Network Service Embedding for Cross-Service Communication

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***Abstract*—Network Function Virtualization (NFV) facilitates the deployment and orchestration of network services (NSes) on virtualized infrastructures. NFV orchestration, in its prevailing form, deals with NSes independent to each other. This introduces significant limitations to cross-service interactions, *i.e.,* a service that requires the consumption of (part of) another service. In an evolving service ecosystem that promotes cross-service interactions, orchestrating NSes with their cross-service communication (CSC) requirements into account is of crucial importance.**

In this paper, we propose a CSC-aware NS embedding heuristic that optimizes NS placement, not only based on inner-component resource and communication demands, but also with respect to another deployed NS that will be consumed. To this end, we study potential types of CSC and introduce a new data structure, namely *VNF embedding tree*, which is used to generate the most appropriate embedding sequence. Assessing the efficiency of the proposed heuristic using simulations, we uncover significant gains in terms of service co-location without any perceptible embedding efficiency penalty, compared to a baseline heuristic that is oblivious of CSC.

I. Introduction

The advent of Network Function Virtualization (NFV) [1], [2], as a key ingredient for innovation in network processing, has brought virtual network functions (VNFs) to the spotlight of both researchers and practitioners. While NFV emerged to satisfy network processing requirements in the telco domain (*i.e.,* softwarization of middleboxes, such as firewalls and NATs) [3], [4], its scope gradually expanded to cellular networks [5], [6] and other applications in various domains of social and economic activity (*e.g.,* automotive, media, e-health, manufacturing), known as verticals [7]. This evolved service ecosystem creates opportunities for cross-service interactions, in the sense that one network service (NS), *i.e.*, a sequence of VNFs [8], [9], can consume another NS, enhancing its functionality. For example, an augmented reality service offering overlaid metadata for current location could enrich its service delivery by providing personalized recommendations through a social network. Such services could be deployed using dedicated network slices within datacenters [10], [11]. This trend is gaining traction in edge computing for the support of latency-sensitive applications [7].

The orchestration of network services that need to consume others requires particular care. For example, NS embedding or scaling should be handled jointly with the consumed NS. More precisely, the embedding optimization of a NS does not solely pertain to resource/communication demands, but is also pertinent to the placement of the NS that will be consumed. However, the prevailing way of service orchestration deals with NSes independent to each other. As such, placement or scaling decisions are performed only with respect to the individual service/resource requirements. This approach can yield suboptimality in terms of CSC, *i.e.,* the communicating components of the two services may be assigned to datacenter regions (*e.g.,* different racks) with low-bandwidth connection or unnecessary long hop-count, increasing response time.

At first glance, CSC-aware NS embedding (NSE-CSC) could be presumably addressed by NSE methods that account for VNF sharing (*e.g.*, [6], [12]); however, this is not the case. In particular, such studies consider the shared VNFs as an indispensable part of the service graph to be embedded and, if needed, new instances can be spawned within the physical infrastructure. In contrast, CSC implies that the shared VNF(s) comprise an exclusive property of a separate service, hence, the service which requires embedding has no means of replicating them on demand.

Along these lines, we stress on the need for NSE-CSC, with the aim of introducing a new embedding policy dimension, *i.e.,* the co-location of the pair of communicating services. As such, NS embedding should not only take into consideration the various inner-component communication and resource demands, but should also strive to optimize the mapping of CSC links. This problem is further exacerbated by the potentially different types of CSC, depending on whether the entire or part of the service is consumed. Since existing NS embedding methods are, in principle, oblivious of CSC, we propose a new heuristic for the NSE-CSC problem. A key aspect of the proposed heuristic is the *VNF embedding tree*, *i.e.,* a new data structure that aids the evaluation of VNF embedding steps, with the aim of generating the most suitable sequence for the embedding of a VNF-graph. Comparing the proposed heuristic with a baseline heuristic designed for generalized NS embeddings (thereby, not accounting for CSC), our proposed method yields a higher degree of communicating service co-location without any perceptible penalty in terms of embedding efficiency.

The remainder of the paper is organized as follows. In Section II, we elaborate on the notion of CSC and distinguish between three envisaged cases of CSC. Section III describes the problem at hand, with emphasis on the intricacies of CSC with respect to the NS embedding. Section IV introduces

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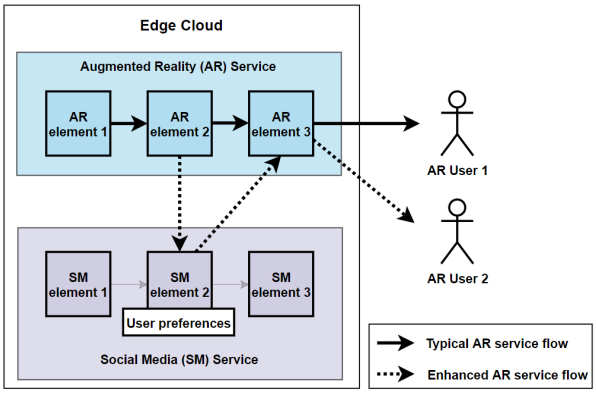


Fig. 1: Cross-service interaction between an augmented reality (AR) service, and a social media (SM) service.

our service models and presents the proposed heuristic, as well as the baseline. In Section V, we present our evaluation environment and compare the efficiency between the two heuristics. Finally, Section VI highlights our conclusions.

II. Cross-Service Communication

Before delving into the NSE-CSC embedding problem, we lay out our perception of cross-service interactions. In this respect, we consider the following service classification: (i) *consuming* services, and (ii) *providing* services. Essentially, CSC provides the means for a *consuming* service to enhance its functionality by gaining access to service elements or functions offered by a *providing* service. Such services may be co-located in the same (edge) cloud infrastructure, opening up an opportunity for peering between the two services [10]. As such, the *consuming* service can be enabled to consume another (*i.e., providing*) service with very low latency, enhancing its functionality and potentially the experience offered to the user. For instance, Fig. 1 illustrates an augmented reality (AR) service co-located with a social media (SM) service. In particular, the AR service retrieves user preferences stored in the SM service; thus, it can offer an enhanced personalized AR experience to users. In this example, the AR is the *consuming* service, while the SM fulfills the role of the *providing* service. Henceforth, a pair of a *consuming* and a *providing* service is referred to as a CSC pair.

We distinguish between three types of CSC, illustrated in Fig. 2. More specifically, *CSC type 1* represents a cross-service interaction, at which a certain VNF of the *providing* service is only consumed. In this case, a subset of the traffic traverses only the *consuming* service (*i.e.*, *VNF A* $\rightarrow$ *VNF B*), whereas the rest of the traffic is redirected through the *providing* service (*i.e.*, *VNF A* $\rightarrow$ *VNF E* $\rightarrow$ *VNF B*). For example, consider a mobile application as the *consuming* service, which offers basic and premium subscriptions. This subscription discrimination exposes basic users to advertisements, while, at the same time, providing an ad-free experience for premium users. In this scenario, *VNF E* of the *providing* service could be a virtualized cache that stores advertising content, which is offered to the *consuming* service. Consequently, traffic associated with basic subscriptions will traverse the path *VNF A* $\rightarrow$ *VNF E* $\rightarrow$ *VNF B*, instead of the path *VNF A* $\rightarrow$ *VNF B*, which will be utilized for premium users.

We further identify an additional CSC type, *i.e., CSC type 2*, at which the *consuming* service accesses a subset of the *providing* service, in the form of a sequence of VNFs, as depicted in Fig. 2. This CSC type pertains to services that require the consumption of a wider spectrum of functions offered by a *providing* service. For example, assume that *VNF A* is a firewall, whereas *VNF E* and *VNF F* correspond to a light and heavy intrusion detection system (IDS), respectively. In this case, flows that are suspicious for intrusion can be subjected to an additional two-level inspection by utilizing the respective VNFs of the *providing* service (*VNF A* $\rightarrow$ *VNF E* $\rightarrow$ *VNF F* $\rightarrow$ *VNF B*). Instead, all remaining traffic will traverse only the VNFs of the *consuming* service.

Last, we consider the scenario where the whole *providing* service needs to be consumed. For instance, assume that the *providing* service is a machine learning (ML) application, composed of VNFs that implement feature selection, model training, model testing, and classification, which practically constitutes an inseparable pipeline. This case is expressed by *CSC type 3*, at which the traffic traverses the entire chain of the *providing* service.

III. Problem Description

The network service embedding problem (NSE) consists in the optimized mapping of virtual nodes and links comprising a VNF-graph, onto physical counterparts on a substrate network, *e.g.*, a datacenter. Whereas the optimization objectives might slightly vary across research studies, the most common one is the minimization of the embedding footprint (*e.g.*, [13], [14], [15], [16], [17]). This is practically translated into VNF consolidation, meaning that the VNF-graph should be mapped onto the minimum amount of servers, while generating the lowest possible amount of traffic. In this respect, inter-rack traffic becomes a highly undesirable implication, seeking its minimization given the oversubscription of datacenter network topologies. For instance, in Fig. 3, the *providing* service is mapped onto *Servers 1* and *2*. *VNFs D* and *E*, as well as *VNFs F* and *G*, communicate through virtual switching (*e.g.*, OVS), while the remaining edge of the VNF-graph (*i.e.*, *VNF E* $\rightarrow$ *VNF F*) is mapped onto a path that traverses the top-of-the-rack (ToR) switch, *i.e.*, *Switch 1*. NSE, being a generalization of the *NP-complete* virtual network embedding (*e.g.*, [18], [19]), is also classified as *NP-complete*, and its combinatorial nature requires greedy embedding methods in order to generate efficient solutions in polynomial time (unless $P = NP$).

The need to establish cross-service interactions introduces additional complexity and challenges into the NSE problem. The main challenge stems from the need to embed *CSC links*, which are marked with bold arrows in Fig. 3. These links establish the required connection between the services of a CSC pair. In case both services are instantiated concurrently, we could rely on existing techniques (*e.g.*, [13], [14], [15], [17]) for their embedding, by merely bundling the respective

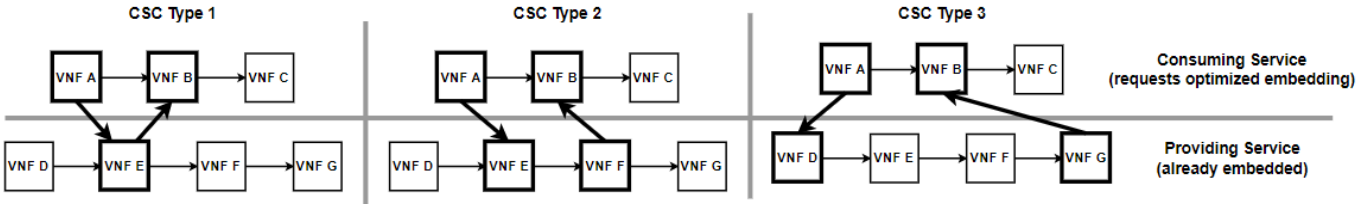


Fig. 2: CSC types stemming from different CSC scenarios.

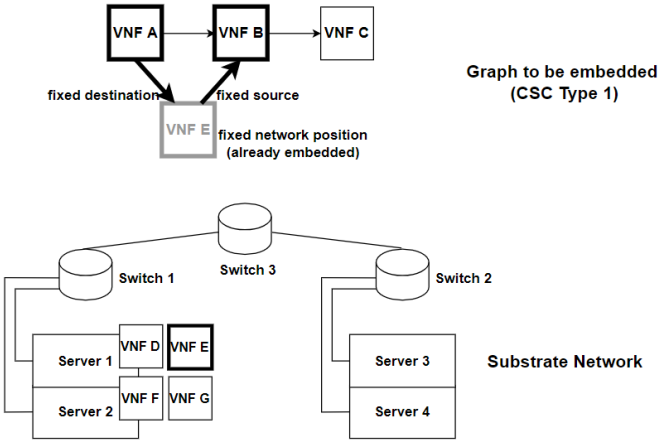


Fig. 3: CSC-aware VNF-graph embedding.

VNF-graphs. In reality, however, this is very unlikely; instead, the reasonable assumption is that the *providing* and *consuming* services will be deployed asynchronously. More precisely, we consider that the *providing* service is already in place (and consumed by its own dedicated clients), before the deployment of the *consuming* service. As such, the *CSC VNFs* of the *providing* service (*e.g.*, *VNF E* for the CSC type 1) will already be fixed on the underlying network infrastructure. Thereby, the NSE optimization should handle these as additional constraints in the assignment of *CSC links*, and, in extension, in the mapping of the entire VNF-graph of the *consuming* service.

To explain this further, notice how the VNF-graph of the *consuming* service is expanded in the *CSC type 1* scenario (top of Fig. 3). In particular, two *CSC links* are inserted, which connect *VNF A* with *VNF E*, and *VNF E* with *VNF B*, respectively. Given that *VNF E* is already placed (in *Server 1*, as shown at the bottom of the same figure), a single end-point of each *CSC link* should be attached to *Server 1*. This introduces additional embedding limitations, compared to the generalized NSE problem, which are further exacerbated in *CSC types 2* and *3*. More specifically, the last two CSC types imply that four VNFs (two VNFs belonging to the *providing* and the other two VNFs being part of the *consuming* service) are involved in the CSC, whereas three VNFs are engaged in *CSC type 1*.

IV. Service Models and Embedding Heuristics

A. Service Models

Network Service Model. A network service can be formulated as a directed graph $G = (V, E)$, which comprises vertices $i \in V$, representing VNFs, and edges $(i, j) \in E, i, j \in V$, expressing virtual links. Each vertex i is associated with a CPU demand d^i, whereas each edge (i, j) has bandwidth requirements, denoted by d^{ij}.

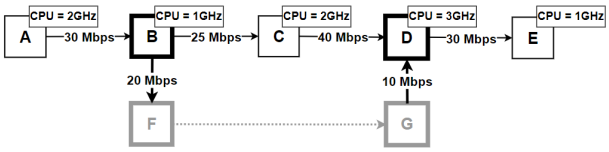
In the problem at hand, we denote the *consuming* service with $G_C = (V_C, E_C)$, and the *providing* service with $G_P = (V_P, E_P)$. According to the discussions in Section III, a CSC path comprises VNFs of both services (*i.e.*, *CSC VNFs*), as well as links that do not exclusively pertain to any service (*i.e.*, *CSC links*). We model $V_C^* = \{i, j\}$ $(i, j \in V_C, i \neq j)$ as an ordered set that holds the *CSC VNFs* of G_C. Similarly, $V_P^* = \{k, l\}$ $(k, l \in V_P)$ holds the respective VNFs of G_P. Note that, in the second case, it could be that $l = k$, corresponding to *CSC type 1*. We also model the set of *CSC links* by $E_{CSC} = \{(i,k), (l, j)\}$ $(i, j \in V_C^*, k, l \in V_P^*)$. The service model augments the modeling of the expanded *consuming* service (ECS), which is as follows:

Expanded Consuming Service (ECS) Model. ECS encompasses the vertices of the initial *consuming* service, plus the *CSC VNFs* of the *providing* service. Furthermore, ECS extends its edge set by adding the E_{CSC} edges, *i.e.,* ECS is modelled as a directed graph $G'_C = (V'_C, E'_C)$, where $V'_C = V_C \cup V_P^*$, and $E'_C = E_C \cup E_{CSC}$. Each element of G'_C is associated with certain resource demands, similar to the case of the typical NS model.

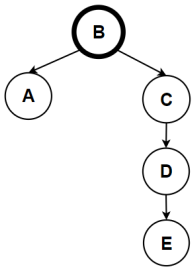
B. NSE-CSC Heuristic

Towards the design of a heuristic algorithm, capable of coping with the complexity of NSE-CSC, we encounter a crucial issue, which stems from the ambiguity of VNF communication dependencies. That is, the *CSC VNFs* $\in V_C^*$ of an ECS will communicate with both their adjacent VNFs included in V_C, as well as with the assigned *CSC VNFs* of the *providing* service. From an algorithmic design perspective, if we prioritize these dependencies based only on communication requirements (*e.g.*, bandwidth demands), we will neglect a key problem aspect, *i.e.,* that we can capitalize on the mapping flexibility of unassigned VNFs. For instance, in Fig. 4a, *VNF B* should be placed in proximity to *VNF A*, *VNF F*, and *VNF C*, which are its adjacent nodes. While its most intense communication occurs with *VNF A*, prioritizing the placement of *VNF B* closer to *VNF F* (which is fixed), and then trying to map *VNF A* and *VNF C* close to *VNF B*, seems a viable approach to NSE-CSC.

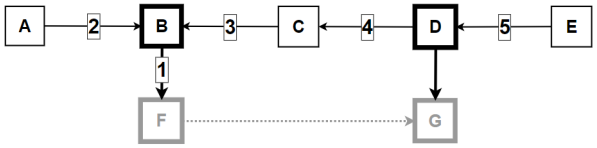
Following this approach for all VNFs of a *consuming* service, we face a critical challenge of NSE-CSC, *i.e.,* how to determine the *VNF embedding sequence*. This term refers



(a) VNF dependency ambiguity in G'_C.



(b) VNF embedding tree.



(c) VNF embedding sequence derived from the tree of Fig. 4b.

Fig. 4: Graphs and structures employed by our heuristic approach for deriving a greedy NSE-CSC policy.

to the sequence, according to which, the embedding algorithm will seek to map the VNFs of the *consuming* service. Apparently, the *VNF embedding sequence* comprises a fundamental aspect of the overall embedding policy, since constructive heuristics, by definition, have no means of stepping back to modify the (partial) solution (although this feature obviously accelerates the solution computation). This means that, if the global embedding policy does not sufficiently address the problem at hand, the generated embeddings will be inefficient. Back in Fig. 4a, let us assume that the embedding commences with *VNF A*, which is therefore placed first within the substrate network. This placement, being oblivious of the need for *VNF B* and *VNF F* co-location, in conjunction with the fact that *VNF F* is already fixed in the network, restricts the optimization possibilities.

VNF Embedding Tree. We introduce a new structure, namely the *VNF embedding tree*, which is used to generate the *VNF embedding sequence*. The construction of a *VNF embedding tree* adheres to the following principles:

1) The root is the *CSC VNF* of the *consuming* service with the lowest CPU requirements.
2) The children of a node are its adjacent VNFs $\in V_C$ that are not yet inserted in the tree.
3) Nodes are, each time, examined for further branching with a depth-first strategy, prioritizing left edges.
4) Left children have higher communication requirements with their parent, compared to their rightmost siblings.
5) A node is leaf if its parent is its only adjacent node, or if its potential children are already in the tree.

For instance, given the G'_C shown in Fig. 4a, *VNF B* will be designated as the root, since $d^B = 1GHz < 3GHz = d^D$. This design decision (*i.e.*, principle 1) stems from our intuition that, keeping a node X with low CPU requirements at higher levels of the tree, increases the probability of co-locating the nodes of entire sub-trees rooted at X. The next step is to obtain *VNF B*'s adjacent VNFs (that belong to the *consuming* service). These are *VNF A* and *VNF C* and, thereby, these are added in the tree as *VNF B*'s children. Given that $d^{AB} = 30 > 25 = d^{BC}$, *VNF A* will be *VNF B*'s left child, whereas *VNF C* will be its right child. No further branching occurs below *VNF A*, since its only adjacent node is its parent, *i.e.*, *VNF B*. On the other hand, there is a link between *VNF C* and *VNF D*; therefore, the latter is a child of the former. Similarly, *VNF E* is placed below *VNF D*, and this completes the tree depicted in Fig. 4b. Note that the proposed tree structure can be applied on non-linear *consuming* service graphs, as well.

Inferring the VNF embedding sequence. The embedding sequence is derived through the following logic: the root of the tree will always be placed towards the already embedded node $\in V_P^*$ that it communicates with, while the rest of the nodes will be placed towards their parent.

The *VNF embedding sequence* is dictated by the visiting order of the tree's nodes, when these are traversed with a depth-first strategy, prioritizing left sub-trees. This, in conjunction with the core logic described above, will result in the *embedding sequence* illustrated in Fig. 4c for the tree of Fig. 4b. In particular, the heuristic will initially seek to place *VNF B* as proximate to *VNF F* as possible. Subsequently, it will try to co-locate *VNF A* with *VNF B*, and then *VNF C* with *VNF B*. Likewise, *VNF D* will be sought to be mapped close to *VNF C*. Finally, *VNF E*'s mapping will depend on the placement of *VNF D*.

VNF co-location policy. The proposed embedding heuristic strives to co-locate *VNF X* towards an already placed *VNF Y*, meaning that it will first attempt to place X in the same server that Y resides. If this is not possible, the heuristic will attempt to embed X in a server belonging to the same rack; otherwise, it will place X in a server within the rack with the least outbound inter-rack traffic. The candidate servers of a rack are selected with a *Worst Fit* logic, if X is not a leaf node, since additional VNFs will pursue their co-location with X (*i.e.*, X's children). If X is leaf, a *Best Fit* approach is followed, since no additional VNFs will seek to communicate with X, thus, the algorithm should allocate CPU as efficiently as possible.

C. Baseline Heuristic

The *baseline* heuristic maps a NS into a datacenter as follows. Initially, it sorts the racks of the datacenter in descending order, according to their average available ToR-to-core switch link bandwidth. Commencing with the first ordered rack, it ranks its servers in descending order, according to their available CPU capacity, and strives to place VNFs

TABLE I: Substrate Network Parameters

Number of core switches	5
Number of racks	10
Number of servers / rack	20
Server CPU capacity	7.2 GHz
Intra-rack link capacity	1 Gbps
Inter-rack link capacity	10 Gbps

TABLE II: NS Request Parameters

Number of VNFs / NS	U[3,8]
VNF CPU requirements	U(.1,.2,.3,.4,.5) * 7.2 GHz
Link bandwidth requirements	U[10,100] Mpbs

TABLE III: Evaluation Environment Parameters

NSE requests / time interval	Poisson(20)
NS type	expiring
NS lifespan	U[3,10] time intervals
Number of time intervals	600

sequentially, starting from the first VNF of the chain. The VNF co-location policy is exercised in the same way with the NSE-CSC heuristic.

V. Evaluation

In this section, we perform a comparison between the proposed NSE-CSC heuristic and the *baseline* variant, using simulations. Initially, we present our evaluation environment and metrics (Section V-A), and, subsequently, we proceed with the discussion of our evaluation results (Section V-B).

A. Evaluation Environment

We have developed a simulation environment for NSE evaluations in Python [20]. All evaluations are carried out on a two-layer fat-tree datacenter network topology. The datacenter consists of 200 servers, which are evenly arranged into ten racks. The corresponding ten ToR switches are interconnected through five core switches. The intra-rack and inter-rack links have capacity of 1 Gbps and 10 Gbps, respectively. The CPU capacity of each server is set to 7.2 GHz (see Table I).

In order to evaluate the NSE-CSC efficiency, we pre-embed ten *providing* services into the datacenter, with each one placed within a single rack. In this way, we do not preclude the existence of efficient solutions (which would be the case, if the VNFs of a *providing* service spanned multiple racks). In this respect, we generate *consuming* services that comprise three to eight, sequentially connected, VNFs. Each VNF requires 10, 20, 30, 40 or 50% of a server's CPU in order to process its inbound traffic. We assume that bandwidth requirements vary for each virtual link in the range of 10 Mbps to 100 Mbps. Furthermore, each *consuming* service requires communication with a single *providing* service, which can be of either *type 1, 2* or *3*, as described in Section II. The aforementioned parameters, summarized in Table II, are obtained from uniformly random distributions.

Towards a more realistic simulation environment, we account for a set of n discrete time intervals $T = \{1, 2, ..., n\}$. At each time interval, a number N of *consuming* services request placement sequentially, where $N \sim Poisson(20)$. Each NS comes with a lifespan k. Therefore, if a NS is embedded at time $t \in T$, it will expire at time $t + k \in T$. During our simulations, k lies within [3,10] (randomly), and $n = 600$.

We compare the two heuristic variants based on the following criteria: (i) co-location efficiency of adjacent VNF pairs (*i.e.*, how proximate two communicating VNFs are placed), (ii) embedding efficiency of *CSC* and *non-CSC* links, (iii) amount of inter- and intra-rack generated traffic, (iv) request acceptance rate (ratio of successfully embedded NSes over the total number of embedding requests), and (v) CPU utilization, which corresponds to the amount of the total CPU allocated to all embedded NSes.

B. Evaluation Results

Initially, we examine the proximity of each pair of adjacent VNFs (*i.e.*, VNFs connected with a virtual edge), after their placement within the substrate network. According to Fig. 5, the NSE-CSC heuristic maps $\approx 30\%$ of such VNF pairs into the same server, whereas the respective percentage for the *baseline* method is slightly above 20%. Regarding the VNF pairs mapped into the same rack (but not in the same server), the NSE-CSC heuristic outperforms the *baseline* variant, since the corresponding percentages exhibit a difference greater than 10%. We further examine the mappings of communicating VNFs in different racks. It becomes apparent that the *baseline* method unfavourably maps nearly half of such VNFs into different racks, while only a quarter falls into the same category for the proposed heuristic. Apparently, this phenomenon is - partially or fully - attributed to the superior capability of the NSE-CSC algorithm to handle the optimized placement of *CSC links*, as opposed to the *baseline* method that merely optimizes the placement of the *consuming* service graph.

In order to gain more insights and identify whether the proposed algorithm skews in favour of the embedding optimization of the *CSC links* to the detriment of the embedding optimization of *non-CSC links*, we present Figs. 6 and 7. In particular, Fig. 6 illustrates the CDF of the hop count of *non-CSC links*, *i.e.*, the edges solely pertaining to the *consuming* service graph. We note that the two-layer hierarchical topology used throughout our simulations implies three possible hop count values for an edge connecting two VNFs, *i.e.,* 0 (same server), 2 (different servers in the same rack), and 4 (different racks). Fig. 6 indicates a similar behavior of the two methods, with respect to the placement efficiency of *non-CSC links*. This is very important, since the embedding efficiency of the *consuming* service part of the ECS graph is similar for both methods, as most of the time (*i.e.*, $\approx 80\%$) the virtual links are confined within a single rack.

However, according to Fig. 7, the heuristic variants perform differently on the mapping of *CSC links*. More specifically, with the NSE-CSC method, $\approx 75\%$ of these links are mapped on paths comprising at most two physical links, meaning that the respective VNF pairs are placed either on the same server or on different servers within the same rack. The corresponding percentage resulting from the *baseline* algorithm is roughly 10%, *i.e.,* 9 out of 10 pairs that comprise both

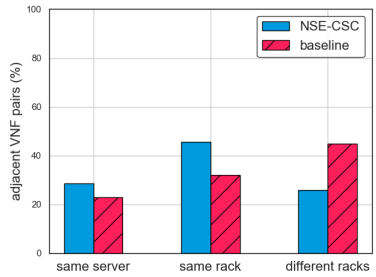


Fig. 5: Distribution of adjacent VNF pairs into same server, same rack, and different racks.

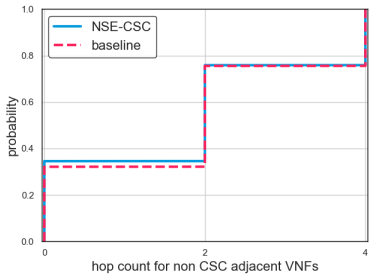


Fig. 6: CDF of the hop count for non-CSC adjacent VNFs.

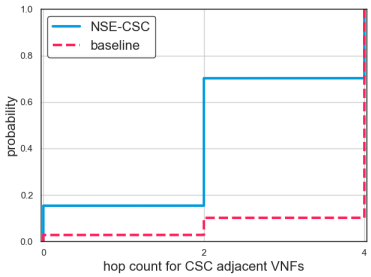


Fig. 7: CDF of the hop count for CSC adjacent VNFs.

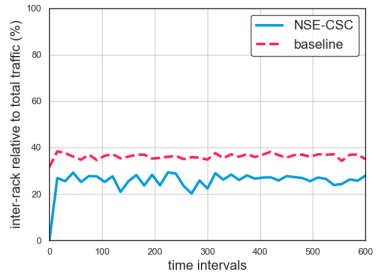


Fig. 8: Ratio of inter-rack traffic to total traffic (total = inter-rack + intra-rack traffic).

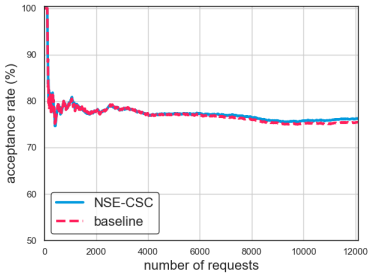


Fig. 9: Acceptance rate of the NSE-CSC and the *baseline* heuristic.

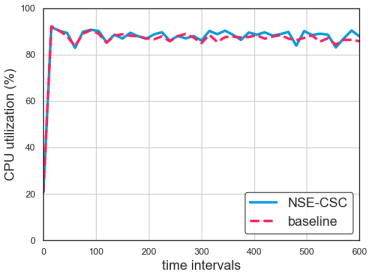


Fig. 10: CPU allocation for the NSE-CSC and the *baseline* heuristic.

consuming and *providing* VNFs are placed across different racks. This alone confirms the insights gained from Fig. 5 about the *baseline* method, regarding the high percentage of VNF pair distribution into different racks.

The previous results indicate that NSE-CSC exhibits a higher degree of intra-rack consolidation, compared to the *baseline*. This is also corroborated by Fig. 8, where the ratio of inter-rack to total traffic across all time intervals is depicted, for both methods. The main insight here is the considerable gap (*i.e.*, $\approx 10\%$) in terms of generated inter-rack traffic (relative to the total traffic) between the NSE-CSC and the *baseline*. Such inter-rack bandwidth conservation by NSE-CSC allows for higher levels of datacenter network oversubscription and, in turn, cheaper switching hardware at the core level of the datacenter topology. Besides the cost reduction, confining traffic within a rack can lead to lower response time and more predictable performance.

Last, we investigate the efficiency of the two heuristics in terms of acceptance rate and CPU allocation. Figs. 9 and 10 indicate that both methods exhibit similar levels of efficiency with respect to these criteria, with only marginal differences that slightly favour the NSE-CSC. The small gain of the NSE-CSC potentially stems from the way it alters the ranking strategy of servers (*Worst / Best Fit*), since the *baseline* method does not incorporate any such feature.

According to our evaluation results and the aforementioned discussions, the proposed NSE-CSC heuristic manages to optimize the placement of ECSes, without any penalty on the embedding efficiency of the *consuming* service part of the graph, or the resource allocation efficiency of the substrate network. Considering also the achievable optimization of the embedding of *CSC links*, we deem NSE-CSC as a viable and efficient solution to the NSE-CSC problem.

VI. Conclusions

In this paper, we tackled the challenging problem of NSE-CSC, *i.e.,* the optimization of NS embedding, subject to CSC requirements. To this end, we designed a new heuristic that introduces a new policy dimension to generalized NS embeddings, *i.e.,* the co-location of the pair of *providing* and *consuming* service. In order to tailor embedding optimization to both CSC and resource demands, we introduced the *VNF embedding tree* in order to derive the most suitable VNF embedding sequence for optimized NSE-CSC. Our evaluation results uncover significant gains for the proposed heuristic, in terms of service co-location. The proposed heuristic, most of the times, achieves the co-location of the CSC pair within a single rack (and sometimes within the same server), ensuring lower service response times, without any perceptible embedding efficiency penalty. Future work will be focused on the investigation of NSE-CSC using an experimental setup (*e.g.,* OpenStack and OSM).

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