# On vNF-SC Deployment and Task Scheduling for Bulk-Data Transfers in Inter-DC EONs

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*(Invited Paper)*

***Abstract*—We study how to deploy vNF service chains (vNF-SCs) and perform task scheduling for bulk-data transfers in inter-datacenter (inter-DC) elastic optical networks (EONs). We call this type of request a data-intensive vNF-SC request. According to the number of required vNF-SCs, the data-intensive vNF-SC requests are classified into linear and multi-branch data-intensive vNF-SC requests. For linear data-intensive vNF-SC requests, we propose a dynamic-programming-based vNF-SC deployment and task scheduling algorithm to minimize the average service completion time (SCT). For multi-branch data-intensive vNF-SC requests, we propose a correlation-aware vNF-SC deployment and task scheduling algorithm to minimize the average SCT, since there are multiple vNF-SC branches that are correlated and the SCT of a multi-branch data-intensive vNF-SC request is determined by the SCT of the latest vNF-SC branch. Simulation results verify that our algorithms can reduce the average SCTs of data-intensive vNF-SC requests of the two types effectively.**

***Index Terms*—Network Function Virtualization, vNF Service Chain, Bulk-Data Transfer, Elastic Optical Networks.**

## I. Introduction

Network function virtualization (NFV) emerges as a revolutionary technology in today's telecommunication industry [1]. Traditionally, to enable a network service, service providers (SPs) need to deploy a sequence of network functions that are implemented in dedicated middleboxes in the networks. With NFV, virtual network functions (vNFs) can be realized on general-purpose servers that perform the same functions as the traditional middleboxes but can be put on the market, maintained, and upgraded more easily and timely. Based on vNFs, network services can be deployed in a more flexible way, which can significantly shorten new services' time-to-market. Having massive IT resources, datacenter (DC) infrastructures become the premium NFV infrastructure points-of-presence for various vNFs. Meanwhile, since network services are more likely to traverse multiple DCs, inter-DC networks have to be flexible, programmable and cost-effective to provide SPs with the right service delivery infrastructure [2]. For this, elastic optical networks (EONs) have been envisioned as a promising physical infrastructure for inter-DC networks, due to their flexible spectrum management mechanisms [3, 4]. However, for the same reason, how to provision vNF service chain (vNF-SC) services effectively becomes a challenging problem in inter-DC EONs [5].

Basically, to provision a vNF-SC service, SPs need to not only deploy the vNF-SC as requested but also steer traffic among vNFs orderly [6]. When deploying a vNF-SC, SPs need to locate a proper DC to instantiate each vNF required in the vNF-SC, and set up lightpaths (*i.e.*, with considerations of physical impairments [7] and spectrum fragmentation [8, 9]) in between the selected DCs to connect vNFs in the forming of the vNF-SC. As to traffic steering among vNFs, it depends on the type of a vNF-SC request. For a bandwidth-intensive vNF-SC that demands bandwidth-guaranteed connections in between vNFs [10], SPs only need to assign enough frequency slots (FS') on the lightpaths in between vNFs, while for a data-intensive vNF-SC that needs to transfer a specific amount of data through a sequence of vNFs before a deadline [11, 12], SPs need to not only perform task scheduling in the selected DCs but also reserve FS' on the lightpaths in between vNFs for bulk-data transfers to meet the deadline [13]. Hence, the provisioning of a data-intensive vNF-SC is more complex than that of a bandwidth-intensive vNF-SC.

Previously, researchers have studied the service provisioning problems of bandwidth-/data-intensive vNF-SC requests under different network scenarios [14–16]. However, the proposed solutions in these studies cannot be directly applied in inter-DC EONs, since they have not yet considered the unique spectrum management mechanism in EONs [17]. For this reason, aiming to optimize the IT and bandwidth resources jointly [18], we studied affiliation-aware vNF placement and vNF-SC deployment for bandwidth-intensive vNF-SC requests in inter-DC EONs in [5, 19–21]. Meanwhile, due to the complexity of serving data-intensive vNF-SC requests in inter-DC EONs, the related work is still rare, which makes it crucial to carry out research in this area.

In this work, we investigate how to provision data-intensive vNF-SC requests in inter-DC EONs effectively. According to the number of vNF-SC branches, we classify the data-intensive vNF-SC requests into linear and multi-branch data-intensive vNF-SC requests. We first build the network model and propose to utilize 2-dimensional (2D) spectrum fragments on established lightpaths for bulk-data transfers between vNFs, aiming to improve spectrum utilization in EONs while satisfying the quality-of-service (QoS) of data-intensive vNF-SC services. Then, we describe the service provisioning problems of linear and multi-branch data-intensive vNF-SC requests, respectively. For linear data-intensive vNF-SC requests, we propose a dynamic-programming-based (DP-based) vNF-SC deployment and task scheduling algorithm to minimize the average SCT. Based on the DP-based algorithm, we propose a correlated-aware vNF-SC deployment and task scheduling algorithm for multi-branch data-intensive vNF-SC requests, since the SCT of a multi-branch data-intensive vNF-SC request is determined by that of the latest vNF-SC branch. Finally, we run extensive simulations for performance evaluation, and simulation results verify that the proposed algorithms can reduce the average SCTs of data-intensive vNF-SC requests of the two types effectively.

The rest of the paper is organized as follows. Section II presents the problem descriptions. In Section III, we propose vNF-SC deployment and task scheduling algorithms for linear and multi-branch data-intensive vNF-SC requests, respectively. Section IV discusses the simulations for performance evaluation. Finally, we summarize the paper in Section V.

## II. Problem Descriptions

### A. Network Model

An inter-DC EON consists of a DC set $V$ and a lightpath set $L$ in which the lightpaths are established in an EON-based infrastructure for realizing inter-DC connections. To provide vNF-SC services timely, we assume $N$-types of vNFs have been widely deployed in DCs, denoted as set $T = \{vNF_1, vNF_2, ..., vNF_N\}$. Specifically, for DC node $v \in V$, the set of deployed vNFs on it is $T_v \subseteq T$, while for type $f$ vNF, the set of DCs that have deployed such a vNF is $V_f \subseteq V$. The inter-DC EON operates in a discrete-time manner that the network operation status updates every time slot (TS). Each type $f$ vNF can process $\gamma_f$ amount of data in a TS and has an input-to-output data change ratio of $\delta_f$.

Between each DC pair $(s,d) \in V^2$, a lightpath set $L_{s,d}$ is established for supporting bulk-data transfers between vNFs on them. Due to the reality that heterogeneous traffics coexist in networks, we assume dynamic background traffics are running on the established lightpaths, which would generate 2D spectrum fragments on them. Here, a 2D spectrum fragment refers to a non-aligned and isolated unused bandwidth block in both the time and spectrum domains. Due to their small size in both domains, the 2D spectrum fragments are hard to serve bandwidth-hungry services but can be utilized for bulk-data transfers between the vNFs in data-intensive vNF-SCs. Therefore, in this work we try to make full use of 2D spectrum fragments in the EON when serving data-intensive vNF-SC requests to improve spectrum utilization while satisfying the QoS of data-intensive vNF-SC services.

### B. Data-Intensive vNF-SC Deployment and Task Scheduling

Basically, a data-oriented vNF-SC request can be denoted as $R_i(s_i, D_i, \zeta_{i,0}, SC_i)$, where $s_i$ is the source DC, $D_i$ is the destination DC set, $\zeta_{i,0}$ is the data volume generated in the source DC, and $SC_i$ is the set of requested vNF-SCs which process and transfer the initial data, respectively, to the destination DCs. Note that, according to the sizes of $D_i$ and $SC_i$, the data-intensive vNF-SC requests can be classified into linear and multi-branch data-intensive vNF-SC requests.

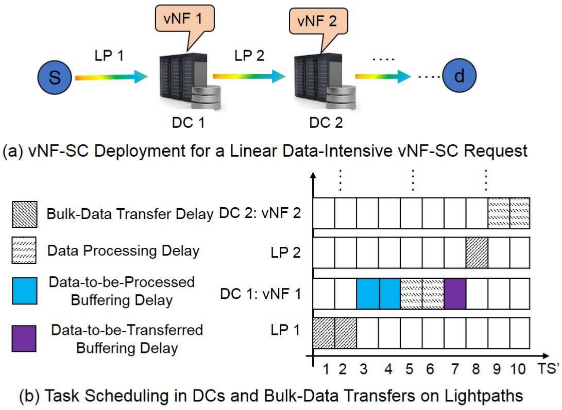


Fig. 1. Example of vNF-SC deployment and traffic steering for a linear data-intensive vNF-SC request.

*1) Linear Data-Intensive vNF-SC Requests:* For a linear data-intensive vNF-SC request, there is an unique destination DC, *i.e.*, $D_i = \{d_{i,0}\}$, and the initial data from the source DC needs to be processed by a set of vNFs in sequence, *i.e.*, $SC_i = \{f^1_{i,0}, f^2_{i,0}, ..., f^{N_0}_{i,0}\}$, before it is received by the destination DC. Hence, to serve a linear data-intensive vNF-SC request, SPs need to:

- select a proper DC $v^j_{i,0}$ from $V_{f^j_{i,0}}$ to instantiate the $j$-th vNF in $SC_i$ that $j \in \{1, 2, ..., N_0\}$, as shown in Fig. 1(a);
- select available lightpaths between the selected DCs to connect the requested vNF-SC, as shown in Fig. 1(a);
- perform task scheduling in the selected DCs and bulk-data transfers on the selected lightpaths, as shown in Fig. 1(b).

Note that, when performing task scheduling in DCs, an uninterrupted service time window needs to be scheduled for each requested vNF to process the incoming data completely, and 2D spectrum fragments need to be reserved on the selected lightpaths for transmitting the processed data to the next vNF or the destination DC accordingly. As shown in Fig. 1(b), the data processing in *vNF* 1 is discontinuous with the frontward bulk-data transfer on *LP* 1 and the backward bulk-data transfer on *LP* 2. Due to this reason, data-to-be-processed buffering delay and data-to-be-transferred buffering delay are introduced in the selected DCs. The SCT of a linear data-intensive vNF-SC request is the summation of the total data-to-be-processed buffering, data processing, and data-to-be-transferred buffering delay in the vNFs and the total bulk-data transfer delay on the lightpaths. In this work, we aim to minimize the average SCT of linear data-intensive vNF-SC requests.

*2) Multi-Branch Data-Intensive vNF-SC Requests:* The initial data from the source node of a multi-branch data-intensive vNF-SC request needs to be transmitted to multiple destination DCs, *i.e.*, $D_i = \{d_{i,0}, ..., d_{i,M}\}$, and multiple vNF-SCs are demanded for the destination DCs, respectively. For this, we have $SC_i = \{\{f^1_{i,0}, f^2_{i,0}, ..., f^{N_0}_{i,0}\}, ..., \{f^1_{i,M}, f^2_{i,M}, ..., f^{N_M}_{i,M}\}\}$, where $M$ is the maximum index of vNF-SCs and $N_j$ is the number of vNFs on the $j$-th vNF-SC branch. To serve a multi-

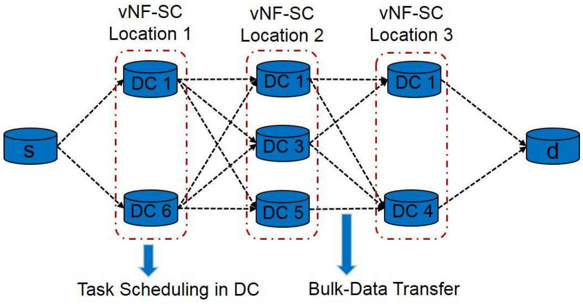


Fig. 2. Example of constructing auxiliary graph in the proposed DP-base algorithm.

branch data-intensive vNF-SC request, SPs need to deploy each vNF-SC branch and steer traffic on it in the same way the linear data-intensive vNF-SC request is served. However, since the SCTs of multiple vNF-SC branches are correlated and the SCT of a multi-branch data-intensive vNF-SC request is determined by the latest vNF-SC branch, correlated-aware vNF-SC deployment and task scheduling algorithms are recommended to optimize the average SCT.

## III. Proposed vNF-SC Deployment and Task Scheduling Algorithms

### A. DP-Based Algorithm for Linear Requests

For linear data-intensive vNF-SC requests, we propose a DP-based vNF-SC deployment and task scheduling algorithm, which can find the solution with a minimum SCT. The detailed procedure is as follows:

**Step 1**: Given the parameters of a request, we construct an auxiliary graph (AG) as shown in Fig. 2. Specifically, for each vNF location in the vNF-SC, we first list all the feasible DC nodes. Then, we connect the source node, the DC nodes in vNF locations, and the destination node as the requested vNF-SC, making all the feasible solutions of vNF-SC deployment for the request are accessible in the AG.

**Step 2**: We evaluate the feasible solutions of vNF-SC deployment with a DP-based method, the recursive relationship of which is described as:

$$t(s_i, f_{i,0}^{j+1}, v_{i,0}^{j+1,l}) = \min_{v_{i,0}^{j,l'} \in V_{f_{i,0}^{j}}} [t(s_i, f_{i,0}^{j}, v_{i,0}^{j,l'}) + t(v_{i,0}^{j,l'}, v_{i,0}^{j+1,l})],$$

where $t(s_i, f_{i,0}^{j}, v_{i,0}^{j,l})$ is the total delay that the initial data from the source node is processed by the $j$-th vNF on the $l$-th DC candidate, and $t(v_{i,0}^{j,l'}, v_{i,0}^{j+1,l})$ is the summation of the data-to-be-transferred buffering delay in the $j$-th vNF on the $l'$-th DC candidate, the bulk-data transfer delay between the $j$-th vNF and the $(j+1)$-th vNF, and the data-to-be-processed buffering delay and the data processing delay in the $(j+1)$-th vNF on the $l$-th DC candidate. To calculate the minimum value of $t(v_{i,0}^{j,l'}, v_{i,0}^{j+1,l})$, we reserve the earliest and largest 2D spectrum fragment on established lightpaths between the two DCs to minimize the data-to-be-transferred buffering delay on $v_{i,0}^{j,l'}$ and the bulk-data transfer delay between $f_{i,0}^{j}$ and $f_{i,0}^{j+1}$, and leverage the task scheduling algorithm we designed in [13] to minimize the data-to-be-processed buffering delay and the data processing delay on $v_{i,0}^{j+1,l}$.

**Step 3**: We select the optimal vNF-SC deployment scheme and perform task scheduling in the selected DCs and bulk-data transfers on the selected lightpaths in the same way the minimum value of $t(v_{i,0}^{j,l'}, v_{i,0}^{j+1,l})$ is calculated in **Step 2**.

### B. Correlation-Aware Algorithm for Multi-Branch Requests

Based on the DP-based algorithm, we propose a correlation-aware vNF-SC deployment and task scheduling algorithm for multi-branch data-intensive vNF-SC requests. Here, the key idea is to serve the most urgent vNF-SC branch first while being aware of the correlation between vNF-SC branches. The detailed procedure is as follows:

**Step 1**: For each pending vNF-SC branch, we leverage the DP-based algorithm to calculate its minimum SCT. If there is a correlated vNF-SC branch that has been served earlier, the pending vNF-SC branch will have a finite deadline which is the SCT of the latest vNF-SC branch that is correlated and has been served, otherwise the deadline of the pending vNF-SC branch is set to infinite. If the gap between its minimum SCT and deadline is smaller than a threshold, the pending vNF-SC branch will be marked as an urgent one, otherwise being treated as a common one.

**Step 2**: After all the pending vNF-SC branches have been evaluated, we serve the most urgent vNF-SC branch that has the minimum gap between its SCT and deadline using the DP-based algorithm. If all the pending vNF-SC branches are marked as common branches, we select the one with the smallest SCT to be served first.

**Step 3**: We update the network status and the deadlines of the remaining vNF-SC branches, and repeat **Steps 1 - 3** until all the pending vNF-SC branches are served.

## IV. Performance Evaluation

We run simulations to evaluate the performance of the proposed algorithms. Specifically, we use the 14-node NSFNET topology in [3] as the EON, in which each node connects with a local DC and between each DC pair there are 2 lightpaths on average. On the established lightpaths, the dynamic background traffic occupies the assigned FS' along the time axis and leaves 2.64% FS' on average as 2D spectrum fragments. The data-intensive vNF-SC requests are generated according to the Poisson traffic model. The number of vNFs requested in a vNF-SC is 5 on average, and the initial data volume is uniformly distributed within $[2, 6]$ FS·TS. For multi-branch data-intensive vNF-SC requests, the number of vNF-SC branches is 3 on average, and the threshold of marking an urgent branch is set to 5 TS'.

Fig. 3 shows the results on average SCT of linear data-intensive vNF-SC requests by the proposed DP-based algorithms. Here, we compare the results under the scenarios with and without task rescheduling. As observed, the proposed DP-based algorithm with task scheduling can achieve much shorter average SCTs, verifying the effectiveness of task rescheduling.

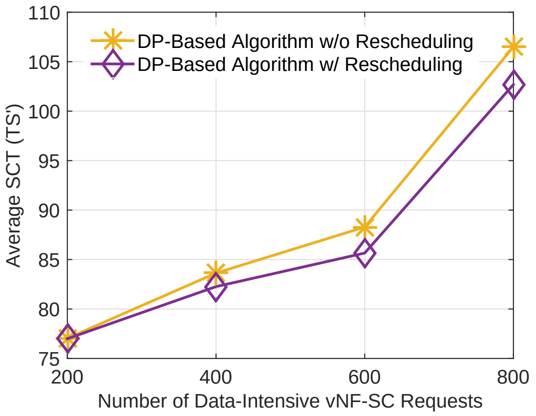


Fig. 3. Average SCT of linear data-intensive vNF-SC requests.

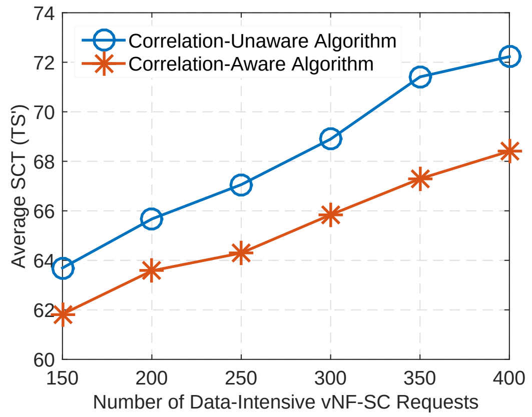


Fig. 4. Average SCT of multi-branch data-intensive vNF-SC requests.

Fig. 4 shows the results on average SCT of multi-branch data-intensive vNF-SC requests by the proposed correlation-aware algorithm. As comparison, we also plot the results by a correlation-unaware algorithm. It is interesting to observe that the proposed correlation-aware algorithm can achieve much shorter average SCTs than the benchmark, which proves the effectiveness of the proposed correlation-aware algorithm.

## V. Conclusion

In this work, we studied the service provisioning problem of data-intensive vNF-SC requests in inter-DC EONs. We classified the data-intensive vNF-SC requests into linear and multi-branch data-intensive vNF-SC requests. We first proposed a dynamic-programming-based vNF-SC deployment and task scheduling algorithm for linear data-intensive vNF-SC requests. Then, considering the correlation between multiple vNF-SC branches, we proposed a correlation-aware vNF-SC deployment and task scheduling algorithm for multi-branch data-intensive vNF-SC requests. Simulation results verified that the proposed algorithms can reduce the average SCTs of data-intensive vNF-SC requests of the two types effectively.

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