Definition and Evaluation of Cold Migration Policies for the Minimization of the Energy Consumption in NFV Architectures

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Abstract. In the Network Function Virtualization (NFV) paradigm any service is represented by a Service Function Chain (SFC) that is a set of Virtual Network Functions (VNF) to be executed according to a given order. The running of VNFs needs the instantiation of VNF Instances (VNFIs) that are software modules executed on Virtual Machines. In this paper we cope with the migration problem of the VNFIs needed in the low traffic periods to switch off servers and consequently to save energy consumption. The consolidation has also negative effects as the energy consumption needed for moving the memories associated to the VNFI to be migrated. We focus on cold migration in redundant architecture in which virtual machines are suspended before performing migration and energy consumption required for transfer of virtual machine memory is the main concern. We propose migration policies that determine when and how to migrate VNFI in response to changes to SFC request intensity and location. The objective is to minimize the total energy consumption given by the sum of the consolidation and migration energies. The obtained results show how the policies allows for a lower energy consumption with respect to the traditional policies that consolidate resources as much as possible.

Keywords: Network function virtualization · Migration Policy · Power consumption · Markov decision process

1 Introduction

Network Function Virtualization (NFV) is emerging as a new network architecture that uses standard IT virtualization techniques to consolidate many network equipment types onto industry standard high volume servers [10]. The service functions are virtualized and executed on Virtual Network Function Instances (VNFIs), that are Virtual Machines running in Commercial-Off-The-Shelf (COTS) servers. The virtualization makes service deployment more flexible and scalable. The efficiency of a network, however, closely depends on the placement of the VNFIs as well as the routing of Service Function Chains (SFCs), characterizing a set of service functions to be executed for a packet flow. For this

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reason efficient algorithms have to be introduced to determine where to instantiate the VNFIs and to route the SFCs by choosing the network paths and the VNFIs involved. The algorithms have to take into account the limited resources of the network links and servers and pursue objectives of load balancing, energy saving and recovery from failure [15]. The task of placing SFC is closely related to virtual network embeddings [9] and may, therefore, be formulated as an optimization problem, with a particular objective. The main proposed solutions are discussed in [15]. For instance Moens et al. [16] formulate the SFC placement problem as a linear optimization problem that has the objective to minimize the number of active servers. The optimization problem and a heuristic have been also introduced in [6] where the processing resource in terms of the number of vcores assigned to each VNFI is also evaluated.

In this paper we consider situations when VNFI placement needs to be changed as traffic demands change over time. Such change of placement, called VNFI *migration*, is desirable for several reasons. Function instances may be migrated to new locations to adapt to changing traffic patterns. We assume a static traffic scenario in which a given number of SFC is offered to the network with bandwidth varying over time. For this reason when the traffic handled by a VNFI decreases, a migration may be triggered in order to consolidate the VNFIs in as few servers as possible with the consequence to save energy. Such migration can be either *hot* or *cold*. Hot (or "live") migration [13] is performed while the network operation is on going. As such the main concern for hot migration is to minimize the QoS degradation that may be incurred while moving VNFIs. We have proposed a hot migration policy in [5] aiming at minimizing the total cost taking into account both the energy consumption and the reconfiguration costs characterizing the QoS degradation. We followed the same approach already proposed in [3,4] in virtual network embedding problems.

In order to avoid QoS degradation and to obtain other benefits like recovery from failure, many network operators have decided to deploy redundant virtual machines so as to guarantee service continuity in the case of one server failure. In the redundant virtual machines scenario is not necessary to perform live migration but it is sufficient a simple *cold migration* [14] in which the virtual machines are suspended before performing migrations. This type of migration can be easier to perform, even if it can be quite disruptive for on going traffic. Here, due to the redundancy of the virtual machines, the main concern is not QoS degradation during migration but rather the *energy consumed during the migration* for transferring the memory associated with migrated virtual machines. For these reasons in this paper we define and investigate two migration policies whose aim is the minimization of the total energy. The first one, referred to as Global Policy, allows for the minimization of the total energy in cycle-stationary traffic scenarios and is applicable to the case in which the entire traffic profile is known. The second one, referred to as Local Policy, is applicable in traffic scenarios in which the knowledge of the current traffic only is assumed.

The paper is organized as follows. Section 2 introduces the problem of the energy consumption minimization in NFV architectures. The Global and Local migration policies are illustrated in Sect. 3. The evaluation of the consolidation and migration energies are reported in Sect. 4. The main numerical results are shown in Sect. 5. Finally the main conclusions and future research items are discussed in Sect. 6.

2 The Problem of the Energy Consumption Minimization in NFV Architectures

Network Function Virtualization (NFV) involves the instantiation of VNFIs in order to execute VNFs belonging to SFCs [7,12]. We assume the case in which each VNFI is executing one VNF of a given type (e.g., a virtual firewall, or a load balancer) and the resources (vcores, RAM memory,...) assigned to it are shared among more SFCs. The problem of SFC routing and allocation of resources to VNFIs has been investigated in [6] where the formulation of the optimization problem is given. Due to the complexity of the problem, the Maximizing the Accepted SFC Requests Number (MASRN) heuristic has been proposed whose outputs are the routing of SFC and the resource dimensioning of the Virtual Machines (VMs) associated to the VNFIs. At the end of the application of the MASRN, a logical network is identified in which the edges are the VNFIs and the links identify which VNFIs are interconnected. This logical network is embedded in the physical network and the MASRN establishes in which physical paths the logical links are routed.

We show in Fig. 1 an example of SFC routing and resource dimensioning in the case of the NFV site reported in Fig. 1 composed by sixteen servers, two switches and two routers. Two SFCs are considered in Fig. 1a. The first one shows that packets need to be processed through two functions: Firewall and VPN Encryption, in that order. The second one involves the execution of a firewall function only.

To support the two SFCs, two VNFI are instantiated by activating the VMs VM_3^{FW} and VM_{11}^{EV} in the servers S_3 and S_{11} respectively. We illustrate in Fig. 1b the routing of the two SFCs considered. The first one uses the memory and processing resources of VM_3^{FW} and VM_{11}^{EV} for the running of the FW and EV VNFs respectively. The second one uses the resources of VM_3^{FW} only. The memory amount and the number of vcores allocated to the VMs are also shown in Fig. 1b. In particular two and three vcores have been allocated for VM_3^{FW} and VM_{11}^{EV} while we assume that the ones available in each server are four.

In order to save energy, server consolidation procedures can be activated in low traffic periods when the needed bandwidth and processing resources decrease. As shown in Fig. 1c, this decrease may lead to the need to allocate only one and two vcores to VM_3^{FW} and VM_{11}^{EV} respectively. We illustrate in Fig. 1d how the migration of the VM_3^{FW} in server S_{11} leads to the advantage of switching off the server S_3.

VNFI consolidation, as shown in the above example, allows for energy consumption saving, unfortunately it involves reconfiguration costs. For this reason sometimes migration could not be recommended or only some migrations should be performed. The investigation of migration policy has been carried out in [5] in the case of hot migration of Virtual Machines. In this case the downtime is minimized with successive stop and copy operations [13] and the main requirement is the one of minimizing the QoS degradation due to the bit loss occurring during the downtime.

In this paper we investigate policies in the case of cold migrations where the virtual machine is suspended before performing the migration and high migration times are involved; in this scenario QoS degradation is not the main concern because this type of migration is applied in case in which the virtual machines are redundant and the switching off of one of them does not impact on the Quality of service. Conversely the main concern in this scenario is the energy consumption due to transferring the bit of the VM memory allocated. This energy consumption characterizes the reconfiguration costs to be taken into account when migration policies, minimizing the total energy cost, have to be identified.

3 Energy Consumption Aware Migration Policies

When traffic reduction occurs, the VNFI can be dimensioned with a number of cores lower than the one evaluated in [6] during the Peak Hour Interval and consolidation techniques can be applied by migrating VNFIs so as to occupy fewer servers and to save power consumption. The migration can be performed when the VNFIs are supported by Virtual Machines (VMs) but at the price of an increase in the energy consumption due to the moving of the memory associated to the VMs. Because this migration energy may impact the total energy consumption, VNFI migration policies have to be defined allowing for a minimization of the energy consumption and consequently a right compromise between energy saving due to consolidation and the energy consumption due to moving memory associated to VMs.

Before illustrating what we intend for optimal migration policy, we introduce the following notations:

- T_i $(i = 0, 1, \cdots)$: traffic state in the period $[t_i, t_i + \Delta)$ of duration Δ; T_i is characterized by the bandwidth $\beta_{i,k}$ $(k = 1, \cdots, N_{SFC})$ of the SFCs offered and N_{SFC} is the number of SFC offered;
- $\mathcal{G}^{\mathcal{PN}} = (\mathcal{V}^{\mathcal{PN}}, \mathcal{E}^{\mathcal{PN}})$: graph of the physical network where $\mathcal{V}^{\mathcal{PN}}$ and $\mathcal{E}^{\mathcal{PN}}$ are the sets of physical nodes and links respectively;
- $\mathcal{G}^{\mathcal{VNFI}} = (\mathcal{V}^{\mathcal{VNFI}}, \mathcal{E}^{\mathcal{VNFI}})$: logical graph where $\mathcal{V}^{\mathcal{VNFI}}$ represents the set of VNFI nodes and $\mathcal{E}^{\mathcal{VNFI}}$ denotes the links between them.

A mapping Γ of $\mathcal{G}^{\mathcal{VNFI}}$ in $\mathcal{G}^{\mathcal{PN}}$ determines in which servers, the VNFIs are hosted and in which network paths the virtual links are routed.

A mapping Γ is admissible for the traffic state T_i when the node processing, memory and link capacity are not overloaded that is when the following conditions hold: (i) the sum of the vcores and memory amount of the VNFIs hosted in any server is lower than or equal to the total number of vcores and memory amount available in the server respectively; (ii) the sum of the capacity

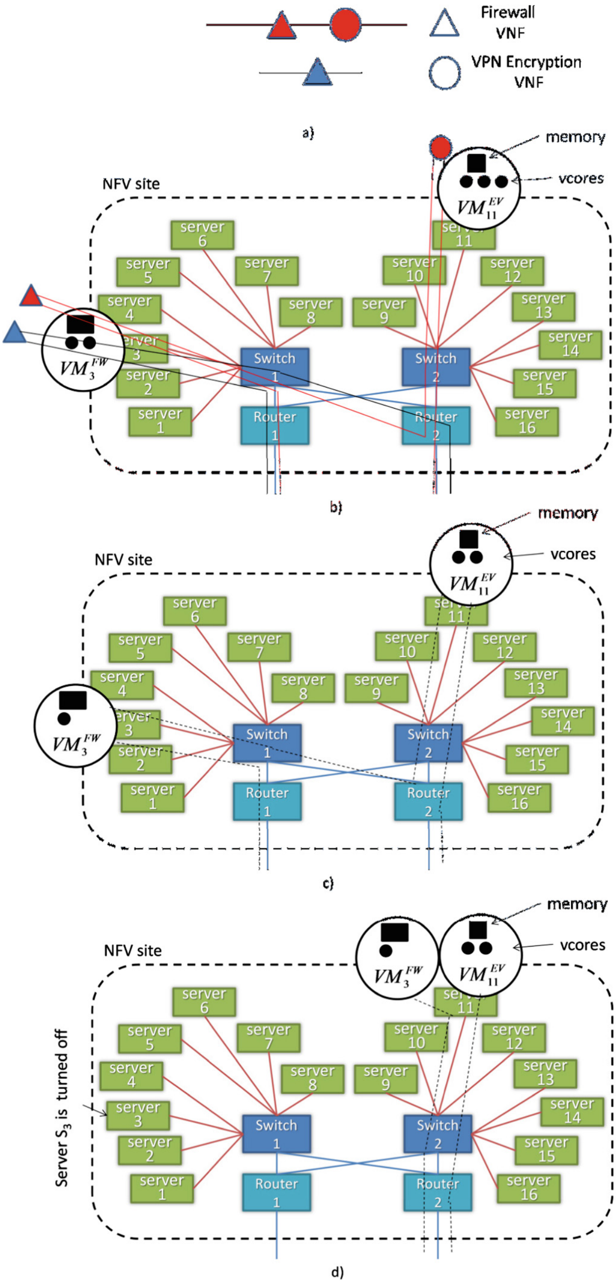

Fig. 1. An example of SFC routing and resource dimensioning for two SFCs (a) in a NFVI site composed by sixteen servers, two switches and two routers; memory and vcores allocated for the virtual machines VM_3^{FW} and VM_{11}^{EV} are shown in the peak hour interval (b) and when the traffic decreases (c); the consolidation application leads to the migration of VM_3^{FW} in server S_{11} (d).

of the logical links routed in any physical link is lower than or equal to the link capacity.

We also define:

- $E^c_{i,\Gamma}$: the consolidation energy defined as the sum of the energy consumption of the servers when the mapping Γ admissible for the traffic state T_i is applied;
- $E^m_{i,\Gamma_a,\Gamma_b}$: the migration energy defined as the energy consumption due to the moving of memories associated to the VNFI when the traffic condition change from T_i to T_{i+1} leads to a mapping change from Γ_a to Γ_b.

The objective is to perform VNFI migrations in the instants $t_i = i\Delta t$ $(i = 0, 1, \cdots)$ so that the mapping is changed and the average total energy is minimized over infinite time horizon.

We introduce the following Optimal Mapping Policy Problem (OMPP) Formulation:
Given

- the traffic states T_i $(i = 0, 1, \cdots,)$
- the set Π of all possibles mappings;

Find the mapping policy

- $\{\Gamma_i, i = 0, 1, \cdots\}$ where $\Gamma_i \in \Pi$ is a mapping applied in instant t_i and admissible in the traffic state T_i;

Minimizing the average energy consumption E_{av} given by:

$$E_{av} = \lim_{K\to\infty} \frac{1}{K} \sum_{i=0}^{K} (E^c_{i,\Gamma_i} + E^m_{i,\Gamma_i,\Gamma_{i+1}}) \tag{1}$$

It is possible to prove that the solution of the optimal migration problem is NP-Hard [5]. For this reason we provide a solution of the problem introduced under the two assumptions described below.

- *Assumption-A: cycle-stationary traffic scenario*. It is well known that traffic matrices in backbone networks exhibit strong diurnal patterns and are typically cycle-stationary [5] with a 24 h cycle and with stationary characteristics in intervals of duration 1 h. For this reason we illustrate how we can solve the OMPP problem under the assumption of cycle-stationary traffic. We denote with N the number of intervals after which the same traffic characteristic occurs again; in this traffic scenario the same condition of traffic occurs every N time intervals that is T_i=T_{i+kN} $(i = 0, 1, \cdots, N-1; k = 1, 2, \cdots)$ where we also assume that T_0 corresponds to the Peak Traffic condition.
- *Assumption-B: choices of a-priory determined mappings*. The mappings Γ_i $(i = 0, 1, \cdots, N-1)$ are selected in a restricted set Θ of possible mappings; the choice of these mappings is accomplished by applying suitable optimality criteria. The mappings of the set Θ are determined by applying the consolidation algorithm proposed in [5] and based on minimization of power consumption.

Under these assumptions the optimal policy, referred to as Global Policy and denoted as $\mathcal{D}^{glo}$, is characterized by the the mappings Γ_i^{glo} $(i = 0, 1, \cdots, N-1)$ minimizing the total energy in a cycle-stationary interval, where Γ_i^{glo} is chosen to belong to the set Θ and it is admissible for the traffic state T_i. The mappings Γ_i^{glo} $(i = 0, 1, \cdots, N-1)$ can be determined by evaluating the optimal policy in a Discrete Time Markov Decision Process [4,11] and by following an approach similar to the one proposed in [5] in the case of hot migration of the VNFIs. The approach is briefly described in Appendix A. Another solution has been proposed in [2] by solving a least cost cycle problem.

We also introduce the Local Policy $\mathcal{D}^{loc}$, less complex than the Global Policy $\mathcal{D}^{glo}$ and adoptable when only the knowledge of the actual traffic is known. Its objective is to perform mapping changes so as to minimize the sum of the migration energy involved in the transition and the consolidation energy consumed by the servers when the new mapping is applied. The mappings Γ_i^{loc} $(i = 0, 1, \cdots, N-1)$ of the policy $\mathcal{D}^{loc}$ are established as follows:

- Γ_0^{loc} is the mapping belonging to Θ, admissible for the traffic state T_0 and with the lowest consolidation energy;
- the mapping Γ_i^{loc} $(i = 1, \cdots, N-1)$ is chosen from the set Θ, it is admissible for the traffic state T_i and it is chosen so as to minimize the sum of the migration energy involved in the transition and the consolidation energy of the mapping Γ_i^{loc} that is the following expression holds:

$$\Gamma_i^{loc} = \arg\min_{\Gamma \in \Theta} (E_{i,\Gamma}^c + E_{i-1,\Gamma_{i-1}^{loc},\Gamma}^m) \tag{2}$$

4 Evaluation of Consolidation and Migration Energy

In the evaluation of the consolidation and migration energy E_{i,Γ_i}^c and $E_{i,\Gamma_i,\Gamma_{i+1}}^m$ respectively, we assume that the main power contribution is due to CPU use because this component has the largest impact among all components [5]. We also assume a power consumption trend linear as a function of the load. As future research item, we will study the cases of more complex dependence [5]. We assume the following expression for the server power consumption P:

$$P = \left[a + (1-a)\frac{A_s}{N_c}\right] P_{max} \tag{3}$$

wherein P_{max} is the maximum server power, a is the ratio of the baseline power to the maximum power, N_c is the total number of vcores and A_s is the average number of packets handled by the server.

Notice as the power consumption is given by the sum of the constant contribution aP_{max} and the one $(1-a)\frac{A_s}{N_c}P_{max}$ dependent on the offered traffic. Next we evaluate the consolidation and the migration energies in the case of cold migration, which involves halting the VM, copying all its memory pages to the destination server and then restarting the new VM. We denote with D the migration time that in this case characterizes the downtime period in which the server stops the executions of the processes.

Next we report the evaluation of the consolidation and migration energies E^c_{i,Γ_i} and $E^m_{i,\Gamma_i,\Gamma_{i+1}}$ in Subsects. 4.1 and 4.2 respectively.

4.1 Evaluation of Consolidation Energy

In the evaluation of consolidation energy E^c_{i,Γ_i} $(i = 0, 1, \cdots, N-1)$ in the traffic state T_i when the mapping Γ_i is applied, we introduce the following parameters:

- N_s: number of servers;
- $x^{\Gamma_i}_{i,j}$: parameters assuming the value 1 if the server j-th $(j = 1, \cdots N_s)$ is turned on in the traffic state T_i when the mapping Γ_i is applied;
- F: number of service function types;
- t^k_p $(k = 1, \cdots, F)$: packet processing time when service function k-th is applied;
- $R^{\Gamma_i}_{i,j,k}$: packet rate of the flows handled by the VMs running the service function k-th in the server j-th.

A consolidation energy is involved when the servers are active in runnings VMs executing the service functions. According to (3), we can write the following expression for E^c_{i,Γ_i}:

$$E^c_{i,\Gamma_i} = \sum_{j=1}^{N_s}(a + \frac{1-a}{N_c}\sum_{k=1}^{F} R^{\Gamma_i}_{i,j,k}\; t^k_p)\; x^{\Gamma_i}_{i,j}\; \Delta_j t \tag{4}$$

where $\Delta_j t$ is the time in which the server j-th is active and it is equal to the stationarity period Δt if the server has been not involved in a switching on process (the server it also turned on in the traffic state T_{i-1}), otherwise the migration time D must be subtracted from Δt. We can simply write:

$$\Delta_j t = \begin{cases} \Delta t & if \;\; server \;\; j-th \;\; is \;\; on \;\; in \;\; T_{i-1} \\ \Delta t - D & otherwise \end{cases} \tag{5}$$

4.2 Evaluation of Migration Energy

The migration energy $E^m_{i,\Gamma_i,\Gamma_{i+1}}$ is characterized by two components: the first one $E^{m,mem}_{i,\Gamma_i,\Gamma_{i+1}}$ is the energy consumption dependent on the total memory amount that has to transferred when a mapping change occurs; the second one $E^{m,ser}_{i,\Gamma_i,\Gamma_{i+1}}$ is dependent on the switching on or switching off of servers and characterized by the baseline power of the servers. Hence we can write:

$$E^m_{i,\Gamma_i,\Gamma_{i+1}} = E^{m,mem}_{i,\Gamma_i,\Gamma_{i+1}} + E^{m,ser}_{i,\Gamma_i,\Gamma_{i+1}} \tag{6}$$

For the evaluation of the energy consumption components we can introduce the following parameters:

- M_k: memory amount allocated to VM running the service function k-th;
- L_{agg}: packet length of the flows carrying the memory bits;

- t_{agg} $(k = 1, \cdots, F)$: processing time of the packets containing the memory bits;
- $v_{i,k}^{\Gamma_i,\Gamma_{i+1}}$: number of VMs migrating and supporting the service function k-th
- $s_i^{\Gamma_i,\Gamma_{i+1}}$: number of servers that are involved in a switching off or switching on process when the traffic state changes from T_i to T_{i+1} and the mapping change from Γ_i to Γ_{i+1} occurs.

$E_{i,\Gamma_i,\Gamma_{i+1}}^{m,mem}$ involves the energy consumption in both origin and destination servers for the transferring of memory bits of the migrated VMs. It is only dependent on the variable component of the server power consumption and can be expressed by the following expression:

$$E_{i,\Gamma_i,\Gamma_{i+1}}^{m,mem} = 2P_{max}\frac{1-a}{N_c}\sum_{k=1}^{F} v_{i,k}^{\Gamma_i,\Gamma_{i+1}}\left\lceil \frac{M_k}{L_{agg}} \right\rceil t_{agg} \tag{7}$$

Notice as the term $E_{i,\Gamma_i,\Gamma_{i+1}}^{m,mem}$ is independent of the migration time D as already observed by some experimental studies [13].

Conversely $E_{i,\Gamma_i,\Gamma_{i+1}}^{m,ser}$ is dependent on the baseline power consumption and it is simply given by:

$$E_{i,\Gamma_i,\Gamma_{i+1}}^{m,ser} = as_i^{\Gamma_i,\Gamma_{i+1}} P_{max} D \tag{8}$$

Finally by inserting expressions (7) and (8) in (6), we can evaluate the migration energy.

5 Numerical Results

We will verify the effectiveness of the VNFI migration policies introduced in Sect. 3. A given number N_{SFC} of SFC requests is generated, each one composed by three VNFs that is a firewall, a load balancer and a Virtual Private Network (VPN) encryption. We also assume that the load balancer splits the input traffic towards a number of output links chosen uniformly from 1 to 3. The execution order of the VNF is randomly chosen for the t-th generated SFC request. An example of graph for a generated SFC is reported in Fig. 2 in which u_t is an ingress access node and v_t^1, v_t^2 and v_t^3 are egress access nodes. The first and second VNFs are a firewall and a VPN encryption respectively; the third VNF is a load balancer splitting the traffic towards three output links. In the considered case study we also assume that the SFC handles traffic flows of packet with length equal to 1500 bytes.

In our analysis, we consider a three levels hierarchical network composed by five core nodes, five edge nodes and six access nodes in which the SFC requests are randomly generated and terminated. The network is reported in Fig. 3. Four NFV sites, as the one illustrated in Fig. 1, are connected to the network. Each of them is equipped with 16 servers. In this configuration, 40 Gbps links are considered except the links connecting the server to the switches in the NFV sites whose the rate is equal to 10 Gbps. The 64 servers are equipped with 48

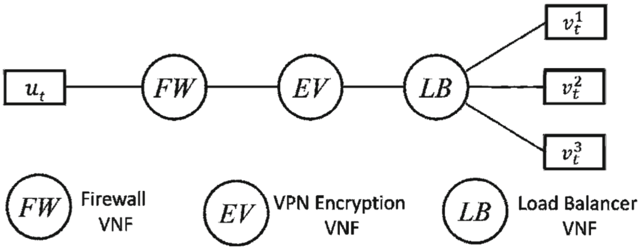

Fig. 2. An example of SFC composed by one firewall VNF, one VPN Encryption VNF and one load balancer VNF that splits the input traffic towards three output logical links. u_t denotes the ingress access node while v_t^1, v_t^2 and v_t^3 denote the egress access nodes.

vcores each one. We assume a vcore technology allowing for the packet processing times equal to 7.08 µs, 0.65 µs and 1.64 µs [1] for the firewall, load balancer and VPN encryption VNFs respectively.

The SFC routing and the dimensioning of the VNFI in terms of vcores is performed during the Peak Hour Interval (PHI) by using the Maximizing the Accepted SFC Requests Number (MASRN) algorithm proposed in [6]. We evaluate the effectiveness of the introduced VNF migration policies when the following case study is considered: (i) $N_{SFC} = 360$ SFCs are generated where the bandwidth $\beta_{0,k}$ of the k-th SFC ($k = 1, \cdots, N_{SFC}$) is uniformly distributed from 500 Mbps to 1 Gbps; (ii) the SFCs are routed in the PHI according to the MASRN heuristic; iii) we assume a cycle-stationary traffic scenario with N=24 intervals and where the bandwidth $\beta_{0,k}(k = 1, \cdots, N_{SFC})$ is modulated by the scale factor τ_i in the i-th interval ($i = 0, \cdots, N-1$) chosen according to the classical sinusoidal trend and given by the following expression:

$$\tau_i = \begin{cases} 1 & if \quad i = 0 \\ 1 - 2\frac{i}{N}(1 - \tau_{min}) & i = 1, \cdots, \frac{N}{2} \\ 1 - 2\frac{N-i}{N}(1 - \tau_{min}) & i = \frac{N}{2} + 1, \cdots, N-1 \end{cases} \tag{9}$$

where $\tau_0 = 1$ and $\tau_{\frac{N}{2}} = \tau_{min}$ denote the scale factors in the peak and least traffic conditions respectively.

The set Θ of mappings chosen a-priori and introduced in Sect. 3 is composed by the elements $\{\theta_i, i = 0, \cdots, \frac{N}{2}\}$ where the mapping θ_i ($i = 0, \cdots, \frac{N}{2}$) is evaluated by applying the VNFI Mapping Minimizing the Power Consumption (VMMPC) consolidation algorithm illustrated in [5] during the interval in which the traffic is characterized by the scale factor τ_i. The VMMPC algorithm, starting from the mapping evaluated by the MASRN algorithm, determines VNFI migrations so as to minimize the number of turned on servers and consequently the power consumption.

Next we evaluate the effectiveness of the policies $\mathcal{D}^{glo}$ and $\mathcal{D}^{loc}$ introduced in Sect. 3. We compare these two policies to the two classical Never Change and Always Change policies $\mathcal{D}^{nc}$ and $\mathcal{D}^{ac}$ respectively. When the $\mathcal{D}^{nc}$ policy

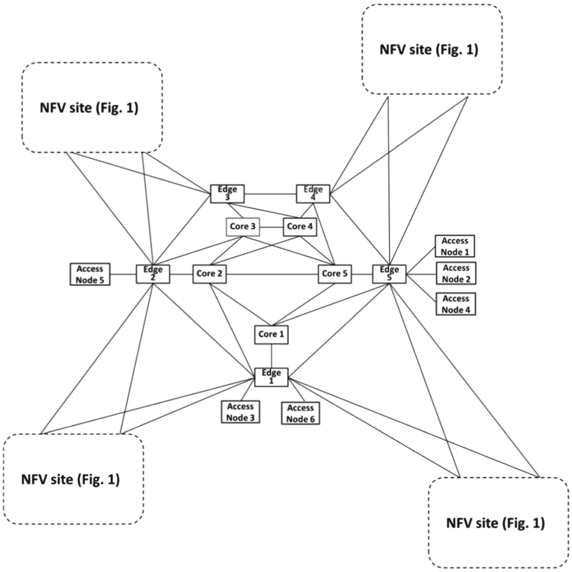

Fig. 3. The network topology is composed by six access nodes, five edge nodes, five core nodes and four NFV sites. Each NFV site is composed by two routers, two switches and sixteen servers connected as represented in Fig. 1.

is selected, the only mapping θ_0 is applied and the migration energy cost is absent. The mapping θ_0 is the one obtained by the application of the VMMPC algorithm during the PHI. It is admissible for all of the traffic conditions and for this reason it is chosen as mapping of the policy $\mathcal{D}^{nc}$. Conversely when the policy $\mathcal{D}^{ac}$ is selected the least power consumption admissible mapping is applied during each traffic state T_i $(i = 0, 1, \cdots, N-1)$. Notice how the policy $\mathcal{D}^{ac}$ allows for the minimization of the consolidation energy consumption at the expense of migration energy.

We report in Fig. 4 the total energy in a cycle-stationary interval of the policies $\mathcal{D}^{glo}$, $\mathcal{D}^{loc}$, $\mathcal{D}^{nc}$ and $\mathcal{D}^{ac}$ as a function of the memory size M associated to each VNFI. We have assumed the same size M for all of the service functions. The traffic profile is characterized by the factor scales expressed by Eq. (9) in which N and τ_{min} are chosen equal to 24 and 0.2 respectively. Finally the parameter a characterizing the ratio of fixed to maximum power consumption of the servers is set equal to 0.7, the migration time D is set equal to 10 s, the memory packet length L_{agg} is equal to 1500 bytes and the processing time t_{agg} of each memory packet is assumed to be 1.6 µs. From Fig. 4 we can observe how the proposed policy $\mathcal{D}^{glo}$ performs better than the policies $\mathcal{D}^{loc}$, $\mathcal{D}^{ac}$ and $\mathcal{D}^{nc}$ for all of the memory sizes and allows for a minimization of the total energy. For instance for $M = 460$ Mb the total energy values 21402 Wh, 23066 Wh, 23570 Wh, 29306 Wh are obtained for the policies $\mathcal{D}^{glo}$, $\mathcal{D}^{loc}$, $\mathcal{D}^{ac}$ and $\mathcal{D}^{nc}$ respectively. As expected

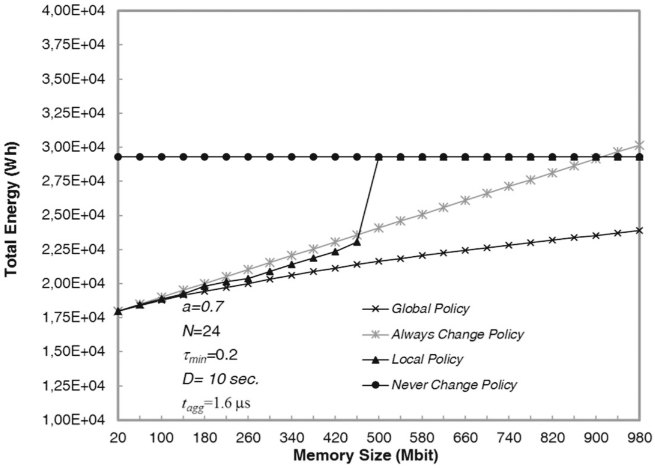

Fig. 4. The total energy of the policies $\mathcal{D}^{ac}$, $\mathcal{D}^{nc}$, $\mathcal{D}^{loc}$ and $\mathcal{D}^{glo}$ as a function of the memory size M associated to each VNFI migrating when $N_{SFC} = 360$, $N = 24$, $t_{agg} = 1.6\,\mu$s, $a = 0.7$ and $D = 10\,$s.

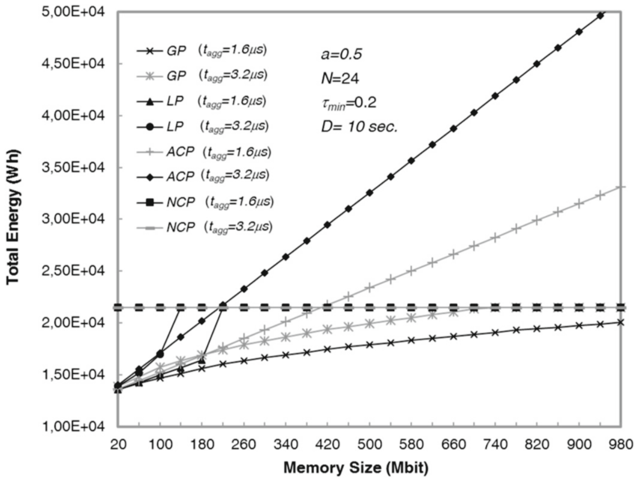

Fig. 5. The total energy of the policies $\mathcal{D}^{ac}$, $\mathcal{D}^{nc}$, $\mathcal{D}^{loc}$ and $\mathcal{D}^{glo}$ as a function of the memory size M associated to each VNFI migrating when $N_{SFC} = 360$, $N = 24$, $a = 0.5$ and $D = 10\,$s. The value of the aggregation processing time t_{agg} is chosen equal to $1.6\,\mu$s and $3.2\,\mu$s.

the policy $\mathcal{D}^{ac}$ reaches the total energy value of $\mathcal{D}^{glo}$ only for low memory size M. In fact in this case the migration energy is negligible and the optimal policy is the one minimizing the consolidation energy that is $\mathcal{D}^{ac}$.

Next we show the impact of the packet memory processing time t_{agg} on the behavior of the proposed policies. In particular in the case $a = 0.5$ we compare in Fig. 5 the total energy of the policies $\mathcal{D}^{ac}$, $\mathcal{D}^{nc}$, $\mathcal{D}^{loc}$ and $\mathcal{D}^{glo}$ for the values of t_{agg} equal to 1.6 µs and 3.2 µs. The increase in t_{agg} leads to an increase in the migration energy due to the higher power consumption of the vcores involved in the migration process. For this reason when $t_{agg} = 3.2$ µs and the memory size M is larger than or equal to 660 Mb, the global policy $\mathcal{D}^{glo}$ is the one in which VNFI migrations are not performed at all and it is convenient to apply the same mapping solution in all of the traffic intervals as the policy $\mathcal{D}^{nc}$ makes. This is the reason for which starting from this memory value, the policies $\mathcal{D}^{glo}$ and $\mathcal{D}^{nc}$ have the same total energy.

6 Conclusions

The aim of this paper is to propose migration policies that establish when and where migrations of VNFI have to be accomplished so as to minimize the total energy characterized by the sum of the consolidation and migration energies occurring when the VNFIs are moved from the initial location. We have introduced two migration policies applicable in cycle-stationary traffic scenarios and when the possible mappings, characterizing where the VNFIs are instantiated, are a-priori determined. One of the two proposed policies, referred to as Global policy aims at minimizing the total energy consumption in the cycle-stationary period duration. We have compared the proposed policies to the Always Change and Never Change classical policies. The obtained numerical results have shown how the Global policy allows for the lowest energy consumption with respect to traditional migration policies.

Appendix A Application of the Markov Decision Process (MDP) Theory for the Determination of the Global Policy

The proposed approach is based on choosing the solution in an a-priori determined and "good" possible solutions set. The assignment of the VNF nodes and links of the graph $G^{VNFI} = (V^{VNFI}, E^{VNFI})$ to server nodes and physical network paths respectively is defined as *mapping*. The global policy $\mathcal{D}^{glo}$ consists in choosing the mapping Γ_h to be applied in each traffic state T_h $(h = 0, 1, \cdots, N-1)$ so as to minimize the objective function expressed by (1). The proposed simplified approach consists in selecting the mappings Γ_h $(h = 0, 1 \cdots, N-1)$ applied in the traffic states T_h $(h = 0, 1, \cdots, N-1)$ by a set Θ; the choice of these mappings is accomplished by applying optimality criteria based on minimization of power consumption, minimization of reconfiguration costs,$\cdots$; not all of the mappings in Θ can be applied in any state T_h but only the admissible ones that do not lead to overcome the link bandwidth and the node processing resources. We denote with $\theta_{h,l}$ $(l = 1, \cdots, n_h)$ the n_h mappings belonging to Θ and admissible for the traffic condition T_h $(h = 0, \cdots, N-1)$; the state diagram reported in Fig. 6 represents the set of admissible mappings for each traffic state; it is organized in N levels where the $h-th$ $(h = 0, 1, \cdots, N-1)$ level is composed by the n_h bi-dimensional states $(T_h, \theta_{h,l})$ $(l = 1, \cdots, n_h)$. The objective is to determine a policy that establishes which mapping to apply when traffic changes happens. Formally a policy is characterized by the set of integer values $\mathcal{D} = \{d_{h,l} \;\; h = 0, 1 \cdots, N-1; l = 1, 2, \cdots, n_h\}$ where $d_{h,l}$ establishes that from the state $(T_h, \theta_{h,l})$, the mapping $\theta_{(h+1) \bmod N, d_{h,l}}$ has to be applied when the new traffic condition $T_{(h+1) \bmod N}$ occurs. Our objective is to determine the policy $\mathcal{D}^{glo}$ that minimizes the total cost in a cycle-stationarity period. We can determine the policy $\mathcal{D}^{glo}$ by finding the optimal policy in a Discrete Time Markov Decision Process (DTMDP) [8,11] whose Markov chain is characterized by the states of Fig. 6. The state and transition costs [8,11] in the DTMDP are as follows. Each state $(T_h, \theta_{h,l})$ is characterized by the consolidation energy cost $E^c_{(\theta_{h,l})}$ that is the energy consumed in the stationary interval T_h when the mapping $\theta_{h,l}$ is applied. Furthermore a transition from the state $(T_h, \theta_{h,l})$ to the state $(T_{(h+1) \bmod N}, \theta_{(h+1) \bmod N,k})$ is characterized by the migration energy cost $E^m_{(\theta_{h,l}, \theta_{(h+1) \bmod N,k})}$ that is the energy consumed to move the virtual machines involved in migration process.

The number of possible *alternatives* [8,11] in the state $(T_h, \theta_{h,l})$ is equal to $n_{(h+1) \bmod N}$ that is the number of mappings applicable when the traffic state transition from T_h to $T_{(h+1) \bmod N}$ occurs. The integer variable $d_{h,l}$ $(d_{h,l} \in [1..n_{(h+1) \bmod N}])$ codes the *alternative* chosen in the state $(T_h, \theta_{h,l})$ that involves the use of the mapping $\theta_{(h+1) \bmod N, d_{h,l}}$. When $d_{h,l}$ has been specified for $h \in [0..N-1]$ and $l \in [1..n_h]$, a mapping policy has been determined. The optimal mapping policy $\mathcal{D}^{glo} = \{d^{glo}_{h,l} \;\; h = 0, 1 \cdots, N-1; l = 1, 2, \cdots, n_h\}$ is the one that minimizes the expected total cost. To determine it we apply the policy iteration method [8,11] that needs the evaluation versus the *alternative* $d_{h,l}$ of both the transition probabilities $p^{j,k,d_{h,l}}_{h,l}$ from the state $(T_h, \theta_{h,l})$ to the state $(T_j, \theta_{j,k})$ and the cost $q^{d_{h,l}}_{h,l}$ to be expected in the next transition out of the state $(T_h, \theta_{h,l})$. The transition probabilities $p^{j,k,d_{h,l}}_{h,l}$ are reported in Fig. 6 for the *alternatives* $d_{h,l} = 1$, $d_{h,l} = k$ and $d_{h,l} = n_{(h+1) \bmod N}$. We can notice as the choice of the *alternative* $d_{h,l}$ involves only a transition with probability 1 from the state $(T_h, \theta_{h,l})$ to the state $(T_{(h+1) \bmod N}, \theta_{(h+1) \bmod N, d_{h,l}})$. Thus we can simply write:

$$p^{j,k,d_{h,l}}_{h,l} = \begin{cases} 1 \;\; if \quad j = (h+1) \bmod N, \quad k = d_{h,l} \\ 0 \;\; otherwise \end{cases} \tag{10}$$

For the evaluation of $q^{d_{h,l}}_{h,l}$ we observe that if the choice of the *alternative* $d_{h,l}$ in the state $(T_h, \theta_{h,l})$ leads not to change the applied mapping, that is $\theta_{(h+1) \bmod N, d_{h,l}} \equiv \theta_{h,l}$, the migration energy costs are not involved and only the energy consumption cost $E^c_{(\theta_{h,l})}$ of applying the mapping $\theta_{h,l}$ has to be considered. Otherwise when a mapping change occurs, also the migration energy cost $E^m_{(\theta_{h,l}, \theta_{(h+1) \bmod N, d_{h,l}})}$ from the mapping $\theta_{h,l}$ to the mapping $\theta_{(h+1) \bmod N, d_{h,l}}$ has

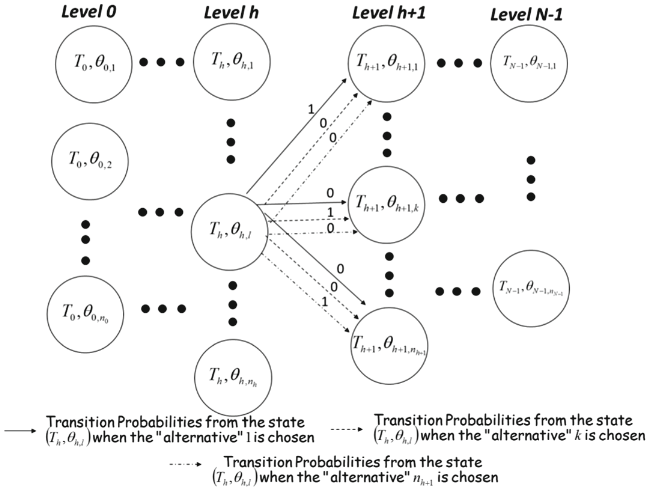

Fig. 6. Bi-dimensional Discrete Time Markov Chain in which each state is characterized by some possible *alternatives*; the choice of an *alternative* in each state determines a mapping policy.

to be added. Hence we can write:

$$q_{h,l}^{d_{h,l}} = \begin{cases} E^c_{(\theta_{h,l})} & if \quad \theta_{(h+1) \bmod N, d_{h,l}} \equiv \theta_{h,l} \\ E^c_{(\theta_{h,l}) + E^m_R(\theta_{h,l}, \theta_{(h+1) \bmod N, d_{h,l}})} & otherwise \end{cases} \tag{11}$$

Once established the transition probabilities $p_{h,l}^{j,k,d_{h,l}}$ and the cost $q_{h,l}^{d_{h,l}}$ as a function of the *alternative* $d_{h,l}$ we can find the policy $\mathcal{D}^{glo} = \{d_{h,l}^{glo}, \;\; h = 0, 1 \cdots, N-1; l = 1, 2, \cdots, n_h\}$ by applying the policy-iteration method [8,11].

References

1. Dobrescu, M., Argyraki, K., Ratnasamy, S.: Toward predictable performance in software packet-processing platforms. In: 9th USENIX Symposium on Networked Systems Design and Implementation, pp. 1–14, April 2012
2. Eramo, V., Ammar, M., Lavacca, F.: Migration energy aware reconfigurations of virtual network function instances in NFV architectures. IEEE Access **5**, 4927–4938 (2017)
3. Eramo, V., Miucci, E., Ammar, M.: Study of migration policies in energy-aware virtual router networks. IEEE Commun. Lett. **18**, 1919–1922 (2014)
4. Eramo, V., Miucci, E., Ammar, M.: Study of reconfiguration cost and energy aware vne policies in cycle-stationary traffic scenarios. IEEE J. Sel. Areas Commun. **34**, 1–17 (2016). doi:10.1109/JSAC.2016.2520179
5. Eramo, V., Miucci, E., Ammar, M., Lavacca, F.G.: An approach for service function chain routing and virtual function network instance migration in network function virtualization architectures. IEEE Trans. Netw. **25**(4), 2008–2025 (2017). http://ieeexplore.ieee.org/document/7866881/

6. Eramo, V., Tosti, A., Miucci, E.: Server resource dimensioning and routing of service function chain in NFV network architectures. J. Electr. Comput. Eng. 1–12, April 2016. article ID 7139852
7. ETSI Industry Specification Group (ISG) NFV: ETSI Group Specifications on Network Function Virtualization, January 2015. http://docbox.etsi.org/ISG/NFV/Open/Published/
8. Fan, J., Ammar, M.H.: Dynamic topology configuration in service overlay networks: a study of reconfiguration policies. In: Proceedings of 25th IEEE International Conference on Computer Communications (INFOCOM), pp. 1–12. Barcelona (Spain), April 2006
9. Fischer, A., Botero, J., Till Beck, M., de Meer, H., Hesselbach, X.: Virtual network embedding: a survey. Commun. Surv. Tutor. IEEE (15), 1888–1906, July/August 2014
10. Gu, L., Tao, S., Zeng, D., Jin, H.: Communication cost efficient virtualized network function placement for big data processing. In: Proceedings of INFOCOM 2016, April 2016
11. Howard, R.A.: Dynamic Programming and Markov Processes. The Massachusetts Institute of Technology (1960)
12. Internet Engineering Task Force (IETF) Service Function Chaining (SFC) Working Group (WG), Halpern, J., Pignataro, C.: Service Function Chaining (SFC) Architecture, RFC 7665 (2015). https://datatracker.ietf.org/doc/rfc7665/
13. Liu, H., Xu, C., Jin, H., Gong, J., Liao, X.: Performance and energy modeling for live migration of virtual machines. Cluster Comput. **14**(6), 249–264 (2013)
14. Medina, V., Garcia, J.: A survey of migration mechanisms of virtual machines. J. ACM Comput. Surv. **46**(3), 1–33 (2014)
15. Mijumbi, R., Serrat, J., Gorricho, J., Bouten, N., De Turck, F., Boutaba, R.: Network function virtualization: state-of-the-art and research challenges. IEEE Commun. Surv. Tutorials **18**(1), 236–262 (2016)
16. Moens, H., Turck, F.: Vnf-p: a model for efficient placement of virtualized network functions. In: Network and Service Management (CNSM) 2014 10th International Conference on. Rio de Janeiro (Brazil), November 2014