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A feedback control approach for energy efficient virtual network embedding☆

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ABSTRACT

Network virtualization is an enabler for intelligent energy-aware network deployment. The existing research usually searches the subset of resources in the whole substrate network passively for the virtual networks (VNs), where resource consolidation achieves the minimization of energy consumption by switching off or hibernating as many network nodes and interfaces as possible. However, the stable active resources for accommodating the VNs help enhance the number of the hibernated nodes and links, which can reduce the energy consumption. A novel method for energy efficient virtual network embedding (EEVNE) is proposed in this paper, which controls the mappable area of the substrate network actively and can find the minimal consolidation of the network resources. In our proposed method, a controller, a check device and an actuator are designed for finding the stable consolidated subset of the substrate resources. Besides, two feedback-control-based EEVNE algorithms are devised to minimize the energy consumption of the substrate network for embedding VNs. Simulation results show that our algorithms significantly save greater energy than the existing algorithms.

1. Introduction

The reduction of energy consumption has become a key issue in the future Internet. In 2011, the energy consumption of the Internet amounted 2% of the overall energy consumption approximately [1,2]. And a decrease in greenhouse gases emission volume of 15–30% is required before year 2020 to keep the global temperature increase below 2 °C [3]. Various studies have been started to research the technology of the energy consumption reduction of the Internet. The resources of the Internet are often supplied for the peak load, which are under-utilized in normal operation. The above problems leave a large room for energy savings [4].

Network virtualization is an important technology for the future Internet, the cloud computing and the software-defined networks [5–8]. In the research of the future Internet, some network virtualization platforms, such as PlanetLab [9], Trelis [10], GeENI [11], and GENI [12], combine general-purpose servers with the high performance network processor subsystems. Since the current power consumption of the network equipment is insensitive to the traffic load [13], switching off or hibernating as many network nodes and links as possible without compromising the network performance is the best approach to minimize the energy consumption [14]. Generally, resource consolidation is an enabler for the intelligent energy-aware network deployment.

Virtual network embedding (VNE) is a key technology in the network virtualization environment[8]. The shared substrate network (SN) is managed by the infrastructure providers, while virtual networks (VNs) are created by the service providers. VNs with the constraints on both nodes (e.g., CPU) and links (e.g., bandwidth) are embedded into the same shared SN, which is known as VNE. The energy efficient VNE (EEVNE) reduces the energy consumption of SN when VN requests are embedded into the shared physical SN. In this paper, we consider the EEVNE in the IP network over the Wavelength Division Multiplexing (WDM) optical network. Energy consumption can be reduced by embedding VNs in a smaller set of substrate resources. Some EEVNE literatures have explored to minimize the energy consumption for accommodating VNs in the future Internet [14–20]. The general optimization models (such as mixed integer program, integer linear program) of EEVNE are proposed to reduce the energy consumption. However, the implementation of those models are not scalable for large scenarios. Many heuristic algorithms of EEVNE are proposed, which try to find the consolidated subset of active substrate nodes and links for the VN requests. As those algorithms search the subset in the area of a whole SN, we call those algorithms as

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passive EEVNE algorithms. Passive EEVNE algorithms have two outstanding disadvantages, listed as:

- Since the VN requests arrive and depart dynamically over time, VNE brings about the dynamical allocation and recycling of the substrate resources, and the consolidated subset of the active physical nodes and links are easily changed. More substrate resources are switched between the hibernated and active states by the dynamical changes. Hence, the more resources enter into the active state, and the unnecessary energy is consumed.
- Searching the feasible solution in the whole SN may require exploring a high number of available resources, which will lead to unnecessary high processing times. There is a small set of the consolidated resources that can meet the resource requirements of VNs in the light loads. Actively controlling the substrate resources for VNs makes the mappable area smaller, and can help reduce the time cost of VNE.

In this paper, a feedback control based approach is proposed for EEVNE, which can minimize the energy consumption effectively. The controller, actuator, check device and control object are designed for finding the minimal active resources. The controller calculates the minimal number of the hibernated links, which is the parameter of the actuator to set the mappable area for the current VNs. The mappable area of SN is the control object, which determines the energy consumption of SN. Check device is used to check whether or not the virtual nodes and the virtual links are embedded in the current mappable area. If the VN is not accepted successfully, the mappable area will be extended gradually by the feedback control method. The minimal stable consolidated subset of the substrate nodes and links can be found actively in the feedback control process of embedding VNs. In our proposed method, the following technologies and justifications are employed.

- An algorithm is proposed to set the mappable area, in which a mappable flag (such as 1) or an unmappable flag (such as 0) may be set for each link and node of the SN. The mappable flagged area is composed of all the nodes and links with a mappable flag. We search one feasible solution for a VN in the mappable flagged links and nodes of SN.
- If the VNE fails to find the solution in the process of embedding the virtual nodes or links, a feedback control approach will be used to extend the range of the mappable flagged area step by step. The feedback control process will stop if the VN is embedded successfully or no additional resources of substrate links and nodes can be extended to be set a mappable flag.
- The number of the mappable flagged links is a global variable, which is used for the subsequent VNE and can improve the efficiency of finding the stable minimal consolidated subset. The relationships among different VN requests are established by the number of the mappable flagged links.

The distinct difference between the passive and active approaches is how to find the minimization of the consolidated subset. The passive approaches search the feasible solution in the whole SN, while our proposed approach finds the feasible solution in the mappable resources of the SN for VNs. The proposed feedback-control-based approach controls the mappable area actively to find the minimization of the stable consolidated subset. Inspired by the existing heuristic algorithms of EEVNE and cost-based VNE, two feedback control based heuristic algorithms are proposed, which can increase the number of the hibernated nodes and links to reduce the energy consumption significantly.

Our main contributions are listed as follows.

- We present a feedback control approach for EEVNE, which controls the mappable substrate resources for embedding VNs actively. Whatever the substrate resources are frequently allocated and recycled, the subset of the substrate resources will always remain stable in the hibernated or active states.
- Due to the NP-hardness of the exact VNE algorithms [21], two feedback control based heuristic EEVNE algorithms are presented to find the minimal stable consolidated subset of the SN actively, where the energy consumption of the SN can be reduced greatly. Compared to the prior arts, our algorithms PR-FB (based on the page rank and feedback control approach) and EA-FB (based on the energy-aware VNE and feedback control approach) save up to 56% and 60% of energy consumptions, respectively.
- Extensive simulations are done to evaluate the performances of our algorithms. The simulation results demonstrate that our algorithms perform better than the existing heuristic algorithms.

The remainder of this paper is organized as follows. In Section 2, we introduce the related work. In Section 3, the VNE problem and the power consumption model are introduced. We propose a feedback control approach and two algorithms of EEVNE in Section 4. In Section 5, we detail the performance evaluations of the solutions and their comparisons with the heuristic solutions. Finally, we conclude this paper in Section 6.

2. Related work

VNE is a key technology in the network virtualization [8], and EEVNE is a hot research field in VNE. Various exact EEVNE models have been proposed. Botero *et al.* propose a mixed integer program (MIP) to minimize the active substrate links and nodes, which provides optimal EEVNE [14]. The MIP formulates the resource consolidation and provides an optimal bound to evaluate the heuristics solutions. However, they only consider the number of the activated nodes and links instead of considering the energy consumption. In [15], the energy consumption minimization of the SN and load balancing are introduced, which result in better embeddings with regard to energy savings and acceptance ratio. Su *et al.* propose an integer linear program (ILP), which minimizes the number of working nodes and intermediate nodes [16]. Rosario *et al.* [17] propose a general optimization model for the load-sensitive equipment. However, those MIP and ILP apply exact algorithms (such as GLPK), which lead to too high time complexity and inapplicability for online VNE.

Since the exact EEVNE models (such as MIP and ILP) are NP-hard problems, some heuristic approaches are proposed. Botero and Hesselbach [15] propose an heuristic approach to reconfigure the allocation of embedding VNs. The relocation implies the migration of the virtual nodes and links from one place to another, which produces the undesirable effects on the virtual routers and links migration for the QoS of working transmissions. Su *et al.* devise an EEVNE algorithm by using the consolidation technique [16]. However, the heavy weight on the difference of remaining CPU of the substrate nodes and requested CPU of virtual nodes is given to the node rank, and more energy is consumed. They observe that the electricity price varies over both location and time, and propose two EEVNE algorithms: a heuristic algorithm and a particle-swarm-optimization-based algorithm [18], which reduce the energy cost. Wang *et al.* [19] minimize the energy consumption by coordinating the power-aware node mapping and the power-aware link mapping. However, the dynamical characteristics are not considered, and the energy is wasted. Chang *et al.* [20] propose an ant colony optimization based algorithm to minimize the energy consumption. However, the energy consumption depends on the population of ants and the number of iterations. In [22], a minimal cost flow based EEVNE model for path splitting is proposed to reduce the energy consumption. For the cloud data centers, the EEVNE algorithms are proposed to reduce the energy consumption [23–27]. Tarutani *et al.* [23] propose a method that