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Energy-aware routing for software-defined networks with discrete link rates: A benders decomposition-*based* heuristic approach

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ABSTRACT

The energy efficiency of wired networks has received considerable attention over the past decade due to its economic and environmental impacts. However, because of the vertical integration of the control and data planes in conventional networks, optimizing energy consumption in such networks is challenging. Software-defined networking (SDN) is an emerging networking paradigm that decouples the control plane from the data plane and introduces network programmability for the development of network applications. In this work, we propose an energy-aware integral flow-routing solution to improve the energy efficiency of the SDN routing application. We consider discreteness of link rates and pose the routing problem as a mixed integer linear programming (MILP) problem, which is known to be NP complete. The proposed solution is a heuristic implementation of the Benders decomposition method that routes additional single and multiple flows without resolving the routing problem. Performance evaluations demonstrate that the proposed solution achieves a close-to-optimal performance (within 3.27% error) compared to CPLEX on various topologies with less than 0.056% of CPLEX average computation time. Furthermore, our solution outperforms the shortest path algorithm by 24.12% to 54.35% in power savings.

1. Introduction

The telecommunication sector is one of the fastest growing sectors, having reached 7 billion mobile subscriptions by the end of 2015 and 7-fold growth in Internet penetration, from 6.5% to 43%, between 2000 and 2015 [1]. According to the same report, the proportion of households with Internet access has also increased from 18% in 2005 to 46% in 2015. The growing number of users, increasing demand and expansion of wireless communications have led to tremendous growth in energy consumption in ICT worldwide. Studies have shown that more than 4.7% of worldwide energy is being consumed by ICT [2,3]. Major organizations in the U.S. spend millions of dollars annually on power consumption [4]. For example, eBay, Akami, Microsoft and Google annually consume 0.6×10^5 MWh, 1.7×10^5 MWh, 6×10^5 MWh and 6.3×10^5 MWh, respectively, which costs \$3.7, \$10M, \$36M and \$38M. The Massachusetts Institute of Technology campus network infrastructure consumes 7×10^5 MWh annually, which costs \$62 million. In the U.K., the total energy consumption of British Telecom has reached 2.6 TWh, which is 10% of total power consumption in the U.K. [5]. Similarly, the total energy consumption of Deutsche Telecom in Germany was approximately 3 TWh in 2007 [5]. Moreover, ICT is responsible for approximately 2% of global CO_2 emissions, which corresponds to approximately 66% of CO_2 emissions in Germany, 100% of the CO_2 emissions caused by international air traffic, and 25% of the CO_2 emissions produced by passenger cars world-wide [6]. With the increasing demand for telecommunication services, energy consumption in this sector is becoming a major concern from both an economic and environmental perspective. This increasing demand calls for more energy efficient and eco-friendly communication networks.

Reconfiguring conventional networks to implement energy efficient policies is challenging due to the vertical integration of the control and data planes at each networking device. The control plane optimizes data handling decisions whereas the data plane forwards data according to the decisions of control plane; both are integrated at each device, thus limiting the ability to achieve adaptive control. In addition, a change in data handling policies requires configuring each device using low-level commands that are often vendor specific [7]. To simplify this complexity and allow for innovation in networking, a new networking paradigm, software-defined networking (SDN), was developed to sunder the control and data planes. The data plane remains at the networking

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devices, whereas the control plane is logically displaced to a central controller. Based on the network status reported by network devices, the central controller adaptively optimizes and remotely configures the entire network [8].

Two major approaches were proposed in the literature for energy saving, namely, rate adaptation, also known as speed scaling, and powering down. The speed-scaling approach reduces the energy consumption of networks by scaling the power consumption of a network element to the amount of traffic it carries [9]. The power down approach conserves energy by switching off unused network elements, which operate either at the full rate or zero rate [10]. In [9], Andrews et al. studied the network-wide integral routing problem with the objective of satisfying a set of demands' rate requirements while minimizing energy consumption. They reported that optimizing routes highly depends on the characteristics of the energy function. In particular, they proposed a constant approximation algorithm for sub-additive functions and showed that no bounded approximation exists for super-additive functions. Andrews et al. extend their work to consider the powering down approach in [10]. They showed that ON-OFF oscillation can be reduced via routing and presented a logarithmic approximation for both energy consumption and end-to-end delay. Nedevschi et al. [11] showed that both speed scaling and power down approaches can bring significant energy saving with negligible end-to-end delay and packet loss. However, the realization of these approaches in conventional networks is challenging, as achieving network-wide energy optimization requires an accurate estimation of the network status; this estimation includes link utilization, a complete traffic matrix and network topology. Therefore, the adoption of these approaches was limited to distributed and per-link implementations, e.g., IEEE 802.3.az, which does not exploit the full energy saving margin of entire networks.

Unlike conventional networks, software-defined networks are intrinsically programmable and status measurable. Under SDN, the central controller receives all traffic flow routing requests; thus, it is aware of the traffic matrix. In addition, forwarding elements measure various network status metrics, e.g., link utilization, connectivity, and delay, and report them to the central controller. Based on the received report, the central controller constructs a network-wide overview of the network status. Therefore, the central controller consolidates traffic routes to power off as many links as possible and scales all link rates to their utilization across the entire network while provisioning traffic requests.

The scope of this work is to design an energy-efficient routing algorithm for the routing application of software-defined networks. This network application resides in the application layer of SDN as shown in Fig. 1. The proposed algorithm allows the controller to configure routes and link rates remotely by updating the network devices flow tables and setting their ports operating rates. This algorithm approximately solves the following SDN routing problem: Given the network topology, a set of data flows and their traffic demands, the available discrete operating rates of each link, find the integral routing paths of data flows and the operating rates of all links so that network energy consumption is minimized and traffic demands are provisioned. In integral routing, each flow is routed on a single path from its source to its destination. This routing is of practical importance in scenarios where either frames are not arbitrarily divisible [12] or packet ordering is not preferable [9]. The power consumption of ports is modeled by a discrete step-increasing discontinuous function of their discrete operating rates [13]. In our previous study [14], we show that discrete discontinuous rates are able to model practical scenarios and brings significant energy savings.

Due to the programmability and configuration flexibility introduced by SDN, several recent studies have proposed energy optimization algorithms for software-defined networks. Markiewicz et al. propose [15] an algorithm that reconfigures the network to maximizes the number of OFF links. Similarly, in [16] a greedy algorithm was presented to reroute traffic so that the number of OFF links is maximized. These algorithms disable unused links to conserve energy while operating ON links at their highest rate. They overlook the energy savings that can be achieved by adjusting the link rates to match their utilization. Zhu et al. [17] develop an energy-aware component in an open-sourced network management platform for data centers. The energy aware-component adopts priority-based shortest path routing and exclusive flow scheduling. Wang et al. [18] present a fast topology-aware heuristic scheme for multi-resource energy-efficient routing in cloud data centers. Energy-aware routing and flow scheduling schemes for data centers leverage the structural regularity and symmetricity of data center topologies as well as the data centers' special traffic characteristics [15]. Therefore, these schemes are inapplicable in corporate or operator networks, which do not exhibit similar topology or traffic characteristics in the data center networks. Wang et al. [19] investigate energy saving via integral routing and rate adaptation in networks with discrete link rates. They proposed a routing solution that transformed the discrete rate function into a continuous one and relaxed the integral routing constraint to convexify the problem. The solution achieves a constant approximation performance for uniform demand and the bounded adjacent steps ratio of the discrete rate function. However, these stringent requirements are difficult to satisfy in current networks. Tang et al. [20] studied the energy-efficient flow allocation problem in networks with discrete link rates. Given a set of candidate paths, they developed two greedy algorithms and one linear programming (LP)-based algorithm to allocate fractions of data flows on the candidate paths; one greedy algorithm is for allocating a single flow, whereas the other two algorithms are for allocating multiple flows. The greedy algorithms outperformed a shortest path baseline solution, whereas the LP-based algorithm provided a close-to-optimal solution. However, it is not clear how different algorithms can be implemented in

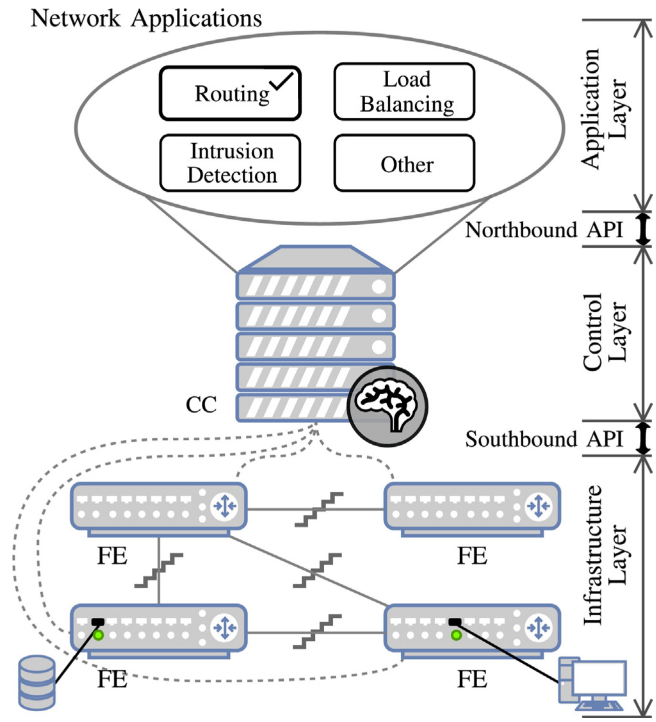

Fig. 1. The SDN three-layer architecture comprising the application layer, control layer and infrastructure layer. The control layer consists of the central controller, "the brain of the network", and interfaces the above and below layer through the northbound and southbound APIs, respectively.