INFORMATION
Volume 18, Number 8, pp.3507-3522

ISSN 1343-4500
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Proposal and Evaluation of a Virtual Router Migration Policy in IP Networks equipped with Adaptive Link Rate Line Cards

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Abstract

The design of an energy efficient IP network is one of the most important challenge that researchers have begun to address in the last decades. A promising resource consolidation technique to improve the energy efficiency of Internet is based on the virtual router migration: when traffic decreases virtual routers are moved and consolidated in fewer nodes of the underlying physical network in order to turn off empty physical nodes. Unfortunately the migration of virtual routers involves reconfiguration costs depending on implementation details and characterized, for instance, by the revenue loss due to Quality of Service (QoS) degradation during the migration process. In this paper we propose a methodology for the evaluation of migration policies taking into account both the operation (in terms of energy consumption) and reconfiguration costs. The technique is applied in networks in which the line cards of the routers implements the Adaptive Link Rate (ALR) technique and whose power consumption is traffic dependent.

Keywords : virtual router, adaptive link, migration policy, power consumption

1 Introduction

The deployment of services based on IP network has resulted in an exponential growth of its users number in the last decade. The consequent growth of network equipment made sure that IP energy consumption became a not negligible factor and the economic and environmental implications have stimulated the researchers to study this problem [1]. The modern IP network suffers also from the well-known ossification problem. A promising technique to overcome this problem is the Network Virtualization: different instances of Virtual Networks (VNs), composed by virtual routers (VRs) connected through virtual links (VLs), are mapped on a physical network [2]. Internet Service Providers are really interested in this kind of solution because it can bring to a better service diversification and management. Routers virtualization techniques, able to divide the physical router resource into multiple isolated and independent virtual instances, have been used for energy saving purpose. In particular, once a virtual network is mapped on the substrate one and the traffic in the network decreases, we can apply a resource consolidation strategy that moving VR from a Substrate Node (SN) to another and reconfiguring the related VL allows for turning off idle substrate nodes and saving energy [3]-[4]. Technique of power saving based on the virtualization and migration have been studying in datacenter environment [5] where virtual machines are consolidated in few servers in the low traffic periods [6]-[8]. In these studies only server processing and memory capacity constraints are taken into account when virtual machines are moved among servers. Conversely when these techniques are applied in telecommunication networks, link capacity constraints have to be also considered. The problem of determining in which SNs the VRs have to migrate to minimize the network power consumption under a given traffic condition is referred to as optimal VR migration problem. It is possible to prove that this problem is NP-Hard [6]. For this reason we have developed an heuristic [1] that allows the VR migration problem to be solved in low time computational complexity.

The migration of virtual networks involves reconfiguration costs that derive from the potential degradation of quality of service during the migration process [9] that could, in turn, lead to the a revenue loss for the network operator. When these migration costs are significant, it may be better not to migrate a VN despite the potential for energy savings. A virtual network *migration policy* would aim to manage this trade-off between reduced operations cost due to energy savings and network migration costs due to QoS degradation.

The main contributions of this paper are the following: i) to introduce a methodology for the evaluation of migration policies with the aim of minimizing the sum of the network operation (in terms of energy consumption) and reconfiguration costs; the objective of the migration policy is to choose in each day period one among some possible mappings of VRs in SNs; ii) to extend the proposed heuristic in [1] for the evaluation of the candidate mappings with the possibility of turning off SNs hosting more than one VR that leads to explore a higher number of SNs candidate to be turned off; iii) to study the benefits of the virtual router migration technique when jointly used with the Adaptive Link Rate (ALR) technique that consist in the capabilities of router line-cards to perform power management (sleep modes, clock gating, speed scaling) as a function of traffic load [10].

The rest of the paper is organized as follows. The proposed mapping policy is described in Section 2. We show in Section 3 the virtual router migration technique and describing the main steps of an heuristic that determines which VRs have to migrate and in which SN the migration has to occur. Section 4 is devoted to results and comments. The conclusions and future research items are finally reported in Section 5.

2 Proposal of a Migration Policy

Virtual Router (VR) migration is a really promising technique to improve energy efficiency in IP networks. The most part of modern physical routers can host instances of virtual routers generally using software or firmware called hypervisor whose function is to divide the physical resources and manage the access of VRs to those resources. In this context the task of virtual network mapping consists in creating instances of virtual routers on the substrate nodes, properly selected, and route the Virtual Links (VL) on the physical paths. Exploiting the daily traffic fluctuation in IP networks and the VR migration technique we have defined a power consumption saving solution [1]. When the traffic decreases, and the network resources are not all necessary, a certain number of VRs are moved from a substrate node device to another, as well as the related VLs are remapped on new physical paths in the network, in order to consolidate resources and save power. Clearly the migration has to be performed so that a given level of Quality of Service (expressed in terms of delay and packet loss) is guaranteed and that leads to satisfy link and node processing capacity constraints.

We show examples of mappings in Fig. 1 where we report a Substrate Network (SN) (Fig. 1.a) composed of 4 physical routers and 5 links and a Virtual Network (VN) (Fig. 1.b) composed of 4 virtual routers and 6 virtual links respectively. The use of resources of the VN in the SN is represented in Fig. 1.c and Fig. 1.d in high and low traffic conditions respectively. In the case of high traffic condition all the network resources are active and each virtual router uses one physical router in a dedicated way. Conversely during a low traffic condition the use of shared resource allows for the switching off of some physical routers (R2,R3), links (R1-R3, R3-R4,R1-R2, R2-R4). Some virtual routers, virtual links use the remaining resources in a shared way. For instance the virtual routers VR1,VR2 and VR3,VR4 are in execution on the same physical routers R1 and R4 respectively. Furthermore all of the virtual links are mapped on link R1-R4 except the virtual links VR1-VR2 and VR3-VR4 that are supported inside the router R1 and R2 respectively. The migration of virtual networks involves reconfiguration

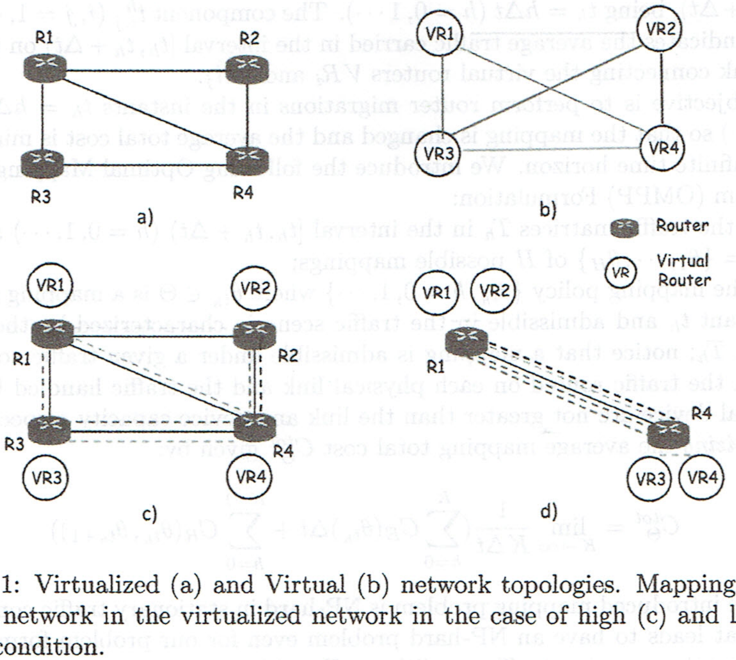

Figure 1: Virtualized (a) and Virtual (b) network topologies. Mapping of the virtual network in the virtualized network in the case of high (c) and low (d) traffic condition.

costs that derive from the potential degradation of quality of service during the migration process [9]. For this reason migration policies have to defined that aim to manage this trade-off between reduced operations cost due to energy savings and network migration costs due to QoS degradation.

Before illustrating what we intend for optimal migration policy, we introduce the following notations. N_{PHY}, number of physical devices; PHY_i $(i = 1, \cdots, N_{PHY})$: $i-th$ physical device; $\Lambda_{PHY} = \{PHY_i, i = 1, \cdots, N_{PHY}\}$, set of physical devices; E, set of physical links; $G_{PHY}(\Lambda_{PHY}, E)$, directed graph representing the physical network; $N^{max}_{i,j}$, maximum number of paths in the physical network between the physical nodes PHY_i and PHY_j; $\wp^h_{i,j}$ $(i, j = 1, \cdots, N_{PHY}; h = 1, \cdots, N^{max}_{i,j})$, $h-th$ path between the physical nodes PHY_i and PHY_j; N_v, number of virtual routers; VR_i $(i = 1, \cdots, N_v)$, $i-th$ virtual router; $\Lambda_{VR} = \{VR_i, i = 1, \cdots, N_v\}$, set of virtual routers; E_v, set of virtual links; $G_V(\Lambda_{VR}, E_v)$, directed graph representing the virtual router network.

A mapping Γ of $G_V(\Lambda_{VR}, E_v)$ in $G_{PHY}(\Lambda_{PHY}, E)$ determines in which physical devices, the virtual routers are hosted and in which network paths the virtual links are routed. Formally the mapping Γ can be represented by the vector M^{VR}_Γ and the matrix M^L_Γ. The component $m^{VR}_\Gamma(i)$ $(i = 1, \cdots, N_v)$ of M^{VR}_Γ is an integer reporting the index of the physical device in which VR_i is hosted, that is VR_i is in the physical device $PHY_{m^{VR}_\Gamma(i)}$; the component $m^L_\Gamma(i, j)$ $(i, j = 1, \cdots, N_v)$ of M^L_Γ is an integer reporting the index of the physical path in which the logical link between VR_i and VR_j is routed; in particular the logical link between VR_i and VR_j is routed on the path $\wp^{m^L_\Gamma(i,j)}_{m^{VR}_\Gamma(i), m^{VR}_\Gamma(j)}$.

We also define with $C_E(\theta)$ and $C_R(\theta_i, \theta_j)$ the cost per time unit of the mapping θ and the cost characterizing a mapping change from θ_i to θ_j when router migration occurs respectively. We assume the traffic to be stationary within intervals of duration Δt [11] and we denote with T_h the traffic matrix in the interval $[t_h, t_h + \Delta t)$, being $t_h = h\Delta t$ $(h = 0, 1 \cdots)$. The component $t^h_{i,j}$ $(i, j = 1, \cdots, N_v)$ of T_h indicates the average traffic carried in the interval $[t_h, t_h + \Delta t)$ on the logical link connecting the virtual routers VR_i and VR_j.

The objective is to perform router migrations in the instants $t_h = h\Delta t$ $(h = 0, 1, \cdots)$ so that the mapping is changed and the average total cost is minimized over infinite time horizon. We introduce the following Optimal Mapping Policy Problem (OMPP) Formulation:

Given the traffic matrices T_h in the interval $[t_h, t_h + \Delta t)$ $(h = 0, 1, \cdots)$ and the set $\Theta = \{\theta_1, \cdots, \theta_H\}$ of H possible mappings;

Find the mapping policy $\{\theta_{t_h}, h = 0, 1, \cdots\}$ where $\theta_{t_h} \in \Theta$ is a mapping applied in instant t_h and admissible in the traffic scenario characterized by the traffic matrix T_h; notice that a mapping is admissible under a given traffic condition if both the traffic routed on each physical link and the traffic handled by each physical device are not greater than the link and device capacity respectively.

Minimizing the average mapping total cost C^{tot}_Θ given by:

$$C^{tot}_\Theta = \lim_{K\to\infty} \frac{1}{K\Delta t}\left(\sum_{h=0}^{K} C_E(\theta_{t_h})\Delta t + \sum_{h=0}^{K-1} C_R(\theta_{t_h}, \theta_{t_h+1})\right) \qquad (1)$$

The introduced mapping problem is NP-hard in stationary traffic conditions [12] that leads to have an NP-hard problem even for our problem formulation based on time-varying traffic conditions. For this reason we provide a solution of the previously introduced problem under the cycle-stationary traffic scenario assumption. It is well-known that traffic matrices in backbone networks exhibit strong diurnal patterns and are typically cycle-stationary [11] with cycle period T and with stationary characteristics in intervals of duration Δt. Typically we have values of T and Δt equal to 24 hour and 1 hour respectively. For this reason we illustrate how we can solve the introduced mapping problem under the assumption of cycle-stationary traffic. We denote with Q the number of intervals after which the same traffic characteristic occurs again. We can model the cycle-stationary traffic with the state diagram represented in Fig. 2. We assume that in the instant t_0 the traffic related to the state S_0 is offered to the virtual networks. State transitions occur towards the states S_h $(h = 1, \cdots, Q-1)$ in the successive instants $t_h = h\Delta t$ $(h = 1, \cdots, Q-1)$ up to the instant t_Q in which the system comes back in state S_0 and so on; in particular the system will be in state $S_{h \bmod Q}$ in the instant t_h. The choice of the mappings belonging to the set $\Theta=\{\theta_1, \cdots, \theta_H\}$ is accomplished by applying optimality criteria based on minimization of power consumption; not all of the mappings in Θ can be applied in any state S_h but only the admissible ones that satisfy both link and node processing capacity constraints; we denote with $\theta_{h,l}$ $(l = 1, \cdots, n_h)$ the n_h mappings belonging to Θ and admissible for the traffic condition S_h $(h = 0, \cdots, Q-1)$; the state diagram reported in Fig. 3 represents the set of admissible mappings for each traffic state; it is organized in Q levels where the $h-th$ $(h = 0, 1, \cdots, Q-1)$ level is composed by the n_h bi-dimensional states $(S_h, \theta_{h,l})$ $(l = 1, \cdots, n_h)$.

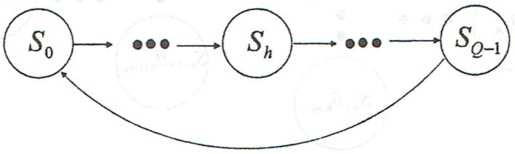

Figure 2: State diagram characterizing a cycle-stationary traffic. S_h is the generic traffic state.

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 $\mathcal{D} = \{d_{h,l} \quad h = 0, 1 \cdots, , Q-1; l = 1, 2, \cdots, n_h\}$ where $d_{h,l}$ establishes that from the state $(S_h, \theta_{h,l})$, the mapping $\theta_{(h+1) \bmod Q, d_{h,l}}$ has to be applied when the new traffic condition $S_{(h+1) \bmod Q}$ occurs. We can represent the policy $\mathcal{D}$ by adding an arrow between all of the state couples $(S_h, \theta_{h,l})$ and $(S_{(h+1) \bmod Q}, \theta_{(h+1) \bmod Q, d_{h,l}})$ in the state diagram of Fig. 4. For instance we report an example of policy in Fig. 4 in the case of parameter values Q=3, n_0=1, n_1=3 and n_2=2. The policy is expressed by the set of integer values $\mathcal{D}=\{d_{0,1}=1, d_{1,1}=2, d_{1,2}=1, d_{1,3}=2, d_{2,1}=1, d_{2,2}=1\}$.

Next we introduce the policy $\mathcal{D}^{loc}$ based on the local cost minimization respectively. Conversely a policy based on the global cost minimization has been proposed in [9].

When a state transition from the state $(S_h, \theta_{h,l})$ occurs, the operation mode of the policy $\mathcal{D}^{loc}$ consists in choosing the mapping that minimizes the sum of the following two cost components: i) the reconfiguration cost involved if an mapping change is performed and the mapping chosen in the traffic state $S_{(h+1) \bmod Q}$ is different from $\theta_{h,l}$; ii) the cost of the mapping chosen in the traf-

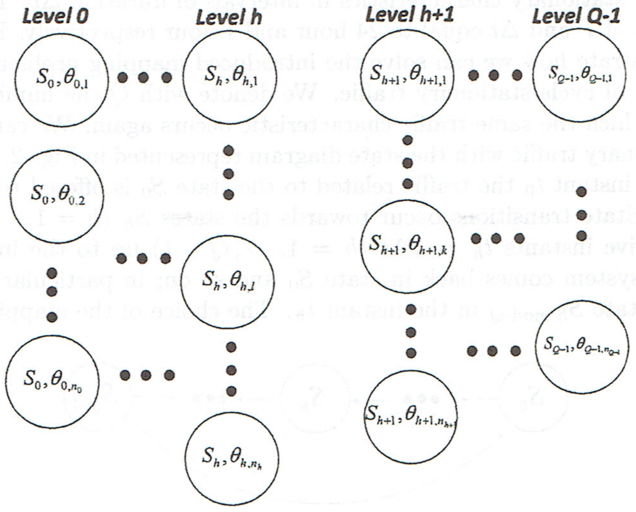

Figure 3: The state $(S_h, \theta_{h,l})$ denotes that in the traffic condition S_h the mapping $\theta_{h,l}$ is applied.

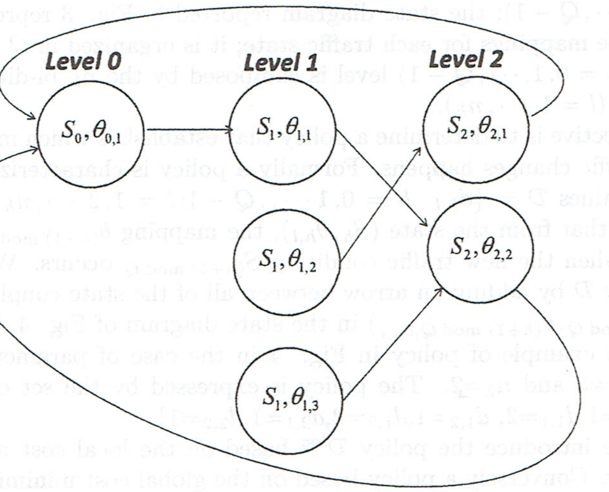

Figure 4: An example of mapping policy characterized by $\mathcal{D}=\{d_{0,1}=1, d_{1,1}=2, d_{1,2}=1, d_{1,3}=2, d_{2,1}=1, d_{2,2}=1\}$

fic state $S_{(h+1) \bmod Q}$. The policy $\mathcal{D}^{loc}$ is characterized by the following integer values $d^{loc}_{h,l}$:

$$d^{loc}_{h,l} = \arg \min_{j \in [1..n_{(h+1) \bmod Q}]} (C_R(\theta_{h,l}, \theta_{(h+1) \bmod Q,j}) + C_E(\theta_{(h+1) \bmod Q,j}))$$
$$h = 0, 1 \cdots, , Q-1; l = 1, 2, \cdots, n_h \qquad (2)$$

Finally notice that the application of the local policy $\mathcal{D}^{loc}$, being based on a local cost minimization, needs only the knowledge of the traffic matrix in the state $S_{(h+1) \bmod Q}$ while it is not requiring the knowledge of the traffic matrices over the overall temporal horizon.

3 MEE Heuristic for Resource Consolidation in a Virtual Router Network

Next we propose an heuristic allowing resource consolidation when the traffic decreases. We will use this heuristic to evaluate the mappings belonging to the set $\Theta=\{\theta_1, \cdots, \theta_H\}$. We apply virtual router migrations to consolidate resource in low traffic scenario. It is well-known the VR migration problem belongs to the NP-Hard class and it can be solved just for substrate/virtual networks with few nodes. In this paper we propose an extension of a previous heuristic, referred as Maximum Energy Efficiency (MEE) [1]. The main limitation of MEE is to try the turning off of only a subset of substrate nodes, the ones that at a given instant host one VR only. The new heuristic proposed in this paper allows for the turning off of substrate nodes that host more than one VR with the consequence of trying the turning off of all of the physical nodes. We refer to the new heuristic as Maximum Energy Efficiency and Multiple Migrations (MEEMM). The main steps of MEEMM are reported in Algorithm 1. In order to describe our heuristic we introduce some notations. We assume the same number N of VRs and SNs. In particular the virtual and substrate networks are overlapped in the maximum traffic scenario with one only VR mapped on one only SN. We introduce the following other notations: $\lambda_{VR_n}(n = 1, \ldots, N)$, total traffic incoming/outgoing in/from VR_n; $\Lambda^{VR}_{PHY_n}$, set of VRs hosted in PHY_n; $\Psi_{PHY_n}(n = 1, \ldots, N)$, set of SNs that are possible destination of VRs hosted in PHY_n; $s_{max} = max_{i \in \{1..N\}} Card(\Psi_{PHY_i})$, the maximum cardinality among sets Ψ_{PHY_i} with $i = 1, \ldots, N$; λ_{PHY_n}, total traffic incoming/outgoing in/from all the VRs hosted in PHY_n; $\lambda^{max}_{PHY_n}$, maximum processing capacity of the SN PHY_n.

The MEEMM heuristic is based on the energy efficiency parameter $\eta_{PHY_n}(n = 1, \ldots, N)$ of an SN defined as

$$\eta_{PHY_n} = \frac{\lambda_{PHY_n}}{P^{tot}_{PHY_n}}, \qquad (3)$$

where $P^{tot}_{PHY_n}$ is the total power consumed by the substrate node PHY_n that is given by.

$$P^{tot}_{PHY_n} = P^{C,RP}_{PHY_n} + \sum_{l=1}^{L_n} P^{LC}_{n,l}(\rho_l), \qquad (4)$$

Algorithm 1 Maximum Energy Efficiency and Multiple Migrations

```
1:  /*Initial mapping phase of VRs and virtual link in substrate nodes
    and substrate paths*/
2:  map each virtual router $VR_n$ on the corresponding substrate node $PHY_n$
3:  map each virtual link in the substrate shortest path
4:  /*Substrate node turning off phase*/
5:  while $\Lambda_{PHY} \neq \emptyset$ do
6:    find $PHY_n \mid \eta_{PHY_n} = \min_{PHY_s \in \Lambda_{PHY}} \eta_{PHY_s}$
7:    $\zeta = \Psi_{PHY_n}$
8:    while $\zeta \neq \emptyset$ do
9:      find $PHY_m \mid \eta_{PHY_m} = \max_{PHY_s \in \zeta} \eta_{PHY_s}$
10:     if $(\lambda_{PHY_m} + \lambda_{PHY_n} \leq \lambda^{max}_{PHY_m}) \wedge$ (the substrate shortest path to/from
        $PHY_m$ carrying the traffic to/from any $VR \in \Lambda^{VR}_{PHY_n}$ can be set up
        according to link capacity constraints) then
11:       for each $VR_s \in \Lambda^{VR}_{PHY_n}$ do
12:         map $VR_s$ into $PHY_m$
13:       end for
14:       turn off $PHY_n$
15:       for each $PHY_s \in \Lambda_{PHY}$ do
16:         update $\eta_{PHY_s}$, $\lambda_{PHY_s}$, $\Psi_{PHY_s}$
17:       end for
18:       go to line 23
19:     else
20:       $\zeta = \zeta \setminus \{PHY_m\}$
21:     end if
22:   end while
23:   $\Lambda_{PHY} = \Lambda_{PHY} \setminus \{PHY_n\}$
24: end while
```

where $P^{C,RP}_{PHY_n}$ is the power consumed by the chassis and the route processor of PHY_n, L_n is the number of active incoming/outgoing links and $P^{LC}_{n,l}(\rho_l)$ is the power consumed by the $l-th$ Line Card. We assume to use ALR Line Cards so that the term $P^{LC}_{n,l}(\rho_l)$ is dependent by the link utilization coefficient ρ_l, given by the ratio of the traffic handled in Line Card $l-th$ to the link capacity. Formally we express $P^{LC}_{n,l}(\rho_l)$ as follows:

$$P^{LC}_{n,l}(\rho_l) = \begin{cases} 0 & if\ \rho_l = 0 \\ P^{LC}_{max,l}(a + (1-a)\rho_l^H) & if\ \rho_l > 0 \end{cases} \tag{5}$$

where the power consumption of the Line Card is zero when it is turned off (ρ_l=0), otherwise its consumption is equal to the sum of a constant contribution, referred to as base power, and a term depending on ρ_l according to a law determined by the coefficient H. In particular H=1 and H=2 denote linear and quadratic trends respectively. The parameter $P^{LC}_{max,l}$ is the $l-th$ Line Card power when the link is 100% loaded ($\rho_l = 1$). The parameter a appearing in expression (5) is the ratio of the base power to the maximum power $P^{LC}_{max,l}$ of the $l-th$ Line Card.

In the rest of this section we illustrate the main steps of the MEEMM Heuristic. The first part of the algorithm is dedicated to map the VRs on the corresponding SNs (line 2) and the virtual links on the substrate paths. The MEEMM heuristic chooses as first candidate to be turned off the substrate node PHY_n with the minimum value of the energy efficiency parameter η_{PHY_n} (line 6). Then it starts exploring the set of substrate nodes $\Psi_{PHY,n}$ in order to find a destination for all the VRs hosted in PHY_n, that have to be moved in order to turn off PHY_n. In particular the nodes in Psi_{PHY_n} are explored in decreasing order of their value of energy efficiency parameter (line 9). Starting from the first node in the set, the algorithm verifies if the capacity constraints on the node and on the links are satisfied (line 10). In particular it verifies that the substrate node PHY_m, possible destination of the migration, has the capacity to manage the the incoming/outgoing traffic of all the VRs hosted in PHY_n and migrating on it. The other constraint is related to the possibility of rerouting the virtual links afferent to the migrating VRs on the substrate shortest paths towards the physical node PHY_m. If these constraints are satisfied, the VRs in PHY_n are moved in PHY_m (line 11-13) and PHY_n can be turned off (line 14). The sets and the values of parameters related to substrate nodes and links involved in the VRs migration process are properly updated (line 16). Unlike the previous MEE heuristic, in this case we allow the migration of multiple VRs from a substrate node to another so that in each iteration of the algorithm we remove from the set Λ_{PHY} only the substrate node PHY_n whether it has been turned off or not (line 23). This second case is due to avoid too long simulations. The algorithm stops when the set Λ_{PHY} becomes empty (line 5). Finally we report a complexity analysis of the proposed algorithm, when the logical links are remapped on the substrate shortest paths using the Dijkstra algorithm. We can observe that: i) the proposed heuristic performs N steps in which at each step the least energy efficient substrate node, among the ones still switched on, is selected; the complexity of these operations is $O(N^2)$; ii) the substrate nodes in which the VRs, hosted in the substrate node to be turned off, can migrate, are selected in order decreasing of energy efficiency; the complexity of these operations is $O(s^2_{max})$; iii) to verify whether any substrate node can be turned off, the MEEMM heuristic has to check whether the VRs hosted in the node can be moved toward another substrate node; this requires the evaluation of at most N substrate shortest paths because N is at most the number of VRs hosted in any substrate node; iv) if a binary heap structure is used to store the candidate list in the Dijkstra algorithm then its complexity is $O(MlogN)$, where N and M are the number of nodes and links of the network. According to these remarks, we can conclude that the time computational complexity of the MEEMM heuristic is $O(N^3 M s_{max}^2 logN)$.

4 Numerical Results

We compare the local mapping policy $\mathcal{D}^{loc}$ to the traditional mapping policies $\mathcal{D}^{ac}$ and $\mathcal{D}^{nc}$ referred to as *Always-Change Policy (ACP)* and *Never-Change Policy (NCP)*. When the ACP policy is adopted, a new mapping is always performed in the case in which a traffic variation happens; the chosen mapping is the one minimizing the energy consumption in that traffic scenario. The NCP policy always adopts the mapping relative to the peak hour traffic scenario so that the reconfiguration costs are equal to zero.

We consider the COST266 topology, reported in Fig. 5.a and composed by 37 nodes and 114 links, as virtual and substrate network [13].

The link and node processing capacities are dimensioned to support peak hour traffic. In this traffic scenario the virtual and substrate networks are identical and each VR is mapped on one and one only SN. We assume that the traffic is uniformly distributed between each couple of VRs and it is routed on the shortest paths of the virtual network. The traffic is scaled so that the most loaded

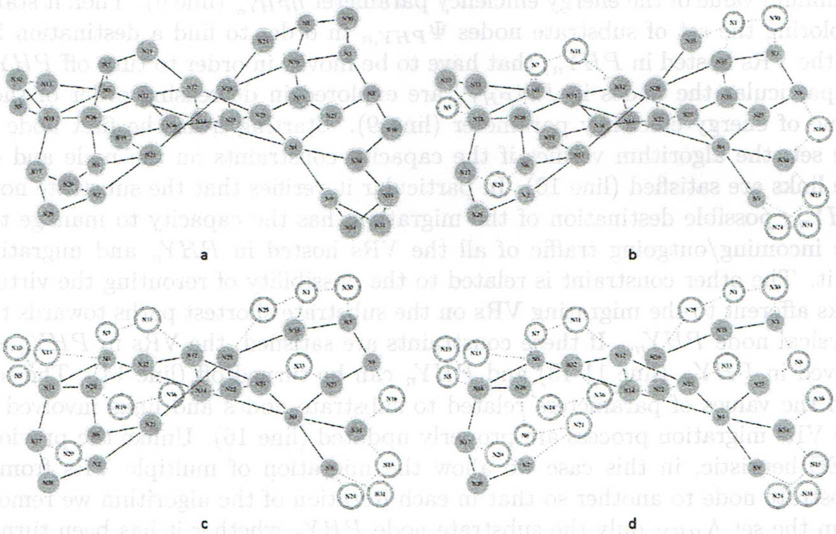

Figure 5: COST266 network topology (a) with 37 nodes and 114 links. Consolidation of VRs in SNs in the case of a=1 and traffic reduction parameter values $b(h)$=0,6 (b), $b(h)$=0,4 (c), $b(h)$=0,2 (d). White circles represent the switched off nodes.

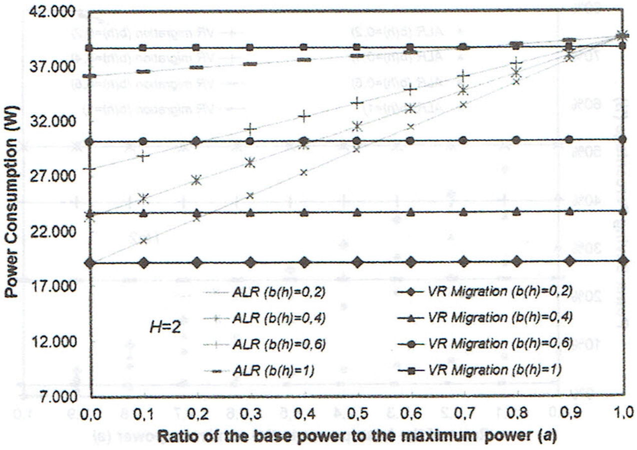

Figure 6: Network power consumption as a function of a in the case in which only the Adaptive Link Rate (ALR) and the VR migration techniques are applied separately. The chosen parameter values of the router consumption model are H=2 and $b(h)$ equal to 0,2, 0,4, 0,6 and 1.

substrate link carries a 10Gb/s traffic. Any link capacity is dimensioned with the minimum number of Gigabit Ethernet Line Cards so as to accommodate the aggregated traffic passing on it. The maximum processing capacity of all of the SNs is assumed to be the one of the most loaded SN. For the fixed contributions of our power consumption model we assume $P_{PR}^{C,RP}$=400W and P_{max}^{LC}=30W [1] that are typical values of power consumption in market core routers.

In order to study the effectiveness of introduced migration policy in reducing the total cost, we assume of scaling the traffic matrix used for the dimensioning of the substrate network by a factor $b(h)$, referred to as traffic reduction ratio. To characterize a classical daily traffic profile we assume the following values of $b(h)$ $(h = 0, 1, \cdots, Q - 1)$:

$$b(h) = \begin{cases} 1 & if \quad h = 0 \\ 1 - 2\frac{h}{Q}(1 - b_{min}) & h = 1, \cdots, \frac{Q}{2} \\ 1 - 2\frac{Q-h}{Q}(1 - b_{min}) & h = \frac{Q}{2} + 1, \cdots, Q - 1 \end{cases} \tag{6}$$

with the parameter Q assuming even values. Notice that $b(0)$=1 and $b(\frac{Q}{2})$=b_{min} denotes the scale factors in the peak and least traffic conditions respectively.

The set Θ of mappings are evaluated as follows. By applying router virtual migration technique illustrated in Section 3, we obtain a mapping for each traffic scenario characterized by a value of the parameter $b(h)$. Due to the symmetric traffic conditions $b(h)$=$b(Q - h)$ $(h = 1, \cdots, \frac{Q}{2} - 1)$, we have totally $\frac{Q}{2} + 1$ mappings characterizing the set Θ=$\{\theta_0, \theta_1, \cdots, \theta_{\frac{Q}{2}}\}$ where θ_h is the mapping evaluated when the traffic scale factor is equal to $b(h)$.

Initially we show for each value of $b(h)$ the power saving that the ALR and VR migration techniques allow us to obtain when applied separately. In Figs. 6 and 7 we report the power consumed and the power saving with respect to the peak hour traffic scenario respectively as a function of the parameter a, the ratio

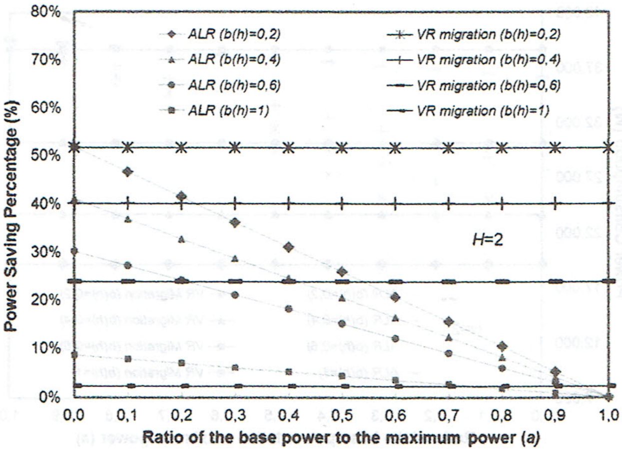

Figure 7: Power saving percentage as a function of a achieved when the ALR and VR migration technique are applied separately and in the case in which the chosen parameter values are H=2 and $b(h)$ equal to 0,2, 0,4, 0,6 and 1.

of the base power to the maximum power of any Line Card. In particular if a=1 it means that the Line Cards of the network do not support ALR techniques and their power consumption are constant and independent of the offered traffic. The grey curves in the Figs. 6 and 7 represent the power consumed when the substrate nodes are equipped with ALR Line Cards and the black curves show the consumption when the VR migration technique is used. Obviously these last curves are constant and independent of a. We choose values of $b(h)$ equal to 0,2, 0,4, 0,6 and 1. Further we assume that the power consumed by the Line Cards grows versus the offered traffic on the related link according to a quadratic trend (H=2). As expected, we can notice from Fig. 6 that when the base power decreases ($a \rightarrow 0$), the power consumption of ALR Line Cards decreases. Clearly this trend is more evident when the traffic reduction ratio $b(h)$ increases. The ALR technique allows for a power saving even in the traffic scenario $b(h)$=1. That is consequence of the use of a modular capacity and multiple of 1 Gb/s that does not allow the saturation of the link capacities even during the peak hour.

It is still evident that the ALR technique shows better performance when a is low and for higher values of $b(h)$ with the possibility in this case of employing the spare capacity better than the VR migration technique. For instance in the extreme case of $b(h)$=1 and a=0, the ALR technique allows for a power saving of 8% while the VR migration technique is not effective in moving virtual routers leading to a power saving of 1% only.

Next we show the results in the case in which the ALR and VR migration techniques are applied jointly. The power consumption is reported in Fig. 8 in the cases in which the only ALR technique is applied (grey lines) and when ALR and VR migration techniques are applied jointly (black lines). In Fig 9 we report the percentage of saved power due to the application of the ALR and the VR migration techniques respectively, compared with the power consumed by the network at the peak hour ($b(h)$=1) without any energy saving strategy

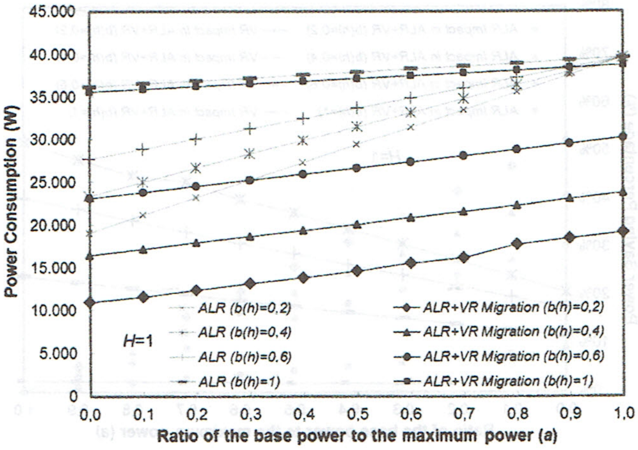

Figure 8: Network power consumption as a function of a in the case in which only the Adaptive Link Rate (ALR) technique and both ALR and VR migration techniques are applied. The chosen parameter values of the router consumption model are H=1 and $b(h)$ equal to 0,2, 0,4, 0,6 and 1.

(a=1). In this case study the value of the parameter H is chosen to be equal to 1. It is evident that the two sets of curves have an opposite trend, in particular for low values of a ALR reaches higher percentage of saved power with respect to the VR migration technique. Conversely when a increases the VR migration technique provides higher power saving percentage. For example when a=0,1 and $b(h)$=0,6 the ALR and the VR migration techniques allows 27% and 13% power saving respectively. For a=0,9 and $b(h)$=0,6 the power saving percentage becomes 3% and 23% respectively.

Next we report some curves of the total cost of the introduced migration policy $\mathcal{D}^{loc}$ compared to the two classical policies $\mathcal{D}^{ac}$ and $\mathcal{D}^{nc}$. We give the following meaning to the operation and reconfiguration costs. The operation cost depends only on the applied mapping and characterizes the cost of the power consumption. In particular we assume a cost of one cost unit (c.u.) per Watt of power consumed. The reconfiguration cost characterizes the revenue loss that a network operator has to tackle for the QoS degradation due to the virtual routers migration. The degradation is a consequence of the information loss occurring in the migration downtime DT [9] in which the virtual router is not able to carry on its function. For this reason the reconfiguration cost is given by the lost data amount migrated during the downtime expressed in Gbit multiplied the factor σ that is the cost expressed in c.u. that the network operator has to undergo due to the loss of 1 Gbit of information.

The total cost of the policies $\mathcal{D}^{loc}$, $\mathcal{D}^{ac}$ and $\mathcal{D}^{nc}$ is reported when the following parameter values are chosen: $T = 24h$, $N = 16$, $\Delta t = 1,5h$, $b_{min} = 0,2$, DT=2sec, a=0,2. We report in Figs 10 and 11 the cases H=1 and H=2 respectively. From the figures we can notice that though the policy $\mathcal{D}^{loc}$ may have performance worse than the policy $\mathcal{D}^{ac}$ for low values of σ, it is able to limit the reconfiguration costs in the case of high values of σ that leads to have a total cost lower than or equal to the one of the policy $\mathcal{D}^{nc}$.

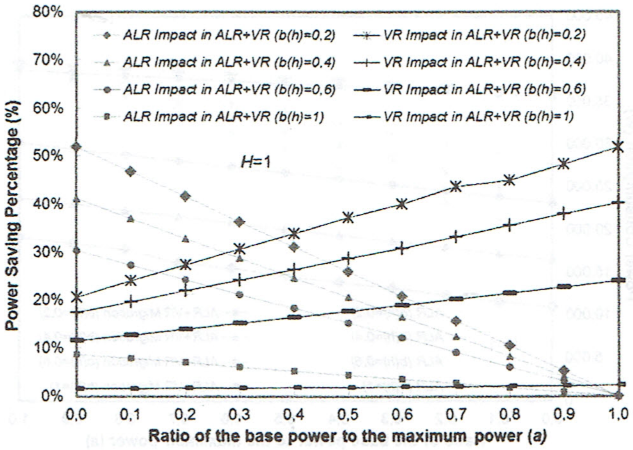

Figure 9: Power saving percentage as a function of a achieved when the ALR and VR migration technique are applied jointly and in the case in which the chosen parameter values of the router consumption model are H=1 and $b(h)$ equal to 0,2, 0,4, 0,6 and 1.

5 Conclusion

The contribution of this paper is twofold. First we have defined and evaluated a migration policy to reduce the reconfiguration costs due to data loss during the migration of the VRs. We have also studied the performance of two power saving strategies for IP networks when applied together. The first one is the ALR technique that guarantees a power consumption dependent on the offered traffic on the related links. The second strategy is the VR migration technique that allows the consolidation of VRs in fewer substrate nodes in low traffic scenario. We proposed the MEEMM heuristic that moves VRs among substrate nodes considering their energy efficiency and allowing multiple migrations from any physical node. Our results show that when the base power of ALR Line Cards is low the ALR technique gives better performance than the VR migration technique, in terms of power saved in the network. On the contrary when the base power grows, reaching the maximum power of the Line Cards, the VR migration technique provides better performance than ALR. Finally we have shown how the introduced migration policy is effectiveness in reducing the reconfiguration costs.

ACKNOWLEDGMENT

The work described in this paper was been funded in part by the National Science Foundation grant CNS-1319490 and by GreenNet FIRB (MUR) project.

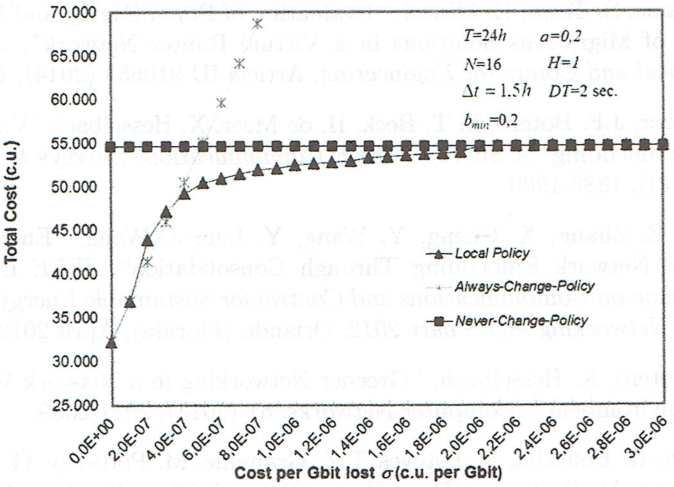

Figure 10: Total Cost as a function of the cost per Gbit lost σ when the following parameter values are chosen: $T = 24h$,$\Delta t = 1,5h$, $N = 16$, $b_{min} = 0,2$, a=0,2 and H=1. The results for the optimal, ACP and NCP policies are reported in the case of downtime values DT=2 sec.

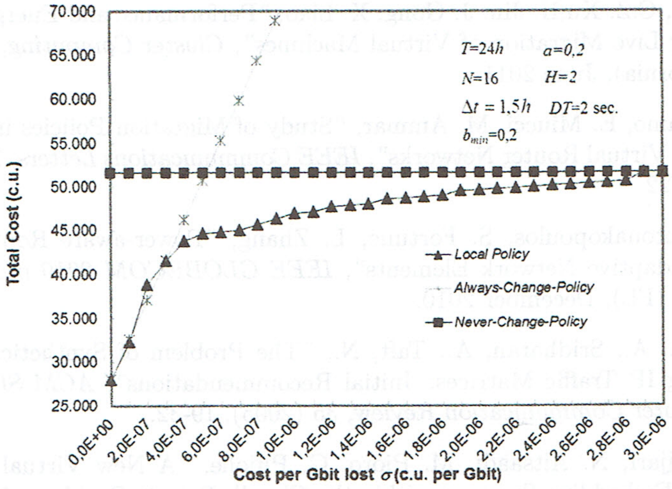

Figure 11: Total Cost as a function of the cost per Gbit lost σ when the following parameter values are chosen: $T = 24h$,$\Delta t = 1,5h$, $N = 16$, $b_{min} = 0,2$, a=0,2 and H=2. The results for the optimal, ACP and NCP policies are reported in the case of downtime values DT=2 sec.

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