

Energy Efficient Virtual Network Embedding

Juan Felipe Botero, Xavier Hesselbach, Michael Duelli, Daniel Schlosser, Andreas Fischer and Hermann de Meer

Abstract—Waste of energy due to over-provisioning and over-dimensioning of network infrastructures has recently stimulated the interest on energy consumption reduction by Internet Service Providers (ISPs). By means of resource consolidation, network virtualization based architectures will enable energy saving. In this letter, we extend the well-known virtual network embedding problem (VNE) to energy awareness and propose a mixed integer program (MIP) which provides optimal energy efficient embeddings. Simulation results show the energy gains of the proposed MIP over the existing cost-based VNE approach.

Index Terms—Network Virtualization, Virtual Network Embedding, Green Networking, Mixed Integer Programming, Energy Efficiency.

I. INTRODUCTION

Rising energy costs and an increased ecological awareness recently have caused concerns about the energy consumption of network and service infrastructures. As a consequence, the reduction of energy consumption has become one of the prime priorities of ISPs. Current networks are designed for peak loads, making heavy use of over-provisioning to ensure proper operation even in the face of high demand. However, this causes a high resource under-utilization and, along with it, unnecessary energy consumption. The average link utilization in backbone networks of large ISPs is estimated to be around 30–40% [1]. This situation has substantially increased interest in the research field of green networking. Recent work has been devoted to reduce the energy expenditure in networking technologies and protocols [2].

Network virtualization [3], by means of resource consolidation (several virtual instances in one physical resource), will be an enabler for energy savings in future infrastructure networks. Applying virtualization of network resources leads to the problem of allocating virtual network demands to physical network resources, known as Virtual Network Embedding (VNE). Conducting the objective of the VNE to the minimization of the energy consumption, the physical network can

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This work has been supported by the Spanish Government, MICINN, under research grant TIN2010-20136-C03, the “Comissionat per a Universitats i Recerca del DIUE” from the “Generalitat de Catalunya”, the Social European Budget (“Fons Social Europeu”), by the European Network of Excellence Euro-NF FP7-ICT-2007-1, Grant No. 216366, the European FP7 MANTYCHORE, ALL4GREEN, Fit4Green and ResumeNet projects (Grant agreements No. 261527, 288674, 249020 and 224619 respectively). It has been also funded within the COMCON project by the Federal Ministry of Education and Research (BMBF) of the Federal Republic of Germany (Förderkennzeichen 01BK0917, GLab).

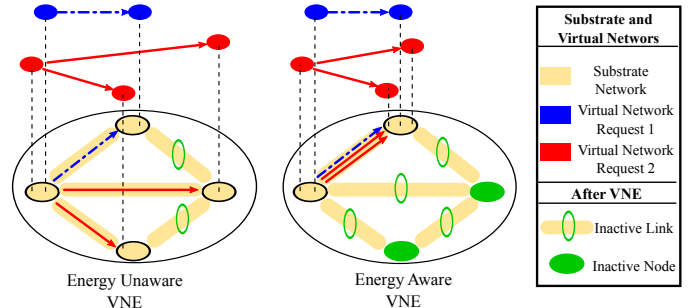


Fig. 1: VNE consolidating network resources

be dynamically dimensioned for current traffic demand rather than for peak demand. Due to current power consumption insensitiveness of network equipment to traffic load [4], the best approach to minimize the energy consumption is to switch off or to hibernate as many network nodes and interfaces as possible without compromising the network performance. The energy-aware dynamic network embedding will mainly exploit periods of low traffic demands, when some routers and interfaces can be switched off by rerouting the traffic to a smaller set of consolidated network equipment with increased utilization, as shown in Fig. 1.

By means of resource consolidation, network virtualization enables the energy efficient use of network infrastructure.

In this letter, we introduce the virtual network embedding energy aware problem (VNE-EA), where the goal is to allocate the set of virtual network requests in a reduced group of physical network equipment, and propose a Mixed Integer Program (MIP) to optimally solve it. Integer Linear Programs (ILPs) are in many practical situations, \mathcal{NP} -complete, therefore, the implementation of our VNE-EA model is not scalable for large scenarios. However, this exact formulation represents an optimal bound for future energy-aware VNE heuristics. To the best of our knowledge this is the first attempt to formulate VNE for energy awareness.

The remainder of this letter is organized as follows. In Section II, we present the VNE-EA problem and its MIP formulation. Section III presents the performance evaluation of the problem solution and its comparison with the exact solution of the cost-based VNE. Finally, Section IV concludes the letter and presents future work.

II. MODELING GREENER NETWORKS

A Virtual Network (VN) is a combination of network elements (nodes and links) on top of a Substrate Network (SN) where virtual nodes are interconnected through virtual links. The VNE deals with the efficient mapping of a set of Virtual Network Requests (VNRs) to substrate nodes (routers or switches with virtualization capabilities) and links. A VNR

is a set of virtual nodes that must be mapped to a set of substrate nodes with sufficient processing power (PP) resources to accomplish their PP demands, and a set of virtual links to be mapped to a set of paths in the substrate network with sufficient bandwidth resources to accomplish their bandwidth demands.

Embeddings can be optimized with regard to several parameters, such as: embedding cost, link bandwidth, energy-efficiency, security, etc.

Current approaches have solved VNE looking for the minimization of the sum of bandwidth and PP resources (commonly called **embedding cost**) spent by the substrate network to embed a VNR, in this way the spare resources of the SN increase as well as the probability of embedding the next VNR and, as a consequence, the percentage of rejected VNRs diminishes. A summary of the main VNE proposals can be found in [5].

In this paper, we go further by proposing a MIP formulation of the VNE for energy awareness where the objective is to realize the mapping of the virtual network in a small set of substrate node and links (called active resources). In this way the remaining unused interfaces and nodes can be deactivated by switching them off to minimize the overall network consumption of the substrate network.

For the sake of simplicity, we consider that network resources are homogeneous with regard to their energy consumption, this can be the case of substrate networks reduced to just one ISP segment (access, transport or core) where network equipment shares similar characteristics. Our model is proposed based on previous cost-based VNE formulations [6], [7].

The proposed MIP model looks for the minimization of the energy consumption by switching off as many network nodes and links as possible. It is worth noting that each time a link is switched off, energy is saved in the pair of interfaces on its ends (also switched off) and that the switching off of a node is not done independently of its interfaces (i.e. a node can be switched off, only when all its interfaces are also switched off).

VNE-EA Formulation

Inputs:

$G(V, A)$ and $G^k(V^k, A^k)$ are directed graphs indicating the topology of the substrate network and the VNR k respectively. $ND_{PP}(i^k)$ and $LD_{BW}(i^k, j^k)$ are the bandwidth and PP demands of the virtual node i^k and the virtual link (i^k, j^k) respectively, while $NR_{PP}(i)$ and $LR_{BW}(i, j)$ are the PP and bandwidth resources of the substrate nodes and links. $MaxDegree$ denotes the maximum node degree of the substrate network. NO_i and $LO_{(i,j)}$ are two binary parameters taking a value of '1' if the substrate node i - link (i, j) , respectively, is active before the mapping and '0' otherwise. $match(i^k)$ is the set of candidate substrate nodes available to map the virtual node i^k .

Variables:

$f_{i',j'}^{(i,j)}$ denotes the flow (bandwidth) mapped from substrate node i' to substrate node j' that passes through substrate

link (i, j) . $x_{i^k}^i$ is a binary variable indicating whether the virtual node i^k is allocated in the substrate node i . $LD_{BW}^{i,j}$ is the amount of bandwidth allocated from substrate node i to substrate node j that will support the demanded bandwidth of one or more virtual links (i^k, j^k) , $LD_{BW}^{i,j} = \sum_{(i^k, j^k) \in A^k} LD_{BW}(i^k, j^k) x_{i^k}^i x_{j^k}^j, \forall i, j \in V$.

$z_{(i^k, j^k)}^{i,j}$ is an auxiliary binary variable equal to $x_{i^k}^i \cdot x_{j^k}^j$ introduced to avoid the non-linearity of the formulation (see [6]). Finally, $\rho_{(i,j)}$ and α_i are binary variables indicating whether the substrate link (i, j) and node i , respectively, are activated after the mapping.

VNE-EA MIP

Objective Function

$$\min \sum_{i \in V: NO_i=0} \alpha_i + \sum_{(i,j) \in A: LO_{(i,j)}=0} \rho_{(i,j)} \quad (1)$$

The objective is to minimize the inactive substrate links and nodes that are activated after the mapping of one VNR is performed.

Constraints

Transformation Constraint:

$$\sum_{(i^k, j^k) \in A^k} LD_{BW}(i^k, j^k) z_{(i^k, j^k)}^{i,j} = LD_{BW}^{i,j}, \forall i, j \in V \quad (2)$$

Constraint (2) introduces the z variable to avoid the non-linearity on the formulation. Variable $LD_{BW}^{i,j}$ is also introduced in this constraint.

Flow Related Constraints:

- Source flow constraints:

$$\sum_{(i,h) \in A} f_{i,j}^{(i,h)} - \sum_{(h,i) \in A} f_{i,j}^{(h,i)} = LD_{BW}^{i,j}, \forall i, j \in V \quad (3)$$

- Destination flow constraints:

$$\sum_{(h,j) \in A} f_{i,j}^{(h,j)} - \sum_{(j,h) \in A} f_{i,j}^{(j,h)} = LD_{BW}^{i,j}, \forall i, j \in V \quad (4)$$

- Input-Output flow constraints:

$$\sum_{(i,l) \in A} f_{i',j'}^{(i,l)} = \sum_{(l,j) \in A} f_{i',j'}^{(l,j)}, \forall i', j' \in V, l \in V \setminus \{i', j'\} \quad (5)$$

Eqs. (3)- (5) are flow conservation constraints.

Constraints to ensure that $z_{(i^k, j^k)}^{i,j} = x_{i^k}^i x_{j^k}^j$:

$$\sum_{i \in V} z_{(i^k, j^k)}^{i,j} = x_{j^k}^j, \forall (i^k, j^k) \in A^k, \forall j \in V \quad (6)$$

$$\sum_{j \in V} z_{(i^k, j^k)}^{i,j} = x_{i^k}^i, \forall (i^k, j^k) \in A^k, \forall i \in V \quad (7)$$

$$x_{i^k}^i + x_{j^k}^j - z_{(i^k, j^k)}^{i,j} \leq 1, \forall (i^k, j^k) \in A^k, \forall i, j \in V \quad (8)$$

The correlation between variables x and z is introduced in constraints (6)- (8). $z_{(i^k, j^k)}^{i,j}$ will be 1 only if $x_{i^k}^i$ and $x_{j^k}^j$ are 1.

Capacity Constraints:

$$\sum_{i',j' \in V} f_{i',j'}^{(i,j)} \leq LR_{BW}(i,j) \rho_{(i,j)}, \forall (i,j) \in A \quad (9)$$

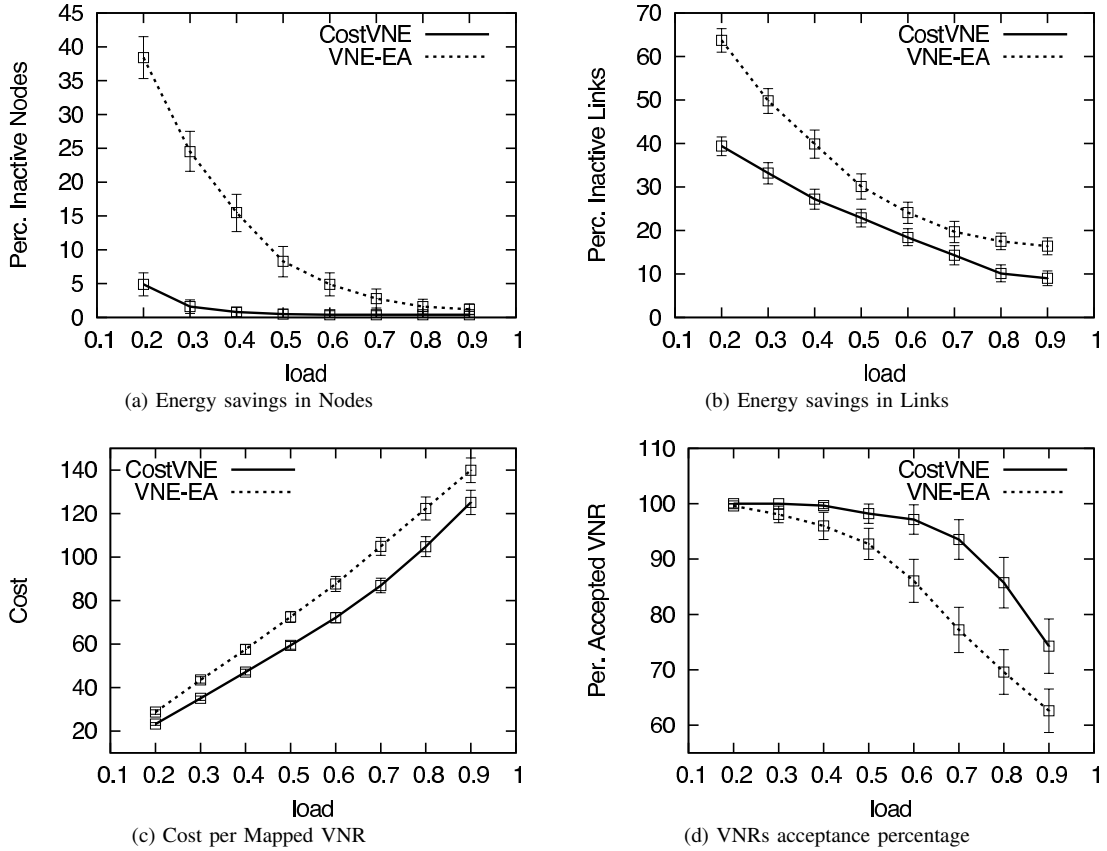


Fig. 2: Comparison between cost based and energy aware VNE

$$\sum_{i^k \in V^k} x_{i^k}^l ND_{PP}(i^k) \leq NR_{PP}(l), \forall l \in v \quad (10)$$

Node and link capacity constraints are indicated in (9) and (10). In (9) we assure that $\rho_{(i,j)}$ will be set to '1' when $\sum_{i',j' \in V} f_{i',j'}^{(i,j)} > 0$ (i.e. when substrate link (i,j) is active) and '0' otherwise.

One Substrate Node per Virtual Node Constraint:

$$\sum_{i \in V} x_{i^k}^i = 1, \forall i^k \in V^k \quad (11)$$

$$x_{i^k}^i = 0, \forall i \notin match(i^k) \quad (12)$$

Eq. (11) assures that just one substrate node is assigned to each virtual node while Eq. (12) makes sure that virtual node i^k is mapped from its candidate set.

Active substrate node constraints:

$$\sum_{(i,j) \in A} \rho_{(i,j)} + \sum_{(j,i) \in A} \rho_{(j,i)} \geq \alpha_i \quad (13)$$

$$\sum_{(i,j) \in A} \rho_{(i,j)} + \sum_{(j,i) \in A} \rho_{(j,i)} \leq \alpha_i \cdot MaxDegree \quad (14)$$

Finally, Eqs. (13) and (14) show the correlation between variables ρ and α , setting a node as active (switched on) when at least one of its incoming or outgoing links is also active.

III. PERFORMANCE EVALUATION

VNE-EA was implemented and evaluated using the ALEVIN framework¹ [5]. To evaluate its performance, instead of comparing VNE-EA against near-optimal cost-based heuristics, we compared it against an exact optimal VNE cost algorithm (CostVNE) [6] that minimizes the embedding Cost = $\sum_{(i,j) \in A} \sum_{i',j' \in V} f_{i',j'}^{(i,j)} + \sum_{i \in V} \sum_{i^k \in V^k} x_{i^k}^i ND_{PP}(i^k)$.

One would expect that the minimization of the embedding cost also minimizes the overall energy consumption based on the fact that it minimizes the consumed power processing and bandwidth needed to perform the VNE and, consequently, it would be useless to propose another energy-aware VNE solution. However, due to the insensitiveness of current networking equipment's energy consumption to traffic load, VNEs leading to equal cost may drastically differ in their energy consumption as can be seen in Fig. 1.

The comparison is performed for a set of scenarios with different SNs, each hosting a number of VNs, such that the SN resources are put under a certain load ratio. That is, the value of $\sum_{i \in V} NR_{PP}(i)$ and $\sum_{(i,j) \in A} LR_{BW}(i,j)$, is distributed among the set of virtual networks demands $-ND_{PP}(i^k)$ and $LD_{BW}(i^k, j^k)$ - so that the mapping of the whole set of VNRs will cause an average resource load, with different ratios $\{0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9\}$, in the SN.

In this work, we uniformly distribute the resource values

¹<http://alevin.sf.net>

between 0 and $NR_{pp}^{max} = LR_{BW}^{max} = 100$. As MIP problems are hard to solve and their complexity grows exponentially with their size, we chose a small number of nodes for the substrate and virtual networks, 15 and 5 respectively. Substrate and VNRs topologies were probabilistically generated using the Waxman algorithm [8], currently implemented in ALEVIN, with an average graph connectivity of 0.25. To explore the impact of consolidation, we consider 30 VNs to be embedded in each scenario. To obtain statistically significant results, we performed 50 runs for each scenario which results in 12000 virtual network embeddings. Results are shown with a confidence level of 95%.

Fig. 2 presents the obtained results with regard to three different metrics: percentage of inactive links and nodes, incurred cost in the SN and the percentage of accepted VNRs after performing the embedding. From these results we can extract the following observations:

- *Good energy savings for low loads:* Figs. 2a and 2b show that, after performing the embedding, the VNE-EA solution allows to obtain greater energy savings for low loads (e.g. night traffic). In the best case (with a load of 0.2), VNE-EA allows to switch off or hibernate almost 25% more links and 35% more nodes than the CostVNE solution, resulting in a similar percentage of energy gain (we consider homogeneous consumption in nodes and links). On the other hand, the energy gains for high loads are almost negligible (0% nodes and less than 7% links can be switched off after the embedding with a 0.9 of load).
- *Increased cost for VNE-EA:* the energy gains achieved by VNE-EA lead to an increased cost of the embedding as shown in Fig. 2c. This is due to the fact that the VNE-EA approach tries to embed each VNR in the minimum set of active networking equipment without considering the embedding cost.
- *Almost equal acceptance ratio for low loads:* CostVNE approach aims to leave as much free network capacity as possible to increase the probability of accepting new incoming VNRs. In case of low traffic load periods, presented in Fig. 2d, the increase in the cost does not affect considerably the percentage of accepted VNRs which reach almost the same level (no difference for 0.2 load and up to 5% for 0.5) than the costVNE approach. As a consequence, for such periods, VNE-EA would allow to realize network dynamic re-planning maintaining almost the same VNR acceptance ratio while considerably reducing the energy consumption of the whole network.
- *Trade-off between energy savings and VNRs acceptance ratio:* For high loads, energy gains, though considerably reduced, are possible with VNE-EA, but at the price of reducing the VNR acceptance ratio. This is due to the difficulty of allocating VNRs with greater demands in a short number of active substrate network equipment that will be highly loaded and, as a consequence, more prone to reject future VNRs. When the load increases, VNE-EA's energy gains in links and nodes diminish (Figs. 2a

and 2b show that VNE-EA under loads from 0.6 to 0.9 can switch off up to 6% nodes and 7% links), while its acceptance ratio decreases at higher rates than the CostVNE's (Fig. 2d shows that VNE-EA maps from 10% to 16% less VNRs than CostVNE under loads from 0.6 to 0.9). There is therefore a trade-off between energy and VNR acceptance ratio that will lead the ISP to choose either VNE-EA or costVNE depending on its goals.

IV. CONCLUSION AND FUTURE WORK

In this letter, we presented a novel energy-aware MIP formulation for the VNE problem. Extensive simulations verify that, when the SN is under low traffic loads (up to 50%), our proposal substantially reduces the energy consumption (up to 35% in nodes and 25% in links) in the SN without drastically affecting the acceptance ratio (up to 5%).

The solution of VNE-EA provides an optimal bound to evaluate future solutions able to obtain near-optimal results over larger network scenarios in reasonable running times. In future work, we intend to develop energy-aware re-allocations of cost-based embeddings to increase energy savings without modifying the VNRs acceptance ratio even in the case of high loads. Taking into account the networking equipment that can be found in the different segments of an ISP (access, transport and core) and the recent development of green ICT equipment - where the energy consumption depends on the load - we also intend to extend VNE-EA to include the consumption of heterogeneous networking equipment evaluating several energy consumption models.

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[.] Juan F. Botero, Xavier Hesselbach, Michael Duelli, Daniel Schlosser, Andreas Fischer and Hermann De Meer. Energy efficient virtual network embedding. *IEEE Communications Letters*, Volume [NA], pages [NA], 2012. See <http://www.net.fim.uni-passau.de/papers/Botero2012a> for full reference details (BibTeX, XML).