A Composition Selection Mechanism for Chaining and Placement of Virtual Network Functions

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***Abstract*—Virtual Network Functions (VNF) reduce the complexity to deploy a Network Service (NS), yielding flexibility, and scalability to attend new market appliances and minimizing the required investments. An ordered set of VNFs to serve a NS is called a Service Function Chain (SFC). Most of the literature works deal with SFCs generation and embedding as independent problems, not taking into account the residual substrate network (SN) status during the SFCs generation stage. Furthermore, a NS can award some flexibility regarding the VNFs sequence, i.e., only a subset of VNFs have a fixed precedence requirement. Following this idea, the network operator may enjoy some options to serve a NS. In this work, we introduce a new embedding approach which selects the SFC composition that best fits the residual SN, leading to a better performance in the chaining and placement of VNFs. The results showed that the composition selection mechanism increases performance compared to traditional models that use a fixed composition, improving resources sharing, and increasing the network operator revenues. Also, we demonstrated that the generation of an optimal SFC for a NS does not always lead to the best acceptance rates in a network with partially consumed resources.**

***Index Terms*—Network function virtualization, virtual network functions, resource allocation, chain composition.**

I. INTRODUCTION

Network Function Virtualization (NFV) is a new networking paradigm which proposes an alternative way to attend a NS, simplifying the design and deployment of Network Functions (NF). The major innovation brought by NFV networks is related to NFs operation, which was formerly run exclusively on proprietary hardware, of low reuse, and expensive, and can be now virtualized into generic machines, of general-purpose, and low dependency between hardware and software. These aspects generate benefits inherent to cost reduction (e.g., capital and operational expenses CAPEX/OPEX), in addition to providing a more rational use of SN resources [1]–[5].

VNFs are found in different telecommunication contexts such as routers and NATs in switching; VPN in tunneling gateway; load balancers in application optimization; firewalls in security functions, and others. To attend this demand increasing and heterogeneous of VNFs, a challenging task arises: the management of the most diverse VNFs with low CAPEX and OPEX [1], [6]–[8].

One of the challenges faced by network operators is to map the SFCs efficiently in an SN with a limited capacity of available resources [2], [9]. Additionally, different SFCs can satisfy the same NS since the order of VNFs is not always fixed, i.e., some VNFs have a precedence requirement, while others show to be flexible [10], [11]. For example, cryptography must occur before the decryption or DPI must occur before NAT. However, some VNFs support different chaining possibilities, e.g., there's no explicit dependency between a proxy server and a WAN optimizer [10], [12]–[14].

One of the main challenges of NFV deployment is resource allocation management, since the demands of SFCs must share the same SN resources. This problem is known as the NFV Resource Allocation Problem (NFV-RA), and can be divided into different sub-problems [3], [10], [13], [14]. Two of them belong to the NP-Hard class and relate to the investigation proposed in this work:

***(i)* SFC Composition Problem** (SFCC) - Corresponds to the chain composition generation. In the creation of a SFC, the order of the VNFs should respect the dependence among some functions while minimizing resource consumption. As the output, this phase generates the SFC that will be processed in the embedding sub-problem. A point to be considered is that the order of function chaining can cause changes in the required bandwidth between VNFs [10], [12]–[14].

***(ii)* VNF Placement and Chaining** (VNF-PC) - Performs the instantiation, placement, and chaining of the virtual devices requested by the SFC in the SN. In VNF-PC, it is required to allocate the VNF instances and place the clients (end-points) in a feasible region of the SN, besides providing an ordered routing between the pairs of instantiated components [2], [7], [11], [15]–[17].

To execute the NFV-RA, a network operator receives the VNFs demand and a set of sequencing constraints to meet a NS. Most of the literature works deal with both phases independently, where SFCC is solved before VNF-PC [2], [10], [13]–[15]. The main problem of solving SFCC and VNF-PC separately is that SFCC tends to provide a SFC optimized for the client of NS (e.g., low bandwidth consumption), but which neglects the residual state of the SN. As a consequence, the network operator can show problems in embedding a specific SFC and even reject the request.

Since some VNFs do not present dependence constraints, it is possible to give the network operator the flexibility of

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choosing among alternative compositions that serve the same NS. Considering the constraints between some VNFs and exploring possible non-dependencies, a NS can be served by a set $\mathcal{T}$ of alternative SFCs. Hence, the VNF-PC problem is expanded to select from a set $\mathcal{T}$ of SFCs provided by the client the composition that is most beneficial for implementing the NS over the residual SN.

To solve the Composition Selection problem along with the VNF-PC, we developed an Integer Linear Programming (ILP) model. We assume as a hypothesis that the composition selection promotes an increase in the revenue of the network operator and further facilitate the deployment and performance of NFV networks. Moreover, this paper aims to show that even an optimal SFC produced by the SFCC step may not be ideal when embedded in a residual SN with limited resources and can be deprecated about other alternative SFCs.

Figure 1 shows two SFCs mapped on the same SN. Considering the $SFC1$ already embedded, the operator should choose between the optimal and alternative compositions $SFC2$ to be embedded. In VNF-PC, the requested VNFs can be instantiated in any N-PoP present on SN, as long as there are available resources. However, one way to reduce the OPEX and CAPEX is to encourage resource sharing by grouping equal VNFs in the same N-PoP, as performed by $SFC1$ and the alternative composition of $SFC2$ in Figure 1.

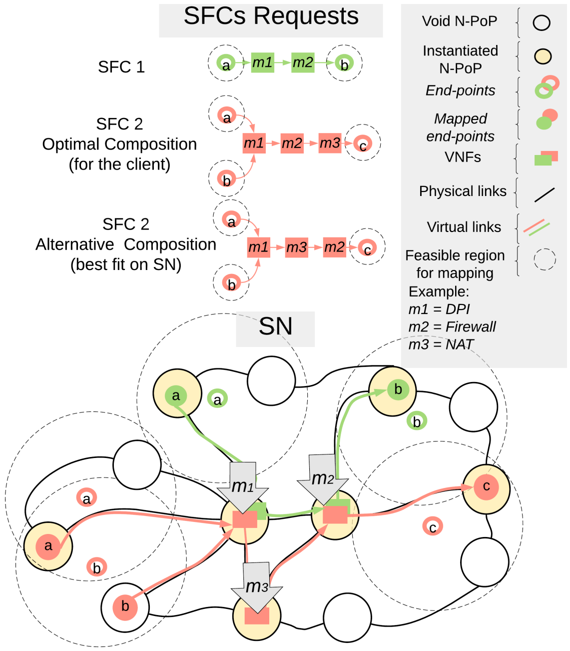

Fig. 1. Two different SFCs mapped over the same SN, sharing the same DPI and NAT instances.

In our work, we deal in a scenario where the network operator must process the NS request as soon as it arrives. It is up to the network operator to implement a set of management mechanisms for allocation of the SFC when it is active, and restoration of resources when it completes its lifetime [18].

In this paper, we focus on maximizing the acceptance rate and the revenue of network operators, and in addition, to answer the following research question: Is it necessary to solve SFCC to optimality in order to generate a proper embedding of the SFC? This research question is based on the premise that the optimal solution of the SFCC is computationally expensive and does not guarantee the best solutions in the VNF-PC phase, if they are solved separately.

The remainder of this paper is organized as follows. In Section II, we present a short review of the literature. In Section III, the formal problem description is presented. Section IV presents the performance evaluation of the proposed approach. In Section V, we conclude the paper with final remarks.

II. RELATED WORK

NFV is a new networking paradigm with a wide, innovative and growing literature in terms of new approaches and concepts for generating new and better solutions [1], [3], [19].

The authors of [10] solve the SFCC in an optimal way using a ILP model, generating an SFC composition with minimum demands of bandwidth and subject to precedence constraints in the chain. Due to the combinatorial nature of the SFCC, the authors of [13] present a heuristic to solve the problem, which uses the same concept presented before in [10]. The differential of the [13] proposal is associated with scalability and lower execution time that heuristic approaches can generate in relation to exact models.

The work by [2] presents an ILP model and a heuristic for VNF-PC, taking a predefined SFC composition as input. In both approaches, the objective function tries to reduce the number of instantiated network functions. In [20], an approach for mapping SFCs through ILP in the context of mobile networks is presented. The authors of [20] emphasize that mobile networks scenario is characterized by the point that network topologies are not previously known, similar to the proposal investigated in our work.

The proposal presented by [14] employs a recursive heuristic called CoordVNF for integrating SFCC and VNF-PC. The heuristic CoordVNF tries to minimize SN bandwidth usage. However, the work of [14] does not examine the influence of optimal or alternative SFCs in the VNF-PC. In contrast to [14], our work shows that it is not necessary to solve the SFCC to optimality to produce good results in the VNF-PC.

III. VNF PLACEMENT AND CHAINING WITH COMPOSITION SELECTION

Notation and model description: The VNF-PC with Composition Selection can be modeled through ILP. Let $G = (N, L)$ be a weighted directed graph representing the SN, where N is the set of N-PoPs. Each $i \in N$ has a maximum CPU_i and a storage ST_i capacity. Also, each $i \in N$ has a maximum number of supported instantiations VM_i, and a defined geographical position (x_i, y_i). Let L be the set of directed physical links that connect the N-PoPs $i \in N$, so that each link $(i, j) \in L$ has a maximum bandwidth capacity BW_{ij} (BW_{ij} is not necessarily equal to BW_{ji}).

Let F be the set of different available NF. Each function $m \in F$ can be potentially virtualized on each N-PoP $i \in$

N, according to the demand requirement of each SFC. To be instantiated, each function $m \in F$ has a unit cost involved, represented by η^m, to be funded by the network operator for different instances used in different N-PoPs $i \in N$.

Let $\mathcal{T}$ be the set of SFCs compositions for a given NS. If $|\mathcal{T}| = 1$, only a SFC composition attend the NS, and if $|\mathcal{T}| > 1$, there are more alternative compositions that can be evaluated to select one that best fits the SN. Each $\tau \in \mathcal{T}$ composition is a SFC established to serve the NS.

Each SFC $\tau \in \mathcal{T}$ is represented as a weighted directed graph $G^\tau = (N^\tau, L^\tau)$. Let $N^\tau = \{N^\tau_{end} \cup N^\tau_{vnf}\}$ be the set of virtual nodes, where N^τ_{end} is the set of terminal end-points and N^τ_{vnf} is the set of VNFs to be configured. Each $k \in N^\tau_{end}$ has a preferred geographical position for the mapping (x_k, y_k). Each $k \in N^\tau_{vnf}$ requires a cpu^τ_k and a storage capacity st^τ_k. Let L^τ be the set of virtual links that connect the different virtual nodes $k \in (N^\tau_{end} \cup N^\tau_{vnf})$. Each link $(k,l) \in L^\tau$ requires a bandwidth demand bw^τ_{kl}. Finally, each SFC request has a maximum end-to-end mapping delay (SFC_{dl}) to be respected, an arrival time SFC_{te} and a lifetime SFC_{td}.

The VNF-PC with Composition Selection solution consists of the feasible mapping of exactly one alternative $\tau \in \mathcal{T}$ of the SFC request, given by mapping $f : G^\tau \to G$, always respecting the residual conditions of SN resources and the full demands of each incoming SFC.

Decision Variables:

- $y^\tau \in \{0,1\}$, indicates whether SFC composition $\tau \in \mathcal{T}$ was mapped.
- $w_{mi} \in \{0,1\}$, indicates whether an instance of the function m was assigned to the N-PoP i.
- $z^\tau_{ik} \in \{0,1\}$, indicates whether virtual node $k \in N^\tau$ of the composition $\tau \in \mathcal{T}$ was assigned[1] to the N-PoP i.
- $x^{\tau kl}_{ij} \in \{0,1\}$, indicates whether virtual link $(k,l) \in L^\tau$ was mapped[2] on the physical link $(i,j) \in L$.

Constraints:

$$\sum_{i \in N} z^\tau_{ik} \geq y^\tau, \forall k \in N^\tau_{vnf}, \tau \in \mathcal{T} \quad (1)$$

$$\sum_{i \in N} z^\tau_{ik} a^\tau_{ik} \geq y^\tau, \forall k \in N^\tau_{end}, \tau \in \mathcal{T} \quad (2)$$

$$\sum_{\tau \in \mathcal{T}} y^\tau \leq 1 \quad (3)$$

$$\sum_{k \in N^\tau_{vnf}: tipo(k) = tipo(m)} z^\tau_{ik} \leq w_{mi}, \forall m \in F, i \in N, \tau \in \mathcal{T} \quad (4)$$

$$\sum_{k \in (N^\tau_{end} \cup N^\tau_{vnf})} z^\tau_{ik} \leq 1, \forall i \in N, \tau \in \mathcal{T} \quad (5)$$

$$\sum_{k \in N^\tau_{vnf}} z^\tau_{ik} cpu^\tau_k \leq CPU_i, \forall i \in N, \tau \in \mathcal{T} \quad (6)$$

$$\sum_{k \in N^\tau_{vnf}} z^\tau_{ik} st^\tau_k \leq ST_i, \forall i \in N, \tau \in \mathcal{T} \quad (7)$$

$$\sum_{m \in F} w_{mi} \leq VM_i, \quad \forall i \in N \quad (8)$$

$$\sum_{(k,l) \in L^\tau} x^{\tau kl}_{ij} bw^\tau_{kl} \leq BW_{ij}, \forall (i,j) \in L, \tau \in \mathcal{T} \quad (9)$$

$$\sum_{(i,j) \in L} \sum_{(k,l) \in L^\tau} x^{\tau kl}_{ij} \leq SFC_{dl}, \forall \tau \in \mathcal{T} \quad (10)$$

$$\sum_{(i,j) \in L} x^{\tau kl}_{ij} - \sum_{(h,i) \in L} x^{\tau kl}_{hi} = z^\tau_{ki} - z^\tau_{li}, \\ \forall i \in N, (k,l) \in L^\tau, \tau \in \mathcal{T} \quad (11)$$

Constraints 1 guarantee that each VNF $k \in N^\tau_{vnf}$ required by the composition $\tau \in \mathcal{T}$ is mapped to a N-PoP. Constraints 2 guarantee that each *end-point* $k \in N^\tau_{end}$ required by the composition $\tau \in \mathcal{T}$, is mapped to a N-PoP in the feasible region a^τ_{ik}. The auxiliary parameter $a^\tau_{ik} \in \{0,1\}$ has the value 1 if only if the *end-point* k is in the same mapping region as the N-PoP $i \in N$, or 0 otherwise. Constraints 3 ensure that only one SFC composition is mapped among the given alternatives. Constraints 4 assure the assignment of all instances demanded by the VNFs $k \in N^\tau_{vnf}$ on N-PoPs, by coupling with binary variables w_{mi}, which indicate that an instance with the function m was created on the N-PoP. Constraints 5 guarantee that each virtual node $k \in (N^\tau_{end} \cup N^\tau_{vnf})$ is mapped to exactly a different N-PoP. Constraints 6 ensure that the processing capacity of each N-PoP is assured for each demand of VNF required by each composition $\tau \in \mathcal{T}$. Constraints 7 guarantee that the storage capacity of each N-PoP is enough to process each required VNF demand for each composition $\tau \in \mathcal{T}$. Constraints 8 assure that the capacity of each N-PoP in accommodating different VM is respected. Constraints 9 guarantee that the available bandwidth of physical links is not exceeded by mapping each composition $\tau \in \mathcal{T}$. Constraints 10 ensure that the maximum delay (SFC_{dl}) allowed for each SFC is respected (calculated according to the number of links that a route crosses from its source to its destination). Last, constraints 11 guarantee the mapping of virtual connections for a composition $\tau \in \mathcal{T}$, through physical paths of links $(i,j) \in L$ of the SN.

Objective function: Maximize the revenue and resources sharing. Given by the difference between the revenue (SFC^γ) paid by the clients of the accepted NS, the costs with the number of virtualization licenses (η^m), and the expenses with the lease of InPs links (ϵ_{ij}), defined by:

$$\text{MAXIMIZE: } \sum_{\tau \in \mathcal{T}} SFC^\gamma y^\tau - \sum_{i \in N} \sum_{m \in F} \eta^m w_{mi} - \\ \sum_{\tau \in \mathcal{T}} \sum_{(k,l) \in L^\tau} \sum_{(i,j) \in L} \epsilon_{ij} x^{\tau kl}_{ij} \quad (12)$$

IV. Performance Evaluation

Numerous factors are associated with NFV parameters, as well as the variability of devices that can be used. This work considers a simplified model, with some values based on real

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[1] Each virtual node in the same SFC must be assigned to a different physical node. This action reduces the impact of a node infrastructure failure [21].

[2] Each virtual link can be mapped onto a physical path containing one or more links.

costs of Amazon[3] and others were reproduced from literature works [22]–[24]. It is important to note that those parameters can be easily modified in the model for future applications.

A preprocessing was performed to form the set $\mathcal{T}$, which contains the best SFC compositions to minimize bandwidth consumption. Each set $\mathcal{T}$ has at least 1 SFC, being limited to the maximum of 5 alternative SFCs. The size of each set can vary depending on the number required VNFs and their precedence relations. The SFCs arrive at the TSP according to a *Poisson* distribution with a rate of 8 SFC per 200 time t (high density instance *S3*), 2 SFC per $200t$ (median density instance *S2*), and 1 SFC per $200t$ (low density instance *S1*)[4].

Our evaluation quantifies the advantages of VNF chaining and placement with composition selection. For comparison purposes, we use approaches that do not use composition selection. We also show that the generation of optimal SFCs does not necessarily lead to an optimal mapping in the residual SN. To this end, three approaches were proposed:

(*i*) ILP-c*, performs the placement and chaining of the SFC considering the optimal composition $c^* \in \mathcal{T}$, i.e., with lower total bandwidth consumption;

(*ii*) ILP-c$^-$, performs the placement and chaining of the SFC considering the worst composition $c^- \in \mathcal{T}$, i.e., with higher total bandwidth consumption;

(*iii*) ILP-$\mathcal{T}$, performs the **selection**, placement, and chaining of the compositions $c \in \mathcal{T}$ which best fits the residual SN at the time of the mapping (analyzes all compositions from $\mathcal{T}$).

Acceptance ratio: The composition selection mechanism leads to higher acceptance ratio and profit. In the S1 and S2 scenarios (Figure 2), the ILP-c* and ILP-$\mathcal{T}$ present a high acceptance rate, but ILP-c$^-$ shows a lower acceptance rate compared to the other approaches. These experiments demonstrate that a poor composition choice can have a significant negative impact on the acceptance rate of service providers. However, we observe that the ILP-$\mathcal{T}$ approach obtained an slightly larger acceptance rate than ILP-c*, which corroborates our hypothesis, wherever an optimal composition generated by SFCC, may not be optimal when mapped to a residual SN.

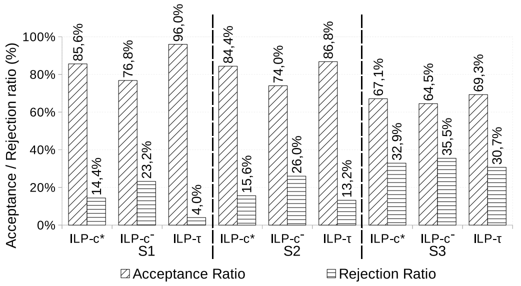

Fig. 2. Acceptance and rejection rates at the end of $25.000t$, varying the density of the SFCs scenarios (S1, S2 and S3) and maintaining the same SN.

Increase in consumption of physical resources: S3 has a high rejection rate for the three approaches, regardless of composition choice. This fact indicates that the high SFCs demand generated an overload in the resources available on the SN. All approaches led to a significant increase in the bandwidth usage, inducing an increase in the rejection rate noted in the scenario S3. CPU and storage consumption have also increased but are still far from the available capacity. This scenario with high bandwidth consumption and low CPU and storage usage indicates a possible SN fragmentation.

Impacts on Profit: Although the ILP-c* approach theoretically has minimal bandwidth demand, it does not generate the highest profits and does not have a higher acceptance rate. In this case, ILP-c* under performs ILP-τ, which results in higher instantiation costs, less sharing of functions and lower revenues. The ILP-τ approach, besides obtaining higher acceptance rates (Figure 2), improve the network operator profit. The increase in profit indicates that an optimal SFC, if created without knowledge of residual SN, can be deprecated in relation to an alternative composition that best fits the SN at the processing moment, providing mapping flexibility for the network provider, as well as potential economies with CAPEX and OPEX.

Runtime Analysis: ILP-c* has a better execution time than ILP-τ. However, ILP-c* needs to generate the optimal SFC, i.e., two NP-hard problems must be solved to generate the SFC embedding. Moreover, as observed in Figure 2, the optimal SFC may not be the ideal on the residual SN. Although the ILP-τ approach has a longer execution time for mapping, it is also promising in terms of profitability and acceptance rate. Also, ILP-τ does not need to generate an optimal SFC for the embedding solution, but it works with a set of alternative compositions for serving the NS, i.e., unlike ILP-c*, ILP-τ needs to solve one NP-hard problem.

V. CONCLUSION AND FUTURE WORKS

Aiming to generate more flexibility for the network operators, this work proposed an ILP approach for the placement and chaining of virtual network functions with composition selection. The VNF-PC with composition selection introduces a flexibilization of the SFC compositions, exploring the resource sharing; reducing rejection rate, and maintaining an economic usage of SN resources.

The simulations showed that the generation of the SFCs even when running to optimality guarantees, does not induce an optimal mapping on a residual SN. This occurs because the SFCC does not consider the residual state of the resources available at the processing moment. In the experiments, the flexible choice of alternative compositions promotes resource sharing and generates a lower cost of VNF instantiation. Therefore, the ILP-τ approach differs from the other approaches and tends to increase the service providers profit.

The choice of an exact approach is justified in order to know stronger limits of revenue and acceptance rate in the comparison of the different approaches. In future work, we plan to develop a heuristic approach and explore more real and complex topologies of SFCs and SN.

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