# Optimization of Network Service Chain Provisioning

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***Abstract*—Software-Defined Networking is a new approach to the design and management of networks. It decouples the software-based control plane from the hardware-based data plane while abstracting the underlying network infrastructure and moving the network intelligence to a centralized software-based controller where network services are deployed. The challenge is then to efficiently provision the service chain requests, while finding the best compromise between the bandwidth requirements, the number of locations for hosting Virtual Network Functions (VNFs), and the number of chain occurrences.**

**We propose two ILP (Integer Linear Programming) models for routing service chain requests, one of them with a decomposition modeling. We conduct extensive numerical experiments, and show we can solve exactly the routing of service chain requests in a few minutes for networks with up to 50 nodes, and traffic requests between all pairs of nodes. We investigate the best compromise between the bandwidth requirements and the number of VNF nodes.**

## I. Introduction

Software-Defined Networking (SDN) is a promising technology for controlling networks with a greater flexibility, in the context of dynamic traffic but also in the context of the steady increase of the traffic due to applications such as video on-demand or cloud gaming. SDN not only forwards traffic, but processes it as well, throughout network functions or network services.

The Network Function Virtualization (NFV) initiative was launched in the late 2012 with the intention to address the operational challenges and high costs of managing the closed and proprietary appliances deployed throughout the communication networks [1]. By virtualizing and consolidating network functions traditionally implemented in dedicated hardware (called middleboxes), using cloud technologies, network operators can achieve greater agility and accelerate new service deployments while driving down both operational (OpEx) and capital costs (CapEx) [2]. In any given network, some nodes are selected in order to be VNF node. Any virtual network function (VNF), hosted on such a node, may then run on a single or on a set of Virtual Machines (VMs), instead of having custom hardware appliances.

Service Function Chaining (SFC) refers to an ordered sequence of service functions that a specific flow must go through. It is used by cloud providers and network operators to set up suites or catalogs of connected services that enable the use of a single network connection for many services, with different characteristics. For instance, cloud providers must host enterprise applications that access databases and make bulk data transfers to and from customers' private networks constantly while communications service providers carry email, voice, video, Web traffic and downloads. Each data type benefits from specific types of related services. For instance, an email service chain, for example, would include virus, spam and phishing detection and could be routed through connections offering no delay and with jitter guarantees. The question is then to perform efficiently the service chaining provisioning, i.e., where to place instances of VNFs on servers in a NFV infrastructure to accommodate the traffic for a given set of SFC requests. However, operators/providers have multiple competing goals to consider when placing VNFs. On the one hand, they may want to use as few servers as possible in order to minimize operating costs and leave open servers for future needs [3], [4]. On the other hand, they may want to minimize the bandwidth requirement, as an indirect way to ensure low end-to-end network latency for their customers.

Our work considers an *exact* model that can be solved *optimally* and that provides the minimum bandwidth SFC provisioning for a given selection of VNF nodes, so that we can investigate the *best compromise between the bandwidth requirements and the number of VNF nodes.* To the best of our knowledge, *we are the first to propose an exact model, which scales well with the number of nodes and requests.* We are able to solve within a few minutes instances with almost 10.000 different demands.

The paper is organized as follows. In the next section, we discuss the related work. In Section III, we formally state the Service Function Chain Placement Problem. We then propose two original Integer Linear Programming (ILP) models to solve it in Section IV, with one ILP model using a decomposition modelling scheme. Solutions of both models are discussed in Section V and we investigate the best compromise between the number of VNF locations and the bandwidth requirements. Numerical results are presented in Section VI. Conclusions are drawn in the last section.

## II. Related work

Following the NFV initiative in 2012 [1], several surveys are now available on NFV, see, e.g., [5], [6], [7] where the various NFV challenges are discussed. Multiple works proposed exact and partial mathematical formulations for the SFC provisioning problem. Several objective functions have been considered. In Martini *et al.* [8] and Riggio *et al.* [9], the authors only solve the placement and routing for each request independently. Savi *et al.* [10] propose an exact formulation in which the number of VNF nodes is minimized. Their model takes into account additional costs inherent to multi-core environment. However, they only provide results on a small network. A heuristic based on an ILP is proposed in Gupta *et al.* [11]. The authors only consider the $k$-shortest paths for every request in the network and a simplified node capacity constraint, for which only one function per node can be deployed. Mohammadkhan *et al.* [12] propose an exact model along with heuristics aiming at minimizing the maximum usage of CPU and links. The scope of the experiments is limited to the case in which the number of cores per service is limited to one. Luizelli *et al.* [4] provide an exact model minimizing the number of instances of functions in the network. However, they consider only a couple of tens of requests. In Bari *et al.* [13], the authors consider the operational expenditure (OpEx) for a daily traffic scenario as their objective function. The ILPs proposed in the works mentioned above do not scale for larger networks. To the best of our knowledge, using column generation, our work is the first to optimally solve the problem of SFC placement in a network with 50 nodes and for all-to-all demand scenarios. This model is also used as the base of the solution to the energy aware routing and placement of SFC proposed in [14].

## III. Service Function Chain Provisioning Problem

The SDN network is represented by a graph $G = (V, L)$ where $V$ represents the set of nodes and $L$ the set of links. Each request is characterized by a source $v_s$, a destination $v_d$, a chain $c$ (i.e., a sequence of Virtual Network Functions (VNFs)) and requires $D^c_{sd}$ units of bandwidth. Let $F$ be the set of network virtual functions, indexed by $f$, with $n_F = |F|$. Each service chain $c$ is defined as a sequence of Virtual Network Functions (VNFs), with some functions possibly repeated. We denote by $n_c$ the number of functions in $c$, i.e., the length of the sequence. $C$ is the set of all service chains. The number of cores required by function $f$ in any chain is equal to $\Delta_f$ per unit of bandwidth, i.e., $D^c_{sd} \times \Delta_{f^c_i}$ cores for request $(v_s, v_d, c, D^c_{sd})$ where $f^c_i$ denotes the $i$th function of chain $c$. Only a subset of nodes $V^{\text{VNF}} \subset V$ can host VNFs. Indeed, deployment of VNFs can be made on general purpose servers or standard IT platforms like high-performance switches, service, and storage, see, e.g., [5] for more details. Running a VNF requires a certain amount of resources, e.g., CPU, memory, disk, while the amount of required resources usually depends on the volume of traffic that passes through it. Consequently, each node $v \in V^{\text{VNF}}$ has a given core capacity $\text{CAP}_v$. Similarly, each link $\ell$ of the network has a transport capacity of $\text{CAP}_\ell$. A summary of the notations can be found in Table I.

| | |
|---|---|
| $G$ | $= (V, L)$ optical (grid) network |
| $V^{\text{VNF}}$ | $\subseteq V$ = subset of nodes which are enabled to host virtual network functions |
| $\mathcal{SD}$ | Set of node pairs with some demand |
| $D^c_{sd}$ | bandwidth demand from $s$ to $d$ for chain $c$ |
| $\Delta_f$ | # required cores per bandwidth unit for function $f$ |
| $\text{CAP}_\ell$ | transport capacity (bandwidth) of link $\ell$ |
| $\text{CAP}_v$ | core capacity of node $v$ |
| $n_c$ | length (i.e., number of functions) of the chain $c$ |
| $f^i_c$ | the $i^{th}$ function in chain $c$ |

Table I: Notation

The objective is to minimize the amount of bandwidth used in the SDN network in which all service chains are provisioned. It follows that each chain is assigned a path in which functions of $c$ are encountered in the same order as in $c$, with some functions possibly located at the same node. Both core node and transport capacities must be satisfied.

### A. Layered Graph

Following a similar idea as in [15], we use a layered graph $G^{\text{L}}$ that is defined as follows. The initial network graph $G$ is transformed into a *layered graph* $G^{\text{L}}$ by adding $\max\limits_{c \in C} n_c$ layers to the graph (counting $G$ as the base layer, i.e., layer 0) and each layer is an exact copy of the original graph. For every node $v \in V$, let $v^i$ denote the corresponding node in the $i$th layer $(i = 1, \dots, n_c)$. Every $(i-1, i)$ layer pair is connected vertically by links from $v^{i-1}$ to $v^i$.

Finding a path and a chain placement for a request $(v_s, v_d)$ with chain $c$ consists in finding a path from node $v_s$ on the first layer to node $v_d$ on the $n_c$th layer. Indeed, each layer represents the progression of the chain, e.g., being on the second layer means that the first function of the chain is already executed. The placement of the node is given by the link used to switch between layers.

Both Integer Linear Programming (ILP) models presented in the next section use the layered graph.

## IV. Optimization Models

We first present an Integer Linear Program, called NFV_ILP, in Section IV-A and then a reformulation of it within a Column Generation decomposition one, called NFV_CG, in Section IV-B.

### A. Model NFV_ILP

This Integer Linear Program is based on the *layered graph* described in Section III-A. It is written as follows.

Variables

- $\varphi_\ell^{sd,c,i} \in \{0,1\}$, where $\varphi_\ell^{sd,c,i} = 1$ if $(v_s, v_d, c, D_{sd}^c)$ is provisioned on link $\ell$, 0 otherwise.
- $a_v^{sd,c,i} \in \{0,1\}$, where $a_v^{sd,c,i} = 1$ if $f_{sd}^i$ is installed on node $v$. If $v \notin V^{\text{VNF}}$, $a_v^{sd,c,i} = 0$.

Objective: minimization of the required bandwidth in the network

$$\min \sum_{(v_s,v_d)\in\mathcal{SD}} \sum_{c\in C_{sd}} D_{sd}^c \sum_{\ell\in L} \sum_{i=0}^{n^c} \varphi_\ell^{sd,c,i} \qquad (1)$$

Constraints

Flow constraints in order to translate the requirement of a path from source to destination going through the locations of the functions of the service chain requested by the node pair. Only the source node on the first layer and the destination node on the last layer can have a positive outgoing and incoming flow respectively.

$$\sum_{\ell\in\omega^+(u)} \varphi_\ell^{sd,c,i} - \sum_{\ell\in\omega^-(u)} \varphi_\ell^{sd,c,i} + a_v^{sd,c,i} - a_v^{sd,c,i-1} = 0$$
$$v \in V, (v_s, v_d) \in \mathcal{SD}, c \in C_{sd}, 0 < i < n^c \qquad (2)$$

$$\sum_{\ell\in\omega^+(v)} \varphi_\ell^{sd,c,0} - \sum_{\ell\in\omega^-(v)} \varphi_\ell^{sd,c,0} + a_v^{sd,c,0} = \begin{cases} 1 \text{ if } v = v_s \\ 0 \text{ else} \end{cases}$$
$$(v_s, v_d) \in \mathcal{SD}, v \in V, c \in C_{sd} \qquad (3)$$

$$\sum_{\ell\in\omega^+(v)} \varphi_\ell^{sd,c,n_c} - \sum_{\ell\in\omega^-(v)} \varphi_\ell^{sd,c,n_c} - a_v^{sd,c,n_c} = \begin{cases} -1 \text{ if } v = v_d \\ 0 \text{ else} \end{cases}$$
$$(v_s, v_d) \in \mathcal{SD}, v \in V, c \in C_{sd} \qquad (4)$$

Link capacity of the link in $G$ is shared between each layer and cannot exceed $\text{CAP}_\ell$.

$$\sum_{(v_s,v_d)\in\mathcal{SD}} \sum_{c\in C_{sd}} D_{sd}^c \sum_{i=0}^{n^c} \varphi_\ell^{sd,c,i} \le \text{CAP}_\ell \quad \ell \in L. \qquad (5)$$

Node capacity. Each link $(v^{i-1}, v^i)$ between layer is represented by variable $a^i$, so that the placement of a function is described by the usage of a cross-layer link. The capacity of a node is determined by the cross-layer link that are used to switch from one layer to the next.

$$\sum_{(v_s,v_d)\in\mathcal{SD}} \sum_{c\in C_{sd}} \sum_{i=0}^{b^c} \Delta_{f_i^c} D_{sd}^c a_v^{sd,c,i} \le \text{CAP}_u$$
$$v \in V^{\text{VNF}}. \qquad (6)$$

### B. Model NFV_CG

As we will see in Section VI-C, the ILP presented in the previous paragraph does not scale well for medium to large networks. We thus propose a Column Generation model. It relies on the concept of configurations, where a configuration is defined by a potential provisioning for a given request. We describe below the so-called master problem, which selects the best configurations, one for each request. We discuss the solution of the master problem in Section V, in which we use a so-called pricing problem to generate a very limited set of configurations while preserving the LP and $\varepsilon$ ILP optimality of the solution scheme.

More formally, a configuration, i.e., a *Service Path* for a request $(v_s, v_d, c, D_{sd}^c)$ is composed of: *(i)* a network path, i.e., an ordered set of nodes from the source to the destination, and *(ii)* a set of locations for the VNFs in the SFC request. Each *Service Path* is thus specific to a given request and its SFC.

We use the following notations in addition to those in Table I.

- $p \in P_{sd}$, a service path from $s$ to $d$. A service path is composed of a path on the network and a set of pairs $(v, f)$. A pair $(v, f)$ means that the function $f$ is installed on node $v$.
- $a_{vp}^{f} \in \{0, 1\}$, where $a_{vp}^{f} = 1$ if $f$ is installed on node $v$ for service path $p \in P_{sd}^{c}$ wrt $sd, c$
- $\delta_{\ell}^{p} \in \{0, 1\}$, where $\delta_{\ell}^{p} = 1$ if link $\ell$ belongs to path $p$.

Variables

- $y_{p}^{sd,c} \geq 0$, where $y_{p}^{sd,c} = 1$ if demand from $v_s$ to $v_d$ for service chain $c$ is forwarded through service path $p$, 0 otherwise.

Note that each variable $y_{p}^{sd,c}$ is associated to a configuration, i.e., a potential provisioning for request $(v_s, v_d, c, D_{sd}^{c})$.

Objective

$$\min \sum_{(v_s,v_d)\in\mathcal{SD}} \sum_{c\in C_{sd}} \sum_{p\in P_{sd}^{c}} D_{sd}^{c} \, \text{LENGTH}(p) \, y_{p}^{sd,c} \quad (7)$$

As for Model NFV_ILP, the objective is to minimize the amount of bandwidth used in the SDN network. For a path, this amount is its length, i.e., number of hops, multiplied by the bandwidth requirement of the request. The set of constraints can then be expressed as follows.

Exactly one path per demand and per chain:

$$\sum_{p\in P_{sd}^{c}} y_{p}^{sd,c} = 1 \quad c \in C_{sd}, (v_s, v_d) \in \mathcal{SD}. \quad (8)$$

Link capacity: for all $\ell \in L$,

$$\sum_{(v_s,v_d)\in\mathcal{SD}} \sum_{c\in C_{sd}} \sum_{p\in P_{sd}^{c}} D_{sd}^{c} \, \delta_{\ell}^{p} \, y_{p}^{sd,c} \leq \text{CAP}_{\ell}. \quad (9)$$

Node capacity: for all $v \in V^{\text{VNF}}$,

$$\sum_{(v_s,v_d)\in\mathcal{SD}} \sum_{c\in C_{sd}} \sum_{f\in F_c} \sum_{p\in P_{sd}^{c}} \Delta_f D_{sd}^{c} \, a_{vp}^{f} \, y_{p}^{sd,c} \leq \text{CAP}_{v}. \quad (10)$$

## V. Solution Scheme

Model NFV_ILP can be easily solved by an ILP solver such as Cplex. Model NFV_CG requires more attention as, at first look, it has an exponential number of variables. Indeed, its linear relaxation can be solved *exactly* using column generation ([16]), using a limited number of configuration, i.e., variables. Details are given below.

### A. Generalities on Column Generation

The Column Generation solution scheme is a decomposition one that combines the use of the so-called Restricted Master Problem (RMP), i.e., MP with a very small subset of configurations/columns, and the so-called pricing problem, i.e., a configuration generator. Consequently, the Restricted Master Problem selects the best provisioning, one for each request, and the pricing generates improving configurations, i.e., configurations such that, if added to the current RMP, improves the value of its linear relaxation.

RMP and PP are solved alternately until the PP is unable to generate any new improving configuration/service path, for any request. In such a case, the optimal solution of the linear relaxation of Model NFV_CG has been reached, and we derived an ILP solution, using an ILP solver on the last RMP. Accuracy of the ILP solution is measured by $\varepsilon = (\tilde{z}_{\text{ILP}} - z_{\text{LP}}^{\star})/z_{\text{LP}}^{\star}$, where $z_{\text{LP}}^{\star}$ is the optimal value of the LP relaxation, and $\tilde{z}_{\text{ILP}}$ denotes the value of the ILP solution.

### B. Pricing Problem

The role of the Pricing Problem is to generate a valid *Service Path* for a given request. Once again, the formulation relies on the layer graph ($G^{\text{L}}$) introduced in Section III-A. Its objective is defined by the so-called reduced cost (see [16] if not familiar with linear programming concepts).

- $u^{(j)}$ represents the vector of dual variables of constraints $(j)$ in the RMP. Note that these values are given as input to the pricing problem in the column generation solution process.

Variables:

- $a_{v}^{i} \in \{0, 1\}$, where $a_{v}^{i} = 1$ if $f_{i}^{c}$ is installed on node $v$.
- $\varphi_{\ell}^{i} \in \{0, 1\}$, where $\varphi_{\ell}^{i} = 1$ if the flow forwarded on link $\ell$ on layer $i$, i.e., links in each layer in graph $G^{\text{L}}$.

The service path generator (pricing problem) is written for each request $(v_s, v_d, c, D_{sd}^{c})$.

$$\min \quad D_{sd}^{c} \sum_{\ell\in L} \sum_{i=0}^{n_c} \varphi_{\ell}^{i} - u_{sd}^{(8)} + \sum_{\ell\in L} u_{\ell}^{(9)} D_{sd}^{c} \sum_{i=0}^{n_c} \varphi_{\ell}^{i} + D_{sd}^{c} \sum_{v\in V} u_{v}^{(10)} \sum_{i=0}^{n_c} \Delta_{f_{i}^{c}} a_{v f_{i}^{c}} \quad (11)$$

Flow conservation: they correspond to flow constraints (i.e., route) from the $i$th function to the $(i+1)$th function of the service chain associated with the $v_s \rightsquigarrow v_d$ request for which the pricing problem is solved (constraints

(12)), and then flow constraints from the source node to the location of the first function of the service chain (constraints (13)), and similarly from the location of the last function of the service chain to the destination node (constraints (14)). Note that $a_v^i = 0$ for all nodes that are not VNF capable. Observe that the next set of constraints take care of the possibility that several VNFs can be located on the same node, including on the source or destination nodes.

$$\sum_{\ell \in \omega^+(v)} \varphi_\ell^i - \sum_{\ell \in \omega^-(v)} \varphi_\ell^i + a_v^i - a_v^{i-1} = 0 \qquad v \in V, 0 < i < n_c \tag{12}$$

$$\sum_{\ell \in \omega^+(v)} \varphi_\ell^0 - \sum_{\ell \in \omega^-(v)} \varphi_\ell^0 + a_v^0 = \begin{cases} 1 \text{ if } v = v_s \\ 0 \text{ else} \end{cases} \qquad v \in V \tag{13}$$

$$\sum_{\ell \in \omega^+(v)} \varphi_\ell^{n_c} - \sum_{\ell \in \omega^-(v)} \varphi_\ell^{n_c} - a_v^{n_c} = \begin{cases} -1 \text{ if } v = v_d \\ 0 \text{ else} \end{cases} \qquad v \in V \tag{14}$$

Link capacity. For $\ell \in L$,

$$D_{sd}^c \sum_{i=0}^{n^c} \varphi_\ell^i \leq \text{CAP}_\ell. \tag{15}$$

Node capacity. For $v \in V^{\text{VNF}}$,

$$\sum_{i=0}^{n^c} \Delta_{f_i^c} D_{sd}^c a_v^i \leq \text{CAP}_v. \tag{16}$$

## VI. Numerical Results

In this section, we report the numerical results. First, we describe the data sets we used (Section VI-A). Then, we present the performance of NFV_CG in Section VI-B. Next, in Section VI-C, we compare the performance of the two models described in Section IV. Finally, in Section VI-D, we look at the compromise between the number of VNF nodes and the bandwidth requirements.

### A. Data Sets

To emulate a realistic traffic, we used the data in [17] in conjunction with the four chains presented in Table II as in [10]. Each SFC is composed of a sequence of network virtual functions and requires a specific amount of bandwidth. We use the distribution of traffic from [17] to know the number of requests of each service type. For example, a 1TB network load is composed of 699GB of Video Streaming. This amount of traffic correspond to an equivalent of $\frac{699}{4 \times 10^{-3}}$ requests We then choose at random the source and destination for each request and then aggregate the resulting set of requests with respect to their source and destination nodes. Overall, we have a total of $4 \times n^2$ demands (each type of chains for every node pair).

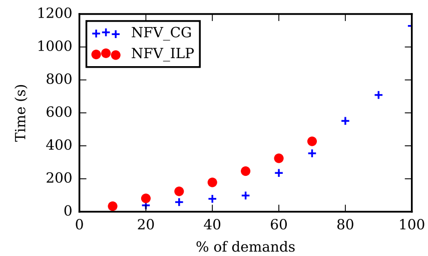



Figure 1: Computational times of NFV_ILP and NFV_CG on the germany50 network.

| Service Chain | Chained VNFs | rate | % traffic |
|---|---|---|---|
| Web Service | NAT-FW-TM-WOC-IDPS | 100 kbps | 18.2% |
| VoIP | NAT-FW-TM-FW-NAT | 64 kbps | 11.8% |
| Video Streaming | NAT-FW-TM-VOC-IDPS | 4 Mbps | 69.9% |
| Online Gaming | NAT-FW-VOC-WOC-IDPS | 50 kbps | 0.1% |

Table II: Service chain requirements [10]

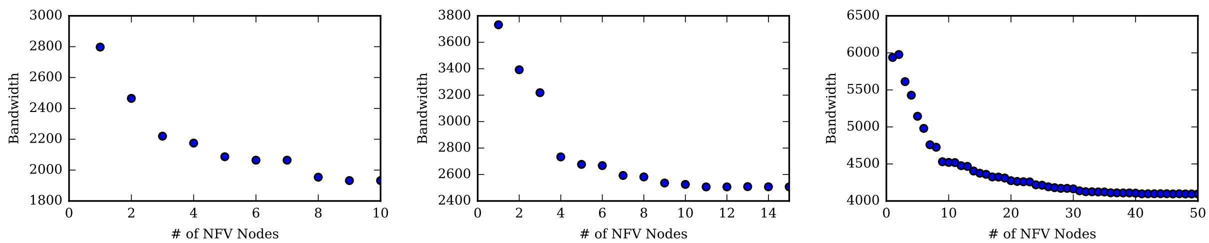
When choosing the set of nodes which can host VNFs, we select the nodes based on their betweenness centrality, which is the number of paths going through the node, when considering the shortest paths between all pairs of nodes. Betweenness centrality is a good indicator of the importance of a node in the network. Programs were tested on three different networks, whose characteristics are described in Table III.

### B. Performance of Model NFV_CG

Table IV summarizes the performance of Model NFV_CG. We present results for the 3 different topologies for a selected number of VNF nodes, around the half of the size of the networks. For each instance, we simulate an overall traffic of 1 Tbps.

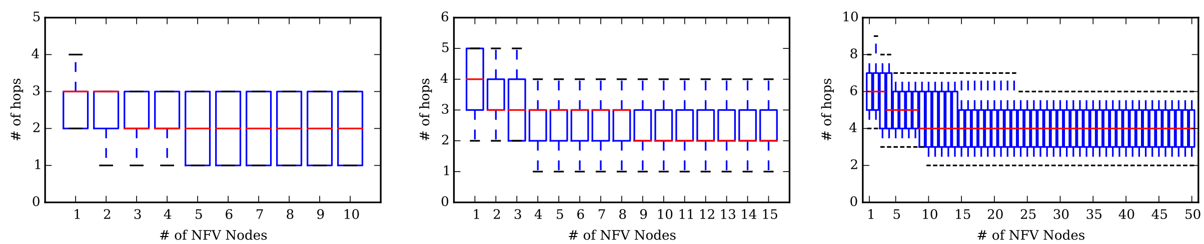
In the last three columns, we give the optimal value of the linear relaxation ($z_{\text{LP}}^{\text{LP}}$), the value of the ILP solution ($\tilde{z}_{\text{ILP}}$) and the accuracy of the ILP solution $\varepsilon$. In most instances, $\varepsilon = 0$, meaning that we obtain the optimal ILP solution For the cases where $\varepsilon > 0$, its value remains very small, meaning that $\tilde{z}_{\text{ILP}}$ is very close to the optimal ILP value.

Lastly, we observe that the number of generated columns is fairly small in order to reach very accurate ILP solutions, taking into account that we need to select one column per request, i.e., 360, 840 and 9800 columns for data instances associated with networks Internet1, Atlanta, and Germany50, respectively.




(a) Internet2 (b) Atlanta (c) Germany

Figure 2: Bandwidth vs. number of VNF nodes with a 1TB offered load.




(a) Internet2 (b) Atlanta (c) Germany

Figure 3: Distribution of the number of hops for each demand vs. number of VNF nodes with a 1TB offered load. Boxes are defined by the first and third quartiles. Ends of the whiskers correspond to the first and ninth deciles.

| Network | Ref. | $\|V\|$ | $\|L\|$ |
|---|---|---|---|
| Internet2 | [18] | 10 | 16 |
| Atlanta | [19] | 15 | 44 |
| Germany50 | | 50 | 88 |

Table III: Network Data

| Network | # traffic requests | # VNF nodes | # generated columns | $z^\star_{\text{LP}}$ | $\tilde{z}_{\text{ILP}}$ | $\varepsilon$ |
|---|---|---|---|---|---|---|
| Internet2 | 360 | 5 | 382 | 2,086.7 | 2,086.7 | 0 |
| | | 6 | 382 | 2,064.8 | 2,064.4 | 0 |
| | | 7 | 379 | 2,064.4 | 2064.4 | 0 |
| Atlanta | 840 | 7 | 1,198 | 2,591.5 | 2,592.9 | $5.4 \times 10^{-4}$ |
| | | 8 | 1,611 | 2,581.7 | 2,581.7 | 0 |
| | | 9 | 1,266 | 2,534.4 | 2,535.8 | $5.6 \times 10^{-4}$ |
| Germany | 9,800 | 24 | 28,083 | 4,217.6 | 4,218.0 | $8.1 \times 10^{-5}$ |
| | | 25 | 28,140 | 4,211.9 | 4,212.3 | $8.8 \times 10^{-5}$ |
| | | 26 | 26,977 | 4,190.7 | 4,191.0 | $7.4 \times 10^{-5}$ |

Table IV: Numerical results

### *C. Comparison ILP vs CG*

In Figure 1, we compare the two models presented in Section IV on the germany50 network. We assume all nodes are VNF enabled nodes and the number of requests varies between 10 and 100% of the requests in an all-to-all traffic scenario.

Model NFV_ILP is solved exactly using the cplex ILP solver, while Model NFV_CG is solved using the solution scheme described in Section V, i.e., with an $\varepsilon$-optimal solution scheme. As the accuracy of the solutions of Model NFV_CG is very good, the solutions of both models are identical. However, NFV_CG takes more time as the number of requests increases. Indeed, when reaching 80% requests in the all-to-all scenario, NFV_ILP does not give any solution anymore, as the cplex solver runs out of memory. Comparatively, NFV_CG outputs an $\varepsilon$-optimal solution with all requests in less than 20 minutes. See Figure 1 for the comparison of computing times, using the ratio of the computational times.

### *D. Bandwidth Requirement and Delay vs. Number of VNF Capable Nodes*

In this set of experiments, we want to study the impact of the number of VNF nodes on the bandwidth requirement and the delay. Generating numerous VNF nodes could be quite costly (e.g., license price, CPU utilization, energy consumption...), and should be compensated by a significant decrease in the bandwidth requirement or justified by inacceptable delays otherwise. Our results show that this is not the case. We next discuss them in detail.

Figure 2 shows the bandwidth used for an overall 1Tbps traffic when the number of VNF nodes varies. As we allow more VNF nodes, the overall required bandwidth in the network decreases. This is as expected. Since every request requires a SFC, their provisioning must go through VNF nodes in the required order, possibly requesting more hops than in one of the shortest paths in the network. However, what we learn from Figure 2 is that, when reaching 50% for VNF capable nodes, the bandwidth gain is getting significantly smaller.

We next investigated the increase of the number of VNFs with respect to the delay, as measured by the number of hops. Results are described in Figure 3 using a box-and-whisker plot. It shows that the median value for the number of hops stabilizes as soon as the number of VNF nodes reaches 3, 9, 9 for the Internet 2, Atlanta and Germany networks, respectively. While the stabilization occurs later with bandwidth requirements, these results say that, indeed, only few requests are affected when increasing the number of VNFs beyond the 3, 9 and 9 values for Internet 2, Atlanta and Germany networks, respectively. Consequently, for homogeneous traffic as in our experiments, there is little advantage both in terms of delays and bandwidth requirements to increase much the number of VNF nodes. It might be slightly different with heterogeneous traffic, depending on the type of traffic that is impacted.

## VII. Conclusions

In this paper, we look at the Service Function Chain placement problem and propose two Integer Linear Program models to solve it. We show that a simple ILP does not scale well for large networks. However, with a decomposition model like Model NFV_CG, we can solve *exactly* the Service Function Chain Provisioning Problem. Taking into account the work of the literature, this is the first model that scales with an increasing number of nodes, but also, with an increase of the number of requests for an increase of the number of nodes pairs with service chain requirements. Model NFV_CG then allowed us to look at the trade off between the network bandwidth requirement and the number of VNF capable nodes.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