Energy-Efficient Service Function Chain Provisioning

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Abstract

Network Function Virtualization (NFV) is a promising network architecture concept to reduce operational costs. In legacy networks, network functions, such as firewall or TCP optimization, are performed by specific hardware. In networks enabling NFV coupled with the Software Defined Network (SDN) paradigm, network functions can be implemented dynamically on generic hardware. This is of primary interest to implement energy efficient solutions, in order to adapt dynamically the resource usage to the demands. In this paper, we *study how to use NFV coupled with SDN to improve the energy efficiency of networks.* We consider a setting in which a flow has to go through a Service Function Chain, that is several network functions in a specific order. We propose a decomposition model that relies on chaining and function placement configurations to solve the problem. We show that virtualization allows to obtain between 15% to 62 % of energy savings for networks of different sizes.

Keywords: Network Function Virtualization, Service Function Chains, Software Defined Networks, Energy Efficiency, Optimization, Column Generation.

1 Introduction

Nowadays, network operators are trying to reduce their operational costs by smartly upgrading their networks using two recent promising paradigms: Software Defined Network (SDN) and Network Function Virtualization (NFV). SDN decouples the data plane from the control plane, and puts the intelligence into a centralized controller. It allows the deployment of advanced dynamic protocols and of finer network optimization based on metrology data, regularly collected by network nodes and sent to the controller.

For security and efficiency reasons, network flows have to go through a number of network functions, e.g., firewall, load balancers, video optimizer controller, which are traditionally implemented on specific hardware. This leads to inefficiency as the hardware is provisioned for peak traffic. NFV paradigm aims at virtualizing the functions to obtain Virtualized Network Functions (VNFs), which can then be implemented on generic hardware. Coupled with SDN, VNFs can be installed dynamically when needed, at the best network location, at the best time, and only for the adequate traffic. This allows a reduction of hardware cost (Capex) and of operational cost (Opex).

One of the important operational cost is the energy used by the network. With the sharp increase of Internet traffic, networks have to be more energy efficient [10]. To this end, Energy-Aware Routing solutions have been proposed, see e.g., [3]. The principle is to aggregate traffic on a number of network equipment as small as possible, in order to turn off the unused ones. SDN and NFV will allow such an implementation into practice by enabling dynamic routing and network function provisioning.

In this paper, we *explore the potential of network virtualization to reduce network energy consumption.* We consider a setting in which a network flow has to go through a *Service Function Chain (SFC)*, that is an ordered sequence of VNFs. We study the problem of minimizing network energy consumption, while both satisfying the link/node capacity constraints and the SFC constraints. We call this problem the Capacitated Energy Efficient Service Function Chain Provisioning Problem, EE-SFCP for short.

Several optimization models were proposed in the literature to solve the Service Function Chain Provisioning problem [14,5,9,11,13,6]. However, these works do not consider the minimization of the network energy consumption under a dynamic traffic. Our contributions are:

- A CG model to solve the EE-SFCP problem on large instances.
- Enhancement of the model with the use of cuts as the EE-SFCP problem is a difficult optimization problem. As a matter of fact, it contains a sharp On-

Off phenomena, as a network device consumes a large portion of its energy as soon as it is used, even if very lightly used. Cuts allow the reduction of the integrality gap.

- Extensive numerical evaluations on networks of different sizes. We show that between 15% to 62% of energy can be saved while respecting the SFC constraints.
- A latency analysis with respect to switching off some network elements for energy savings.

2 Statement of the Problem: SFC and VNF Placement

Notations. We assume the network to be represented by a directed graph $G = (V, L)$, where V is the set of nodes (indexed by v) and L is the set of links (indexed by ℓ). Each node $v \in V$ has a a set of compute, storage and network resources denoted by C_v to host network functions. Within this study, we will assume that the resources are described by a given number of cores. Each link has a bandwidth capacity denoted C_ℓ

Traffic is described by a set of demand requests D, in which each demand d is defined by a 3-tuple (v_s, v_d, c), where v_s is the source of the demand, v_d its destination, and c the requested service chain. Indeed, each demand d is associated with a given application, which is required to pass through a given SFC. Let D^c_{sd} be the bandwidth requirement of demand d.

Let F be the overall set of virtual functions arising in the service chains, indexed by f, and C be the set of service chains, indexed by c. Each service chain c corresponds to a sequence of n_c functions $f^c_1, \ldots, f^c_i, \ldots, f^c_{n_c}$, where f^c_i denotes the ith function of chain c. Note that some functions may appear more than once in a given chain and that for various reasons (e.g., resiliency, privacy), two different functions f and f' may not be allowed to be installed in the same node. Each virtual function f has its one resource requirement and we denote by Δ_f the number (fraction) of cores required by function f per bandwidth unit.

The *Energy Efficient Service Function Chain Provisioning (*EE-SFCP*)* problem consists in jointly provisioning a set D of demand requests coupled with service function chains C and placing virtual functions arising in the chains, in order to minimize the network energy consumption, subject to link and node capacities.

Power Model. Campaigns of measures of power consumption (see, e.g., [2]) show that a network device consumes a large amount of its power as soon as it is switched on and that the energy consumption does not depend much on

the load. Following this observation, on/off power models have been proposed and studied. Later, researchers and hardware constructors have proposed more energy proportional hardware models [12]. To encompass those different models, we use a hybrid power model in which the power of an active link ℓ is expressed as $P_\ell = P_\ell^{\text{ON}} + \frac{\text{BW}_\ell}{C_\ell} P_\ell^{\text{MAX}}$, where P_ℓ^{ON} represents the energy used when the link ℓ is switched on, BW_ℓ the bandwidth that is carried on ℓ, and P_ℓ^{MAX} the energy consumed by ℓ when it is fully capacitated, i.e., when the amount of carried bandwidth equals the transport capacity (C_ℓ^{LINK}) of link ℓ.
We assume that links can be put into sleep mode, by putting to sleep both endpoint interfaces. Two links in opposite direction between a pair of nodes will be assumed to be in the same state (active or in sleep mode), as the send and receive elements of a unidirectional fiber are usually controlled by the same interface. Routers cannot be put into sleep mode, as there are the sources/destinations of network traffic. However, cores may be put into sleep mode and the power used by node v is equal to $P_v = P_v^{\text{UNIT}} \times \#\text{cores}$, with P_v^{UNIT} being the energy consumption of a single core.
Layered Graph. Following an idea similar to [4], we use a layered graph G^{L} that is defined as follows. We add $\max\limits_{c \in C} n_c$ layers to the original graph G and each layer contains a copy of G. For every node $v \in V$, let v^i be the corresponding node in the ith layer ($i = 0, 1, \ldots, n^c$). Every $(i-1, i)$ layer pair is connected by (v^{i-1}, v^i) links. We denote by $L(G^{\text{L}})$ and by $V(G^{\text{L}})$ the set of links and nodes of graph G^{L}, respectively. Provisioning of a chain and node placement of its functions amounts to find a path from node v_s on the first layer (graph G) to node v_d on the n^cth layer. Placement of a function on a node is given by the endpoints of the link used to switch between layers.

We next set a column generation model for EE-SFCP, which makes use of the layered graph G^{L}.

3 Decomposition Models

We first present here a model using Column Generation, *CG-simple*. We then introduce two variants of the models, *CG-cut*, and *CG-cut+*. Indeed, problems dealing with energy-efficiency frequently lead to large integrality gap and bad precision. This is due to the On-Off phenomena of power models, which translates into large steps of the objective function. We thus try to improve the precision of the model by introducing different sets of constraints. We discuss the precision of the models in Section 4.2.

3.1 *Column Generation Formulation*

We propose a column generation formulation that relies on the concept of chaining & function placement configurations: each configuration γ is associated with a 3-uplet (v_s, v_d, c) and defines: *(i)* a potential route for demand D^c_{sd} associated with node pair (v_s, v_d) for chain c and, *(ii)* node placement of the functions of chain c along the potential route. Route is described by parameters δ^γ_ℓ, equal to 1 if link ℓ belongs to the path, 0 otherwise. Node placement is given by $a^\gamma_{vf_i}$, equal to 1 if the ith function f_i of c is located at node v, 0 otherwise. We denote by Γ_d the overall set of configurations for a demand d.

We now define the set of variables. First set of decision variables: $x_\ell = 1$ if link ℓ is on (active), 0 otherwise. Note that links are powered off by pair, i.e., $x_{\ell=(v,v')} = x_{\ell'=(v',v)}$. Second set of decision variables: $y^\gamma_d = 1$ if demand d is routed using configuration γ, 0 otherwise. Integer variables: REQ_v = # required cores in node v.

The objective, i.e., the minimization of the energy, can be written

$$\min \underbrace{\sum_{\ell \in L} P^{\text{ON}}_\ell x_\ell}_{\substack{\text{link switch} \\ \text{on energy}}} + \underbrace{\sum_{\ell \in L} \sum_{\gamma \in \Gamma} \delta^\gamma_\ell \left(\sum_{d=(v_s,v_d,c) \in D} \frac{D^c_{sd}}{C^{\text{LINK}}_\ell} P^{\max}_\ell \right) y^\gamma_d}_{\text{link bandwidth energy}} + \underbrace{\sum_{v \in V^{\text{NFV}}} P_v \, \text{REQ}_v}_{\text{node resource energy}} \quad . \tag{1}$$

The constraint set decomposes into three sets of contraints.

$$\text{One path per demand:} \quad \sum_{\gamma \in \Gamma_d} y^\gamma_d = 1 \qquad d = (v_s, v_d, c) \in D \tag{2}$$

$$\text{Link capacity:} \quad \sum_{d=(v_s,v_d,c) \in D} \sum_{\gamma \in \Gamma_d} D^c_{sd} \, \delta^\gamma_\ell \, y^\gamma_d \leq x_\ell \, C^{\text{LINK}}_\ell \qquad \ell \in L \tag{3}$$

$$\text{Node capacity:} \sum_{d \in D} \sum_{\gamma \in \Gamma_d} D^c_{sd} (\sum_{i=1}^{n_c} \Delta_{f_i} a^\gamma_{vf_i}) y^\gamma_d \leq \text{REQ}_v \leq C^{\text{NODE}}_v \qquad v \in V^{\text{NFV}}. \tag{4}$$

As we faced issues with large integrality gaps, we enhanced model (1)-(4) with different sets of cuts, through the next two models.

***CG-cut* model.** First set of Inequalities in (5) states that, for each node, at least one incident link should always be on. Moreover, second inequality of (5) enforces that at least $n-1$ links should be on to have a connected network (or different if not all-to-all).

$$\sum_{\ell \in \omega^+(v)} x_\ell \geq 1 \qquad v \in V \quad ; \quad \sum_{\ell \in L} x_\ell \geq n-1. \tag{5}$$

***CG-cut+* model.** We enhance further the *CG-cut* model with:

$$x_\ell \geq \sum_{\gamma \in \Gamma_d} \delta_\ell^\gamma \, y_d^\gamma \qquad \ell \in L, \gamma \in \Gamma_d \tag{6}$$

Using (2), it follows that $\sum_{\gamma \in \Gamma_d} \delta_\ell^\gamma y_d^\gamma \leq 1$. It avoids the use of a big M formulation at the expense of a large number of constraints.

3.2 Solution Scheme

In order to solve efficiently the model of Section 3.1, we need to recourse to column generation for solving the linear relaxation, and then to derive an ILP value, using the last restricted master problem.

There is a configuration generator, i.e., pricing problem, for each $d = (v_v, v_d, c) \in D$. Two sets of decision variables are required. First set is made of variables φ_ℓ^i such that $\varphi_\ell^i = 1$ if the provisioning of demand d uses link ℓ in layer i of the layered graph G^{L}, 0 otherwise. Second set contains variables a_v^i such that $a_v^i = 1$ if the ith function (f_i) of chain c for demand $d = (v_v, v_d, c)$ is placed on NFV node v, 0 otherwise.

$$\min \quad \sum_{\ell \in L} P_\ell^{\max} \frac{D_{sd}^c}{C^{\mathrm{LINK}}}_\ell \sum_{i=0}^{n_c} \varphi_\ell^i - u_{sd}^{(2)} + \sum_{\ell \in L} u_\ell^{(3)} D_{sd}^c \sum_{i=0}^{n_c} \varphi_\ell^i + D_{sd}^c \sum_{v \in V} u_v^{(4)} \sum_{i=0}^{n_c} \Delta_{f_i} a_v^i. \tag{7}$$

Path computation (flow conservation constraints):

$$\sum_{\ell \in \omega^+(v)} \varphi_\ell^i - \sum_{\ell \in \omega^-(v)} \varphi_\ell^i + a_v^i - a_v^{i-1} = 0 \qquad v \in V, 0 < i < n^c \tag{8}$$

$$\sum_{\ell \in \omega^+(v)} \varphi_\ell^0 - \sum_{\ell \in \omega^-(v)} \varphi_\ell^0 + a_v^0 = \begin{cases} 1 \text{ if } v = v_s \\ 0 \text{ else} \end{cases} \qquad v \in V \tag{9}$$

$$\sum_{\ell \in \omega^+(v)} \varphi_\ell^{n^c} - \sum_{\ell \in \omega^-(v)} \varphi_\ell^{n^c} - a_v^{n^c} = \begin{cases} -1 \text{ if } v = v_d \\ \;\; 0 \text{ else} \end{cases} \qquad v \in V. \tag{10}$$

$$\text{Link capacity:} \quad D_{sd}^c \sum_{i=0}^{n_c} \varphi_\ell^i \leq C_\ell^{\mathrm{LINK}} \qquad \ell \in L. \tag{11}$$

$$\text{Node capacity:} \quad D_{sd}^c \sum_{i=0}^{n_c} \Delta_{f_i} a_v^i \leq C_v^{\mathrm{NODE}} \qquad v \in V^{\mathrm{NFV}}. \tag{12}$$

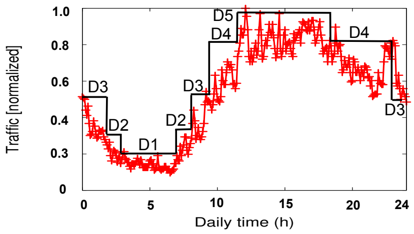


Fig. 1. Normalized daily variation of traffic of a France Telecom network link and multi-period approximation

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 1. Service Chain Requirements [14]

4 Numerical Experiments

We now investigate the energy savings obtained by the CG model.

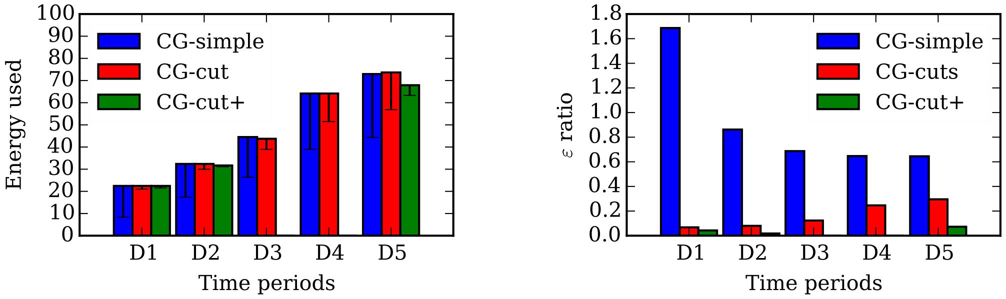
4.1 Data sets

In networks, demand requests have to go through a different chain of network services. In our experiments, we consider four of the most frequent types of requests (applications), see Table 1: Video Streaming, Web Service, Voice-over-IP (VoIP), and Online Gaming. Traffic percentages come from [8]. For each request type, we give the required SFC and its corresponding bandwidth. In total, 6 different functions are used, and each function requires a different amount of cores to be executed.

We tested the CG model on three topologies of different sizes from SNDlib (`http://sndlib.zib.de/`): PDH (11 nodes and 64 directed links), ATLANTA (15 nodes and 44 directed links), and GERMANY50 (50 nodes and 176 directed links).

For each network, we generate a set of demands from the traffic matrices provided in SNDLib: we divide each aggregate flow from a source to a destination into four demands corresponding to the four types of traffic. The original load of the flow is kept and each subflow load is given by the distribution of the last column of Table 1. For example, a flow with a charge of 1 is split into a Web Service, a VoIP, a Video Streaming and an Online Gaming sub-flows with a respective charge of 0.182, 0.118, 0.699 and 0.001.

We tested the solution on a daily traffic to see how much energy can be saved during the day or at night. The variations of traffic come from a trace of a typical France Telecom link shown in Figure 1. Previous work [1] shows that most of the energy savings can be obtained by using a small number of configurations during the day. In our case, we considered 5 different levels of traffic called D1 to D5. D1 represents the period with the lowest amount of



(a) Energy used

(b) $\varepsilon = (\tilde{z}_{\text{ILP}} - z^\star_{\text{LP}})/z^\star_{\text{LP}}$

Fig. 2. Performance of the CG models on *pdh*

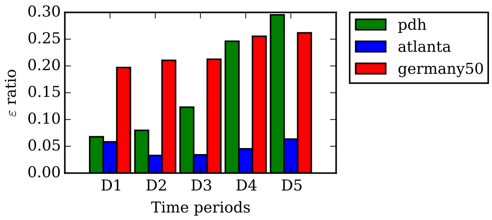


Fig. 3. ε accuracy for different networks & traffic sets

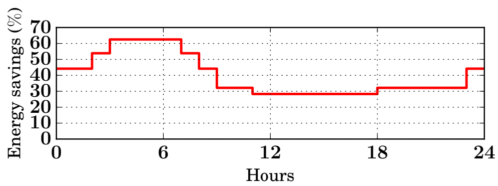


Fig. 4. Energy savings during the day for PDH network.

traffic and D5 the one with the highest.

4.2 Quality of the Column Generation Models

We now compare the performance of the three different CG models (*CG-simple*, *CG-cut*, and *CG-cut+*) with respect to their accuracy as given by $\varepsilon = (\tilde{z}_{\text{ILP}} - z^\star_{\text{LP}})/z^\star_{\text{LP}}$, where $\tilde{z}_{\text{ILP}}$ represents the value of the integer solution of the model and $z^\star_{\text{LP}}$ the value of the linear relaxation. In Figure 2, we compare the solutions founded by the three CG models for the PDH network and for the 5 different levels of traffic. Energy used is given in Figure 2a (Error bars represent the gap given by the relaxation) and ε in Figure 2b. The first observation is that the three models obtain similar energy savings: almost always equal for *CG-simple* and *CG-cut*, and a little bit better (up to 5%) for *CG-cut+*. However, ε dramatically varies. Cuts significantly improves ε: for *CG-simple*, it varies between 169% for the D1 period and 64% for the D5 period, when, for *CG-cut*, ε is between 8 to 30%. The ratio is further improved with *CG-cut+*: between 2 and 7%. As the energy savings are similar for the three models, it shows that the *three CG models provide rather accurate solutions, as confirmed by the solutions and accuracies of the* CG-cut *and* CG-cut+ *models.*

We now *focus on the* CG-cut *model*, as it offers the best compromise in terms of accuracy (wrt *CG-simple* model) and memory requirements (wrt *CG-cut+* model) to solve large networks. Note that it does not allow to get a solution for D3 and D4 periods with *pdh* network.

We provide in Figure 3 the ε values for the three topologies. On *pdh*, ε increases from 7% at period D1 to almost 30% at period D5. For ATLANTA, ε decreases from 6% at D1 to 3% at D3, before increasing back to 6% at D5. For GERMANY50, ε steadily increases from 20 to 26%.

4.3 Energy Savings

Energy Savings. We compare the savings of our solutions with a *legacy scenario* (baseline), i.e., a network with no SDN or NFV implementation. Therein, routing is static, network functions are not virtualized but hardware implemented, with hardware installed in specific positions. Demands use shortest paths between sources, hardware locations, and destinations.

We provide in Figure 4 the energy savings during the day for PDH. Due to lack of space,the results for the other networks can be found in [7]. We see that we obtained important savings using virtualization: between 25 and 62 % for PDH, 15 and 30 % for ATLANTA, and 38 and 42 % for GERMANY50.

Impact on Delay. When some links are put into sleep mode, some of the paths are becoming longer. Due to lack of space, the details can be found in [7]. Therein, we show that the maximum delay of every path stays below the usual 50 ms latency value in Service Level Agreements: experienced delay is about 7, 14 and 25 ms on PDH, ATLANTA and GERMANY50 respectively.

5 Conclusion

In this work, we investigate the potential of network virtualization to reduce the energy consumption of networks. We propose a Column Generation model to solve the problem of minimizing network energy consumption while satisfying the SFC requirements. We obtain between 15 to 62 % of energy savings for network topologies of different sizes.

References

[1] Araujo, J., F. Giroire, J. Moulierac, Y. Liu and M. Remigiusz, *Energy efficient content distribution*, Computer Journal (2016), pp. 1–18.

[2] Chabarek, J., J. Sommers, P. Barford, C. Estan, D. Tsiang and S. Wright, *Power awareness in network design and routing*, in: *IEEE International Conference on Computer Communications (INFOCOM)*, 2008, pp. 1130–1138.

[3] Chiaraviglio, L., M. Mellia and F. Neri, *Minimizing ISP network energy cost: Formulation and solutions*, IEEE/ACM Transactions on Networking **20** (2011), pp. 463–476.

[4] Dwaraki, A. and T. Wolf, *Adaptive service-chain routing for virtual network functions in software-defined networks*, in: *Work. on Hot topics in Middleboxes and Network Function Virtualization (HotMIddlebox)*, 2016, pp. 32–37.

[5] Gupta, A., M. F. Habib, P. Chowdhury, M. Tornatore and B. Mukherjee, *Joint virtual network function placement and routing of traffic in operator networks*, UC Davis, Davis, CA, USA, Tech. Rep (2015).

[6] Huin, N., B. Jaumard and F. Giroire, *Optimization of network service chain provisioning*, in: *IEEE International Conference on Communications (ICC)*, Paris, France, 2017.

[7] Huin, N., A. Tomassilli, F. Giroire and B. Jaumard, *Energy-efficient service function chain provisioning* (2016), Inria Research Report RR-8980.

[8] Index, C. V. N., *Cisco visual networking index: Forecast and methodology 2015-2020*, White paper, CISCO) (2015).

[9] Martini, B., F. Paganelli, P. Cappanera, S. Turchi and P. Castoldi, *Latency-aware composition of virtual functions in 5g*, in: *1st IEEE Conference on Network Softwarization (NetSoft)*, 2015, pp. 1–6.

[10] Matsubara, D., T. Egawa, N. Nishinaga, V. P. Kafle, M.-K. Shin and A. Galis, *Toward future networks: a viewpoint from itu-t*, IEEE Communications Magazine **51** (2013), pp. 112–118.

[11] Mohammadkhan, A., S. Ghapani, G. Liu, W. Zhang, K. Ramakrishnan and T. Wood, *Virtual function placement and traffic steering in flexible and dynamic software defined networks*, in: *The 21st IEEE Int. Workshop on Local and Metropolitan Area Networks*, 2015, pp. 1–6.

[12] Niccolini, L., G. Iannaccone, S. Ratnasamy, J. Chandrashekar and L. Rizzo, *Building a power-proportional software router*, in: *Presented as part of the 2012 USENIX Annual Technical Conference (USENIX ATC 12)*, 2012, pp. 89–100.

[13] Riggio, R., A. Bradai, T. Rasheed, J. Schulz-Zander, S. Kuklinski and T. Ahmed, *Virtual network functions orchestration in wireless networks*, in: *Int. Conf. on Network and Service Management (CNSM)*, 2015, pp. 108–116.

[14] Savi, M., M. Tornatore and G. Verticale, *Impact of processing costs on service chain placement in network functions virtualization*, in: *IEEE Conference on Network Function Virtualization and Software Defined Network (NFV-SDN)*, 2015, pp. 191–197.