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Robust energy-aware routing with redundancy elimination

David Coudert [a,b], Alvinice Kodjo [b,a], Truong Khoa Phan [c,*]

[a] Inria, France
[b] Univ. Nice Sophia Antipolis, CNRS, I3S, UMR 7271, 06900 Sophia Antipolis, France
[c] University College London, UK

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ABSTRACT

Many studies in literature have shown that energy-aware routing (EAR) can significantly reduce energy consumption for backbone networks. Also, as an arising concern in networking research area, the protocol-independent traffic redundancy elimination (RE) technique helps to reduce (a.k.a compress) traffic load on backbone network. Motivation from a formulation perspective, we first present an extended model of the classical multi-commodity flow problem with compressible flows. Moreover, our model is robust with fluctuation of traffic demand and compression rate. In details, we allow any set of a predefined size of traffic flows to deviate simultaneously from their nominal volumes or compression rates. As an applicable example, we use this model to combine redundancy elimination and energy-aware routing to increase energy efficiency for a backbone network. Using this extra knowledge on the dynamics of the traffic pattern, we are able to significantly increase energy efficiency for the network. We formally define the problem and model it as a Mixed Integer Linear Program (MILP). We then propose an efficient heuristic algorithm that is suitable for large networks. Simulation results with real traffic traces on Abilene, Geant and Germany50 networks show that our approach allows for 16–28% extra energy savings with respect to the classical EAR model.

1. Introduction

Recent studies have shown that Information and Communications Technology (ICT) is responsible for 2% to 10% of the worldwide power consumption [25,16]. For example, the Global e-Sustainability Initiative estimated the overall network energy requirement for European telecommunication is around 35.8 TWh in 2020 [13]. To this extend, the backbone networks and more precisely IP routers, consume a majority of energy [5]. While the traffic load has only a marginal influence, the most contribution of energy consumption on router is the number of active elements such as ports, line cards, base chassis [32]. Traditionally, networks are always designed to meet the peak-hour traffic demand. Therefore during normal periods, the traffic load is typically well below the network capacity. Following this observation, people have proposed energy-aware routing (EAR) to minimize the number of used links while all the traffic demands are routed without any overloaded links [16,27,40,24,33].

Another research topic that has also been active recently is traffic redundancy elimination (RE) [2,3,37,41]. Observing that traffic on the Internet contains a large fraction of redundancy (e.g. popular contents such as new movies are often downloaded several times subsequently), a complementary approach uses redundancy elimination (RE) techniques to reduce link load in backbone networks. It consists in splitting packets into small chunks, each is indexed with a small key, that are cached along traffic flows as long as they are popular. Then, keys are substituted to chunks in traffic flows to avoid sending multiple times the same content, and the original data are recovered on downstream routers based on the cache synchronization between the sending and the receiving routers. Therefore, traffic redundancy is removed and traffic volumes of flows between the two routers are reduced. For simplicity, a traffic flow from which redundancy has been removed is called a *compressed flow*. We use interchangeably the notation *compression rate* or *RE rate* to denote how much traffic redundancy can be eliminated.

From energy savings perspective, RE has a drawback since it increases energy consumption of routers [23]. To find a good trade-off, in our previous work, we proposed GreenRE - a model that combines EAR and RE to increase energy efficiency for backbone network [23]. In

* Corresponding author.
E-mail addresses: ptkhoa1984@gmail.com, truong_khoa.phan@inria.fr (T.K. Phan).

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the GreenRE model, each of the demand has a static traffic volume and is associated with a constant factor of redundant traffic. To handle future changes and guarantee a certain level of quality of service (QoS) (avoiding overloaded links), the peak volumes of traffic demand and the lowest RE rates are used as the worst case realization. Such assumption clearly leads to inefficient usage of network resources and poor energy savings. To alleviate this limitation of the GreenRE model, the uncertainty on traffic volumes and RE rates has to be precisely modeled and taken into account in the optimization process. By using this extra information, we are able to obtain a design which is closely related to the dynamics of the traffic pattern, hence significantly increase energy savings compared to previous proposals.

In mathematical literature, the technology-independent Γ-robustness has been introduced in [8,9] and then successfully applied to various network design problems [30,18,17]. This approach is based on an observation that in real traffic traces, only a few of the demands are simultaneously at their peaks. So, the authors considered a parameter $\Gamma > 0$ so that at most Γ demands deviate simultaneously from their nominal traffic volumes. Based on this assumption, the so-called robust solution is a solution that is feasible for any subset of Γ demands simultaneously at their peaks, other demands are being at their nominal values. The originality of the method is the expression of the maximum sum of deviation over all possible subsets of Γ demands as a unique linear program (LP). However, this LP formulation may have an exponential number of constraints. To overcome this issue, the LP formulation is transformed into a compact one using the duality theorem.

In this work, we first present an extended version of the classical multi-commodity flow problem in which traffic flows can be compressed to smaller volumes (with some costs, e.g. energy cost mentioned in this paper). Previous studies have considered robustness either on traffic volumes [30] or on redundancy rates [18]. To the best of our knowledge, this is the first work combining uncertainties in both traffic demand volumes and compression rates. In summary, we make the following contributions:

- From a theoretical point of view, we present an extended multi-commodity flow problem with compressible traffic flows. In addition, we provide a robust model in which uncertainties in both traffic volumes and compression rates are taken into account.
- This extended model can be applied to a vast range of applications in network flows and traffic management. In this paper, as an applicable example, we use this model to increase energy efficiency for a backbone network. We apply this extended model into energy-aware routing and formally define the Robust-GreenRE problem using Mixed Integer Linear Program (MILP).
- Since robust network design is NP-hard problem [10], we propose a heuristic algorithm that is effective for large instances.
- By simulation, we show the energy savings offered by our methods on backbone networks with real-life data traffic traces and compression rate fluctuations.

2. Related Works

2.1. Energy-aware Routing (EAR)

EAR aims at using network protocols to control the whole network, so as to minimize energy consumption while preserving QoS requirements. Before going into details of EAR, we first present an energy profile of a router from a traffic load point of view. An energy profile is defined as the dependence of the energy consumption of a router on its traffic load. In fact, there are several energy profiles in which different functions are used to describe the relationship between energy consumption and traffic load on router [36]. In this section, we present the two main energy profiles: “Idle Energy” and “Fully Proportional” models (Fig. 1).

- Fully Proportional Model: this model represents an ideal case where energy consumption varies linearly with the device utilization, between 0 and E_{max}. As stated in [11], network devices could present such a behavior if techniques like Dynamic Voltage Scaling (DVS), modular switching fabrics, etc. are applied to the components of the devices. Furthermore, the authors in [34] have proposed methods to build a power-proportional software router. Such a model is desired in green networking. However, today network devices are not power-proportional, and it is considered as a futuristic scenario.
- Idle Energy Model: this model is also named “on/off” energy profile. It has been shown in [14] that the energy consumption of today network equipments is not proportional to the quantity of the transported traffic. In practice, network device's energy consumption grows linearly between a minimum value E_0 and a maximum value E_{max} which correspond respectively to the idle state and the maximum utilization state (Fig. 1). For more details, a database of power consumption values for ICT network equipments is presented in [28].

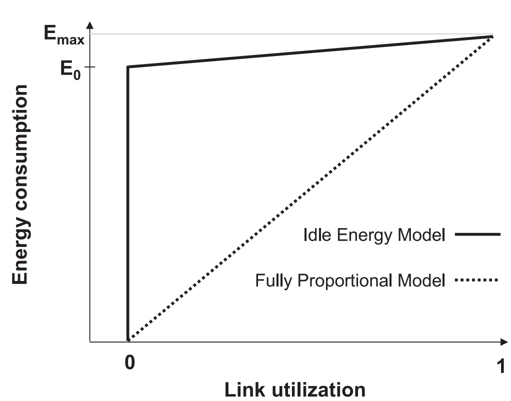

Fig. 1. Energy profiles.