous degree to assist the VNF orchestration.

Definition 2: Given a destination cluster c^t, we first calculate K shortest paths between each destination in the cluster to its source. Then, the **rendezvous destinations** $RR_t(v)$, $v \in V$ includes the destinations in c^t whose path candidate(s) go through node v, and the **rendezvous degree** is $RD_t(v) = |RR_t(v)|$. Hence, to reduce both the spectrum and IT resource utilization, we should place t type VNFs on the DCs with the largest rendezvous degree, i.e., ensuring that the VNFs are placed on the shortest paths with the minimum redundancy.

Fig. 2 shows an intuitive example on how to get the rendezvous destinations and rendezvous degrees. Supposing there are 7 destinations, each of which requests for a t type VNF, we have $c^t = \{d_1, d_2, \cdots, d_7\}$. The arrowed lines in Fig. 2 indicate the path candidates to connect the destinations to their sources. Note that, for simplicity, we set $K = 1$ in the example, i.e., we only calculate the shortest path between each destination in the cluster to its source. Then, we can see that there are three, three, four, and two paths going through *Node* 1, *Node* 2, *Node* 3, and *Node* 4, respectively. *Node* 3 has the largest rendezvous degree as $RD_t(3) = 4$, and its rendezvous destinations are in $RR_t(3) = \{d_1, d_4, d_6, d_7\}$.

[1]Note that, *w.l.o.g.*, we consider a unicast lightpath as a special case of light-tree, which only includes a single destination.

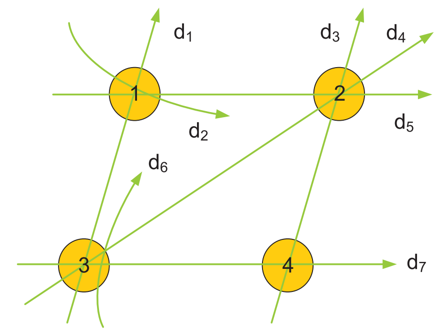


Fig. 2. Example of rendezvous destinations and rendezvous degrees.

Algorithm 2: Rendezvous-based Algorithm (RB)

Input: V, c^t
Output: $\{x_v^{i,j} : d^{i,j} \in c^t\}$

1 obtain $RR_t(v)$ and $RD_t(v)$ for $\forall v \in V$;
2 **while** $c^t \neq \emptyset$ **do**
3 $\quad v' = \arg\max_{v \in V}(RD_t(v))$;
4 $\quad$ **for** *each destination* $d^{i,j} \in \{RR_t(v') \bigcap c^t\}$ **do**
5 $\quad\quad$ **if** $v' \neq s^i$ *and* $C_{v'}$ *is not exhausted* **then**
6 $\quad\quad\quad$ choose v' as the VNF node of $d^{i,j}$;
7 $\quad\quad\quad$ allocate IT resources accordingly;
8 $\quad\quad\quad$ remove $d^{i,j}$ from c^t;
9 $\quad\quad$ **end**
10 $\quad$ **end**
11 $\quad$ remove v' from V;
12 **end**

Algorithm 2 leverages the rendezvous degree to orchestrate M-NFV-Ts efficiently in the IDC-EON. *Line* 1 obtains the rendezvous destinations $RR_t(v)$ and rendezvous degree $RD_t(v)$ for each node $v \in V$. The while-loop that covers *Lines* 2–12 ensures that each destination in c^t is assigned a VNF node. Specifically, *Line* 3 selects node v' with the maximum rendezvous degree as the VNF node, and *Lines* 4–10 place a VNF on v' for the destinations in $\{RR_t(v') \bigcap c^t\}$, and allocate IT resources to process the traffic of these destinations. The destinations are removed from c^t after their VNF nodes having been determined. Until *Line* 10, all the destinations in $RR_t(v')$ have been handled, and *Line* 11 removes v' from V.

Complexity analysis: Since the K shortest paths between each node pair are pre-calculated, the computational complexity of RB is $O(|c^t| \cdot |V| + |c^t|^2)$.

B. *Auxiliary FS-Matrix (AFM) based Algorithms*

Note that, although RB tries to reduce the spectrum utilization by only selecting the DCs on the shortest paths to place the VNFs, it does not optimize the VNF placement to the maximum extent. Therefore, we propose an auxiliary FS-matrix (AFM) model to further improve the performance of the VNF placement. Basically, for each destination $d^{i,j}$ in a cluster c^t, the utilization of spectrum and IT resources on its branch $s^i \rightarrow d^{i,j}$ can be determined when its VNF node $v^{i,j}$ has been determined,

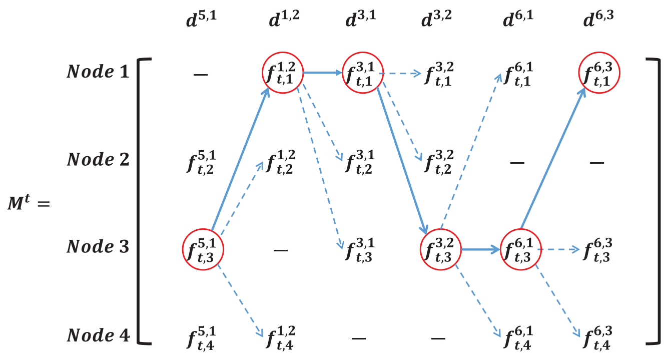


Fig. 3. Example of M^t in the AFM model.

if we only consider the shortest paths for connecting the node pairs. Then, both the total resource usage and the total number of deployed VNF can be estimated[2] when we have selected the VNF nodes for all the destinations in c^t. Meanwhile, with the topology $G(V, E)$, we can enumerate all the possible locations of the VNF node of a destination $d^{i,j}$. Then, the idea is to re-design the optimization based on the possible locations of VNF nodes.

For all the destinations in c^t, we come up with an auxiliary FS-matrix M^t, which has a size of $|V| \times |c^t|$. Each element of M^t is $f^{i,j}_{t,v}$, which represents the total FS usage on the branch $s^i \rightarrow d^{i,j}$ if node v is chosen as the VNF node of $d^{i,j} \in c^t$. Fig. 3 provides an example on M^t, where we have $c^t = \{d^{5,1}, d^{1,2}, d^{3,1}, d^{3,2}, d^{6,1}, d^{6,3}\}$ and assume four nodes in V. As each destination $d^{i,j}$ cannot choose source s^i as its VNF node, $f^{i,j}_{t,v}$ is unavailable when $v = s^i$. Note that, $f^{i,j}_{t,v}$ can also be unavailable if the IT resources on DC v are not enough to carry the requested VNF of $d^{i,j}$. Then, each element in M^t stands for a possible location of the corresponding VNF node, e.g., $f^{5,1}_{t,3}$ records the total FS usage on the branch $s^5 \rightarrow Node\ 3 \rightarrow d^{5,1}$, if destination $d^{5,1}$ chooses *Node* 3 as its VNF node.

1) AFM-MILP: With M^t as an input, we develop an MILP (AFM-MILP) to optimize the orchestrating of M-NFV-Ts in an IDC-EON based on the possible locations of VNF nodes. In addition to the notations and variables defined in Section IV, we incorporate some new ones as follows.

Notations:

- Γ': the set of location-independent VNF types in the IDC-EON, $\Gamma' \subseteq \Gamma$.
- c^t: the destination cluster that includes all the destinations requesting for a $t \in \Gamma'$ type VNF.
- $f^{i,j}_{t,v}$: the total FS usage on the branch $s^i \rightarrow d^{i,j}$, if node v is chosen as the VNF node of $d^{i,j} \in c^t$, $t \in \Gamma'$.
- C'_v: the available IT resources on the DC on node $v \in V$.

Variables:

- $x^{i,j}_{t,v}$: the boolean variable that equals 1 if destination $d^{i,j} \in c^t$, $t \in \Gamma'$ chooses node v as its VNF node, and 0 otherwise.

[2]Note that, the total spectrum usage estimated here is just a reasonably good approximation but might not be the exact value of final solution as a light-tree can make different destinations in an M-NFV-T share spectrum resources.

- $\eta_{t,s}$: the total cost of spectrum usage for serving all the destinations in cluster c^t, $t \in \Gamma'$.
- $\eta_{t,c}$: the total cost of IT resource consumption for serving all the destinations in cluster c^t, $t \in \Gamma'$.
- $\eta_{t,v}$: the total cost of VNF deployment for serving all the destinations in cluster c^t, $t \in \Gamma'$.

Objective:

The optimization objective is to minimize the SP's total cost for serving all the destinations in cluster c^t, $t \in \Gamma'$ in the IDC-EON.

$$Minimize \quad \eta_t = \eta_{t,s} + \eta_{t,c} + \eta_{t,v}. \tag{19}$$

Constraints:

$$\sum_{v \in N^{i,j}} x^{i,j}_{t,v} = 1, \quad \{(i,j) : d^{i,j} \in c^t\}, \forall t \in \Gamma'. \tag{20}$$

Eq. (20) ensures that the requested VNF of each destination in c^t is placed on one and only one DC.

$$h^i_{v,t} \geq x^{i,j}_{t,v}, \ \ \{(i,j) : d^{i,j} \in c^t\}, \forall v \in V, \forall t \in \Gamma' \tag{21}$$

$$h_{v,t} \geq h^i_{v,t}, \ \ \{i : d^{i,j} \in c^t, \forall j \in J^i\}, \forall v \in V, \forall t \in \Gamma'. \tag{22}$$

Eqs. (21)–(22) indicate whether a t type VNF is placed on v.

$$\sum_i h^i_{v,t} \cdot b^i \leq C'_v, \quad \forall v \in V, \forall t \in \Gamma'. \tag{23}$$

Eq. (23) ensures that the placement of VNFs satisfies the IT resource capacity constraint.

$$\eta_{t,s} = w_s \cdot \sum_i \sum_j \sum_v f^{i,j}_{t,v} \cdot x^{i,j}_{t,v}, \forall t \in \Gamma' \tag{24}$$

$$\eta_{t,c} = w_c \cdot \sum_i \sum_v h^i_{v,t} \cdot b^i, \forall t \in \Gamma' \tag{25}$$

$$\eta_{t,v} = w_v \cdot \sum_v h_{v,t}, \forall t \in \Gamma'. \tag{26}$$

Eqs. (24)–(26) obtain the three cost components for spectrum utilization, IT resource utilization, and VNF deployment, after we have served all the destinations in cluster c^t, $t \in \Gamma'$.

Here, in the worst case, if we only consider the most dominating term, the AFM-MILP only needs to determine the values of approximately $(|I| \cdot |J| \cdot |V|)$ variables according to nearly $(|I| \cdot |J| \cdot |V|)$ constraints, where $|J| = \max_{i \in I}(|J^i|)$. Therefore, compared with the MILP in Section IV, AFM-MILP makes the problem scale much smaller and improves the time-efficiency significantly. Meanwhile, we need to point out that as AFM-MILP serves the M-NFV-Ts by handling the destination clusters one-by-one independently, it cannot solve the problem exactly due to this decomposition. Finally, another interesting question to answer is that whether there is a polynomial-time algorithm to solve the optimization in AFM-MILP exactly? Unfortunately, the answer is no.

Theorem: The optimization in AFM-MILP is $\mathcal{NP}$-hard.

Proof: We prove the $\mathcal{NP}$-hardness of the optimization in AFM-MILP by restriction, *i.e.*, restricting away certain aspects of the problem until a known $\mathcal{NP}$-hard problem appears [34].

First of all, we apply the restriction that each M-NFV-T only has one branch (i.e., $|D^i| = 1, \forall i$), and then one copy of IT resources on a DC cannot be shared by any different destinations in cluster c^t. This is because the traffics go into the t type VNF on the DC are from different sources. Secondly, we have $w_s = 0$ and make the minimization of the total spectrum usage irrelevant. Then, we can see that the optimization problem becomes to minimize $\eta_t = \eta_{t,c} + \eta_{t,v}$. According to Eq. (20), the requested VNFs of all the destinations in c^t should be provisioned, and we also know that due to $|D^i| = 1, \forall i$, none of the destinations in c^t can share IT resources. Therefore, the total IT resource consumption simply becomes a constant, and so does the cost term $\eta_{t,c}$. Consequently, the optimization problem becomes to minimize $\eta_{t,v}$, i.e., minimizing the number of the DCs that have a t type VNF deployed on them. Then, we apply the last restriction to ensure that the available IT resources on all the DCs in the IDC-EON are equal, as C'. Finally, if we consider the DCs as bins with a fixed capacity and the destinations' requested VNFs as items with different sizes, the optimization is just transformed into the general case of the bin packing problem, which is known to be $\mathcal{NP}$-hard [34]. Because a special/restricted case of the optimization in AFM-MILP is the general case of a known $\mathcal{NP}$-hard problem, we prove that the optimization in AFM-MILP is $\mathcal{NP}$-hard.

2) AFM based Greedy Search (AFM-GS) Algorithm: As the optimization in AFM-MILP is still $\mathcal{NP}$-hard, we do not try to find a polynomial-time exact algorithm but propose a greedy heuristic, namely, the AFM-based greedy search algorithm (AFM-GS). *Algorithm*3 shows the procedure of AFM-GS. *Line* 1 calculates M^t for all the destinations in cluster c^t. Then, in *Line* 2, we assign each column of M^t a weight as the minimum value of the elements in it, and *Line* 3 reorganizes the columns of M^t in ascending order of their weights. For example, the weight of each column of the matrix $\begin{bmatrix} 2 & 1 & 3 \\ 4 & 5 & 6 \end{bmatrix}$ is 2, 1, 3, respectively. And the reorganized matrix is $\begin{bmatrix} 1 & 2 & 3 \\ 5 & 4 & 6 \end{bmatrix}$. Then, in the first column of M^t, we find the element whose value $f_{t,v}^{i,j}$ is the smallest, place a t type VNF on node v for destination $d^{i,j}$, and allocate corresponding IT resources to the VNF, as shown in *Lines* 4–5. Then, *Line* 6 updates M^t to mark the element as unavailable if the corresponding DC's IT resources are insufficient to carry the corresponding requested VNF. The for-loop of *Lines* 7–12 searches for the VNF nodes for the rest destinations in c^t in a greedy manner. Specifically, *Line* 8 finds the element in a column such that placing a VNF on the corresponding DC minimizes the total cost in Eq. (19). The search procedure of AFM-GS is also illustrated in Fig. 3.

Complexity Analysis: The time complexity of AFM-GS is $O(|c^t| \cdot |V| + |c^t| \cdot log(|c^t|))$.

Algorithm 3: AFM-based Greedy Search Algorithm

Input: V, c^t
Output: $\{x_{t,v}^{i,j} : d^{i,j} \in c^t\}$

1 calculate M^t for all the destinations in cluster c^t;
2 assign each column of M^t a weight as the minimum value of the elements in it;
3 reorganize the columns of M^t in ascending order of their weights;
4 find the element whose value $f_{t,v}^{i,j}$ is the smallest in the first column of M^t;
5 place a t type VNF on node v for destination $d^{i,j}$ and allocate IT resources accordingly;
6 update M^t to mark the element as unavailable if the corresponding DC's IT resources are insufficient to carry the corresponding requested VNF;
7 **for** *each column of* M^t *from the second one* **do**
8   find the element in the column such that placing a VNF on the corresponding DC minimizes the total cost in Eq. (19);
9   place a t type VNF on the corresponding DC for the corresponding destination;
10   allocate IT resources accordingly;
11   update M^t as in *Line* 6;
12 **end**

VI. Performance Evaluation for Network Planning

A. Simulation Setup

We design simulations to evaluate the performance of the proposed algorithms with three topologies, i.e., the six-node topology in [35], and the NSFNET and US Backbone topologies in [30]. We assume that the capacity of an FS is $B_w = 12.5$ Gb/s. For the six-node topology, there are $|\Gamma| = 3$ types of location-independent VNFs, which are uniformly distributed, and the bit-rates of the M-NFV-Ts have an average value of 10 Gb/s. While for the NSFNET and the US Backbone topologies, we assume that there are $|\Gamma| = 8$ types of VNFs, among which the first seven are location-independent while the last one (i.e., *VNF8*) is location-restricted. The distribution of the VNFs is [*VNF1* : *VNF2* : *VNF3* : *VNF4*: *VNF5* : *VNF6* : *VNF7* : *VNF8*] $= [3:3:3:3:3:3:3:1]$. The bit-rates of the M-NFV-Ts are uniformly distributed within $[10, 40]$ Gb/s. The average number of destinations in an M-NFV-T is 3, if not specified. We have $w_s = \frac{1}{(F \cdot |E|)}$, $w_v = \frac{1}{(|\Gamma| \cdot |V|)}$, and $w_c = \frac{1}{(C_v \cdot |V|)}$, to normalize the costs. We use LINGO [36] to solve MILP and AFM-MILP because it provides a simple language to model the optimization problems and performs relatively well on obtaining optimal solutions. While the heuristic algorithms are simulated with MATLAB. All the simulations are run on a computer with a 2.20 GHz Intel CPU and 32 GB RAM. Other simulation parameters are in Table I. We also design a benchmark algorithm that uses random VNF placement (RP) for performance comparison.

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

$\|I\|$	$\|J^i\|$	MILP		AFM-MILP		AFM-GS		RB		RP	
		η	Time	η	Time	η	Time	η	Time	η	Time
2	2	0.14	53.33	0.15	0.25	0.15	0.04	0.15	0.05	0.26	0.02
	3	0.19	98.60	0.20	0.32	0.21	0.03	0.22	0.05	0.39	0.03
	4	0.24	198.20	0.25	0.38	0.25	0.05	0.28	0.04	0.48	0.03
4	2	0.26	208.40	0.26	0.35	0.29	0.02	0.30	0.02	0.44	0.02
	3	0.29	394.60	0.30	0.40	0.32	0.02	0.32	0.04	0.63	0.03
	4	0.32	812.80	0.32	0.42	0.38	0.04	0.37	0.04	0.73	0.04
6	2	0.34	466.75	0.35	0.38	0.39	0.03	0.42	0.03	0.63	0.03
	3	0.43	1129.75	0.43	0.43	0.48	0.03	0.52	0.05	0.86	0.03
	4	0.45	1814.00	0.45	0.46	0.51	0.05	0.49	0.05	0.95	0.06
8	2	0.42	962.75	0.43	0.43	0.51	0.03	0.53	0.05	0.80	0.03
	3	0.51	1669.75	0.51	0.45	0.62	0.04	0.63	0.05	1.07	0.04
	4	0.62	3844.33	0.64	0.49	0.64	0.05	0.79	0.07	1.26	0.05

TABLE I
SIMULATION PARAMETERS FOR NETWORK PLANNING

Topology	Nodes	Directed Links	IT Capacity	Link Capacity
Six-Node	6	16	200 units	10 FS’
NSFNET	14	44	2000 units	200 FS’
US Backbone	28	90	2000 units	200 FS’

B. Simulation Results with the Six-Node Topology

Table II shows the results from the five algorithms with the six-node topology. The total cost η is calculated with Eq. (1). As expected, MILP provides the lowest average total cost among the algorithms, but its running time is also the longest. We can see that all the heuristics can be solved within reasonably short time and provide similar results as those from the MILP. Specifically, MILP is followed by AFM-MILP, whose results on η range within $[1.00, 1.06]$ times of those from MILP. This indicates that AFM-MILP can also orchestrate M-NFV-Ts in the IDC-EON cost-effectively. Meanwhile, we notice that the running time of AFM-MILP is much shorter than that of MILP. The running time can be further reduced by one magnitude with AFM-GS, whose results on η range are $[1.04, 1.25]$ times of those from MILP. These results verify the effectiveness of the AFM-based approaches.

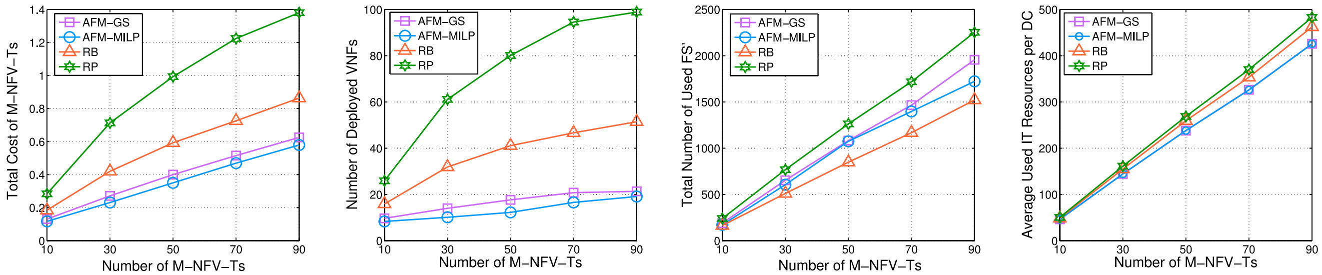
The average total costs from RB range within $[1.03, 1.28]$ times of those from MILP. We can see that AFM-GS outperforms RB in most cases, while the running times of them are comparable. This is because AFM-GS adopts the strategy to place VNFs with the joint consideration of spectrum and IT resource utilization in a more balanced manner, while RB focuses too much on minimizing the spectrum usage and places most of the VNFs along the shortest paths. Finally, we can see that the performance of the benchmark algorithm RP is the worst, since its average total cost is the most and is almost twice as high as those from AFM-GS and RB while its running time is comparable to those of AFM-GS and RB.

C. Simulation Results with Large-Scale Topologies

We then evaluate the heuristics with the NSFNET and US Backbone topologies to investigate their performance further. We first perform simulations with the NSFNET topology and the results are shown in Fig. 4. Fig. 4(a) plots the results on the total cost of provisioning M-NFV-Ts. The results still indicate that AFM-MILP provisions the M-NFV-Ts with the lowest average total cost, followed by AFM-GS, RB and RP, in sequence. This verifies that AFM-MILP also performs well in the relatively large topology, while due to its high complexity, MILP is intractable with large topologies. The average total cost from AFM-GS is close to that from AFM-MILP, and its maximum optimization gap on the total cost from AFM-MILP is only 17.4%. When the number of provisioned M-NFV-Ts keeps increasing, the results on total cost from RB and RP grow more quickly than AFM-MILP and AFM-GS.

We then look into the three cost components in Eq. (1) specifically. The results on the number of deployed VNFs are shown in Fig. 4(b). As expected, AFM-MILP and AFM-GS deploy the smallest numbers of VNFs. Basically, the AFM model's advantage comes from the fact that it enables the algorithms to place VNFs such that the total cost in Eq. (19) can be minimized, i.e., reusing VNFs in a more intelligent way. Compared with RP, AFM-MILP, AFM-GS and RB reduce the number of deployed VNFs by 80.7%, 78.4% and 48.0%, respectively, when 90 M-NFV-Ts are provisioned. Fig. 4(c) shows that the results on the total number of used FS’ from all the algorithms increase approximately linearly with the number of provisioned M-NFV-Ts. RB uses the smallest number of FS’ among the four algorithms, which is because RB tends to put VNFs along the shortest paths. AFM-MILP's performance on FS usage is the second best, followed by AFM-GS, which verifies that the AFM model takes the FS usage into consideration. Finally, Fig. 4(d) illustrates the results on average IT resource consumption per DC, and AFM-MILP and AFM-GS perform the best on this metric.

Table III shows the running time of the algorithms. The running time of AFM-MILP is still the longest and increases exponentially with the number of M-NFV-Ts, while the running time



(a) (b) (c) (d)

Fig. 4. Results from network planning with the NSFNET topology for (a) total cost of M-NFV-Ts, (b) number of deployed VNFs, (c) number of used FS', and (d) average IT resources consumption per DC.

TABLE III
RESULTS ON RUNNING TIME (IN SECONDS) WITH LARGE-SCALE TOPOLOGIES

	Algorithms \ $\|I\|$	10	30	50	70	90
NSFNET	AFM-MILP	1.25	1.93	5.29	8.03	14.06
	AFM-GS	0.10	0.18	0.31	0.43	0.57
	RB	0.21	0.25	0.38	0.53	0.67
	RP	0.13	0.18	0.30	0.47	0.59
US Backbone	AFM-MILP	1.45	3.34	7.26	18.62	27.80
	AFM-GS	0.20	0.25	0.37	0.52	0.73
	RB	0.22	0.27	0.38	0.54	0.77
	RP	0.16	0.22	0.36	0.54	0.62

of AFM-GS is much shorter than it. Compared with RB, AFM-GS also reduces the running time for 26.3% on average. This is because the analysis in Section V shows that the time complexity of AFM-GS is $O(|c^t| \cdot |V| + |c^t| \cdot log(|c^t|))$ and that of RB is $O(|c^t| \cdot |V| + |c^t|^2)$, and thus AFM-GS is more time-efficient than RB. We then perform more simulations with the US Backbone topology, and the results summarized in Fig. 5 and Table III exhibit the similar trends as those with the NSFNET topology.

VII. HEURISTIC ALGORITHMS FOR NETWORK PROVISIONING

In this section, we consider the problem of dynamic network provisioning, where the M-NFV-Ts can be requested dynamically, i.e., they can come and leave on-the-fly.

A. Algorithm Description

Since we already verify the time-efficiency of AFM-GS and RB in static network planning while the running time of AFM-MILP is relatively long for dynamic provisioning, we design online algorithms based on AFM-GS and RB. Then, in each provision period, we use either *Algorithm* 2 r *Algorithm* 3 to serve the pending M-NFV-Ts. Note that, in static network planning, we only try to minimize the number of used FS' in the optimization, but it is known that in network provisioning, spectrum fragmentation may restrict the spectrum utilization in EONs and lead to high blocking probability [37], [38]. Therefore, we modify AFM-GS and RB to consider the fragmentation-aware RSA scheme, i.e., the misalignment-aware spectrum assignment (FMA) in [39], and compare the performance of the modified algorithms with the original ones that only consider the shortest path routing and first-fit spectrum assignment (SPFF). Specifically, we refer to the fragmentation-aware algorithms as AFM-GS-FMA and RB-FMA, while the original ones as AFM-GS-SPFF and RB-SPFF. Finally, we should explain how to handle VNFs on the DCs in a dynamic IDC-EON environment. 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 still use the NSFNET and US Backbone topologies to evaluate the performance of dynamic network provisioning. A DC's IT capacity is 1500 units in the NSFNET topology, while that in the US Backbone topology is 800 units. The other simulation parameters are the same as those in network planning. We generate the dynamic M-NFV-Ts with the Poisson traffic model [40], and in network provisioning, an M-NFV-T can be blocked due to the insufficiency of either spectrum resources or IT resources or both in the IDC-EON.[3]

Fig. 6 shows the simulation results from online provisioning with the NSFNET topology. Fig. 6(a) shows the results on blocking probability from the algorithms. If we keep the base algorithm unchanged with different RSA schemes, AFM-GS-FMA provides 32.8% lower blocking probability than that of AFM-GS-SPFF, and RB-FMA provides 45.2% lower blocking probability than that of RB-SPFF, on average. These results suggest that in a dynamic IDC-EON, we should pay more attention on spectrum fragmentation. Specifically, since the FMA scheme optimizes RSA for reducing fragmentation, the network can serve more requests in the future. When the RSA scheme is the same, AFM-GS provides lower blocking probabilities than RB, i.e., AFM-GS-SPFF outperforms RB-SPFF and AFM-GS-FMA outperforms RB-FMA.

[3]Note that, in the simulations, we first check whether the IT resources in the DCs are sufficient. If not, we mark an M-NFV-T as blocked due to the insufficiency of IT resources. Otherwise, we continue to check whether the spectrum resources are enough. If not, the M-NFV-T is marked as blocked due to the insufficiency of spectrum resources. Hence, the blocking scenario of IT resource insufficiency may also include the blocking cases due to the insufficiency of both resources.

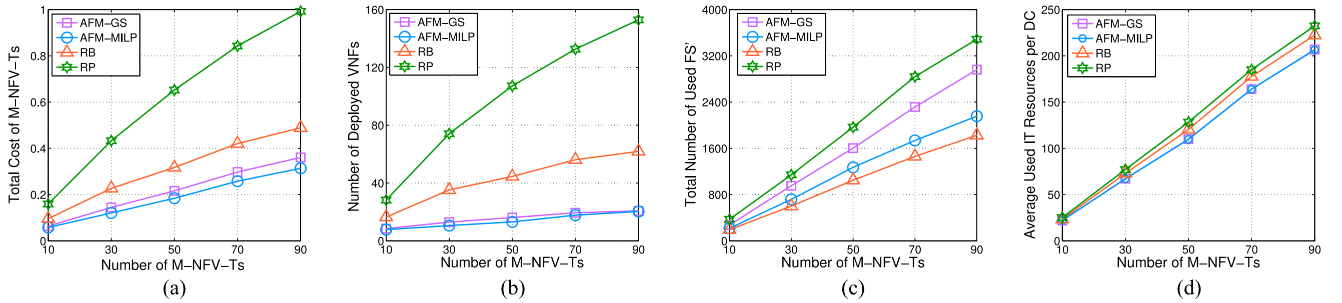


Fig. 5. Results from network planning with the US Backbone topology for (a) total cost of M-NFV-Ts, (b) number of deployed VNFs, (c) number of used FS', and (d) average IT resources consumption per DC.

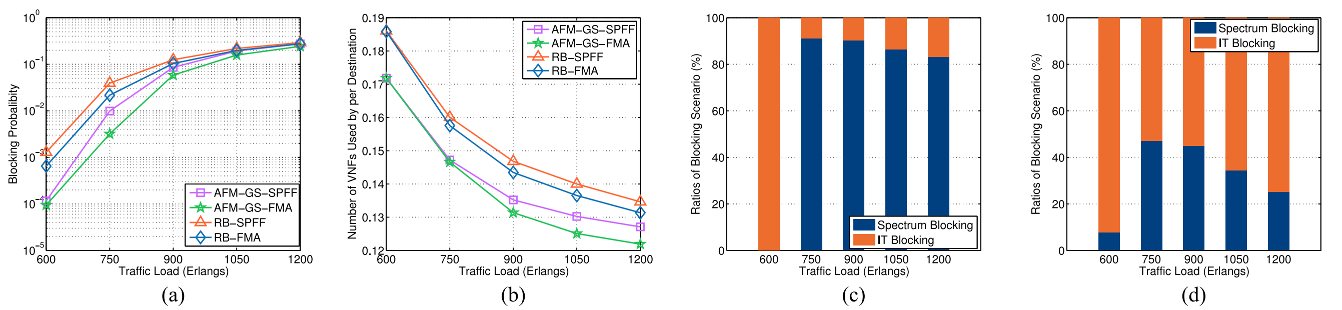


Fig. 6. Results from network provisioning with the NSFNET topology for (a) blocking probability, (b) average number of VNFs used by each destination, (c) ratios of blocking scenarios when using AFM-FMA, and (d) ratios of blocking scenarios when using RB-FMA.

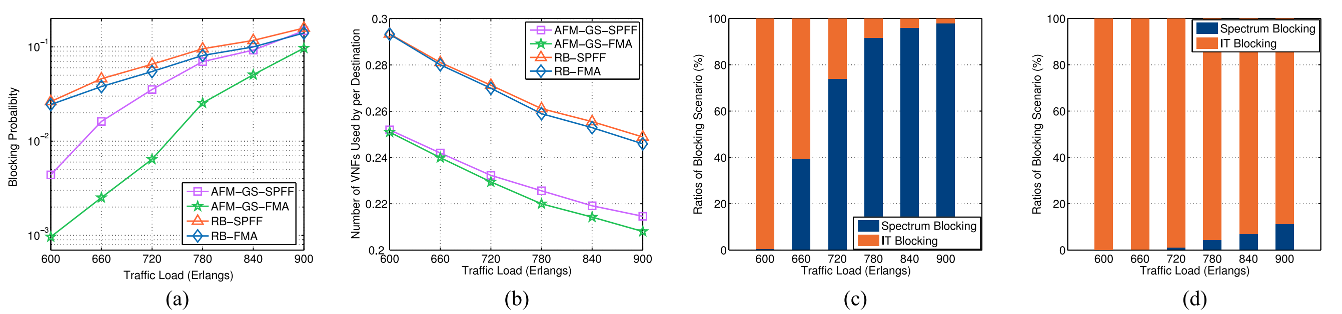


Fig. 7. Results from network provisioning with the US Backbone topology for (a) blocking probability, (b) average number of VNFs used by each destination, (c) ratios of blocking scenarios when using AFM-FMA, and (d) ratios of blocking scenarios when using RB-FMA.

Fig. 6(b) shows the results on the average number of VNFs used by each destination. We observe that the results decrease with the traffic load. This is because when there are more in-service M-NFV-Ts in the IDC-EON, the possibility of sharing VNFs among destinations becomes higher. As AFM-GS-FMA and RB-FMA serve more M-NFV-Ts successfully than AFM-GS-SP and RB-SP, respectively, their performance on VNF sharing is also better. Compared with RB-SPFF, the performance improvement of AFM-SPFF is 7.2% on average for this metric, and the improvement achieved by AFM-FMA over RB-FMA is 7.7% .

Since AFM-GS-FMA and RB-FMA performs better than their counterparts with SPFF, we further investigate the ratios of blocking scenarios (i.e., IT blocking or spectrum blocking) with them and plot the results in Figs. 6(c) and 6(d). Fig. 6(c) shows that with AFM-GS-FMA, the majority of the blocking cases are due to the insufficiency of spectrum resources (i.e., spectrum blocking), which contributes to 70.2% of the M-NFV-T blocking on average. This confirms that AFM-GS-FMA can utilize the IT resources efficiently. On the other hand, Fig. 6(d) indicates that with RB-FMA, IT blocking causes the majority of the blocking cases, i.e., contributing to 69.3% of the M-NFV-T blocking on average.

We also perform simulations with the US Backbone topology, and Fig. 7 summarizes the corresponding results. It can be seen that the results exhibit similar trends as those from the simulations with the NSFNET topology.

VIII. Conclusion

In this paper, we tried to optimize the VNF placement and multicast RSA jointly for orchestrating M-NFV-Ts in an IDC-

EON with the lowest cost. Our study addressed the scenarios of both static network planning and dynamic network provisioning. For network planning, we first formulated an MILP model to solve the problem exactly, and then proposed three heuristic algorithms, namely, AFM-MILP, AFM-GS, and RB. Extensive simulations showed that AFM-MILP and AFM-GS could approximate the MILP's performance for low-cost M-NFV-T provisioning with much shorter computation time, and the average approximation ratios relative to MILP were smaller than 1.06 and 1.25, respectively, with the small-scale six-node topology. While the simulations with large-scale topologies indicated that AFM-MILP performed the best for low-cost M-NFV-T provisioning and could reduce 17.4% of the total cost when being compared with AFM-GS. For network provisioning, we designed two additional online algorithms based on AFM-GS and RB to serve M-NFV-Ts in a dynamic IDC-EON, with the consideration of spectrum fragmentation. Simulation results indicated that AFM-GS-FMA could achieve the best blocking performance for dynamic M-NFV-T provisioning, and it could provide much lower blocking probability than AFM-GS-SPFF.

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Authors' biographies not available at the time of publication.