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Energy management in communication networks: a journey through modeling and optimization glasses

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ABSTRACT

The widespread proliferation of Internet and wireless applications has produced a significant increase of ICT energy footprint. As a response, in the last years, significant efforts have been undertaken to include energy-awareness into network management. Several green networking frameworks consisting in carefully managing the network routing and the power state of network devices have been proposed.

Even though the approaches differ on the technologies and sleep modes adopted, they all aim at tailoring the active network resources to the varying traffic needs in order to minimize energy consumption. From a modeling standpoint, this has several commonalities with classical network design and routing problems, even if with different objectives and in a dynamic context.

While most research has focused on crucial technological aspects of the green networking schemes, there has been little attention so far on the understanding of the modeling similarities and differences of the proposed solutions. This paper fills the gap by surveying the literature on wired networks energy management with optimization modeling glasses. It follows a tutorial approach that guides through the different components of the models with a unified symbolism. A detailed classification of previous work based on the included modeling issues is also proposed.

1. Introduction

The widespread of ICT has caused a significant increase of its energy footprint [1]. Worldwide telecom operators saw their electricity consumption growing from 160 *TWh*/*year* in 2007 to 259 *TWh*/*year* in 2012 [2]. According to [3], ICT-related power consunption reached 4.7% of the total worldwide. Although, year by year, ICT technologies are becoming more power efficient, that will not be enough to reverse the trend, making the ICT sector responsible for up to 23% of global green house gas (GHG) emissions in 2030 [4].

Some studies focusing on single Internet Service Provider (ISP) reveal the following figures: according to [5], Deutsche Telekom networks are responsible for around 0.5% of German yearly electricity expenditure, while [6] showed that the energy consumed by the largest providers such as AT&T or China Mobile reached 11 TWh per year in 2010. [6] also evaluated that consumption figures of medium sized operators like Telecom Italia and GRNET would have approached 400 GWh in 2015.

Recently, a global initiative headed by the GreenTouch consortium [7] aiming at improving by 98% the energy efficiency of telecommunications network by 2020, published a final report presenting all the main achievements [8]. In brief, it is estimated that, by implementing and combining together the initiative findings, energy efficiency in core network would improve by a factor 316 by 2020.

A very large body of work has been published on green networking, including a few survey papers, e.g., [9]. Even though there is a vast and specific literature on IP energy-aware management, to our knowledge, there has not been so far a thorough review and analysis of all the different modeling features of the related optimization problems.

In this paper we present a tutorial-survey of this hot area of research. We first introduce the reader to the family of *energy-aware network management* (EANM) problems, by discussing step by step all their important modeling features. We then classify previous work based on the model characteristics identified and comment on the open issues.

The paper is organized as follows. A brief technological background and a description of the features characterizing differ-

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ent problems within the general EANM framework are given in Section 2. In Section 3 we then discuss EANM from an optimization modeling perspective, guiding the reader through a series of mathematical programming models representing the different problems addressed in the literature and highlighting the strong ties between energy management problems and the classical network design problems widely studied by the operations research community. Section 4 is the survey part of the paper, where the state of the art literature on EANM is classified according to different criteria representing some key characteristics of the models used. The last Section presents a wrap-up of the work that was carried out in the paper and provides some conclusive remarks.

2. Energy-aware network management (EANM): a general overview

IP networks can be made greener by working at different levels [10,11]. First, by re-engineering or developing novel energy-efficient devices and architectures that offer support for energy-efficient operation such sleeping primitives [12] or *pipeline IP forwarding* [13]. Second, by defining local procedures to autonomously adjust the state of a single network device according to real-time measurements [14], and finally by coordinating the management of the whole network infrastructure to optimize both energy consumption and performance of both routing and device configurations (EANM) [9,15–17].

The term *energy-efficiency* has been defined by ITU-T L1310 as the ratio between network total throughput and network energy consumption [18]. Even if this definition captures the basic trade-off between traffic and energy, most of the works in the literature on IP networks, and the mathematical models discussed in Section 3, focus on the minimization of energy consumption for a given traffic profile. According to each specific proposal, this goal is achieved differently, e.g., by reducing the number of active line cards or routers, by smartly routing traffic so as to achieve the optimal device utilization level according to the energy profile. Note that, when not differently specified, the term *device* refers to each general network element, e.g., a router, a link, a line-card, etc. Practically speaking, the goal of EANM is to adapt network consumption to traffic levels. The way EANM is performed relates to the following elements: (i) the power profile of network devices, (ii) the routing protocol, according to which traffic engineering is performed, (iii) the performance requirements requested by each traffic flow, (iv) when and how frequently network re-configurations should be performed, i.e., in advance off-line or in real-time on-line, (v) where to locate the intelligence of the system (centralized or distributed architecture) and finally, (vi) network survivability in case of failures. What is interesting and challenging about EANM is that despite the increase in energy efficiency, it should not degrade network performance or affect any Service Level Agreements existing in the network.

2.1. Power profiles

The power profile of a network device is the curve of power consumption versus traffic load. Depending on the shape of the profile, the network can be operated in an energy-efficient manner according to different policies.

Assuming non-linear power profiles, different approaches can be considered [19]. For instance, in case of cubic power profiles, it would be more energy efficient to distribute the traffic among multiple devices to keep the average utilization as low as possible, while in the presence of logarithmic profiles it would be much more effective to consolidate the traffic over a very restricted set of network elements.

According to recent studies, however, current network devices and their main components, e.g. router chassis and line cards, present an almost linear power profile with a pretty high consumption at zero load (fixed power consumption independent on load) and relatively small increase up to maximum consumption at full load (load dependent power consumption) [10,20–22]. The power needed to maintain a device active even with no load makes up around 90% of the energy consumed during peak utilization periods. We refer to the *Powerlib* database [23] for an accurate collection of consumption figures for several networking devices, both IP and optical, produced by different vendors. Since in practice the profile is almost flat and energy savings can be achieved only switching off the device (sleep mode), power profiles are often approximated with an ON-OFF (step) curve.

Although great efforts have been made to improve the load proportionality of the energy consumption of next generation network devices (see e.g. [24]), the ON-OFF profile characterizes the current devices and makes sleeping the most promising and effective strategy to adapt the consumption of IP networks to the incoming traffic levels. Analytic studies such as [25] and [6] estimate that around 50% energy savings could be achieved. Furthermore, [26–28] remark that sleeping-based strategies remain effective when applied to network devices characterized by a utilization-proportional power profile provided that fixed and proportional consumption components be of the same order of magnitude.

In addition to pure sleeping strategies, the standardization of adaptive link rate (ALR) was thoroughly discussed within the recent drafting of the IEEE 802.3az standard [29]. However, due to hardware and implementation issues, the final draft did not include ALR. The idea was to efficiently adapt the transmission peak rate, and thus the corresponding energy consumption, of Ethernet links [30].According to ALR, the capacity of each Ethernet link is adjusted, e.g., from 100 Mbps to 1 Gbps or from 1 Gbps to 10 Gbps, to satisfy the incoming traffic while transmitting at the less consuming bit-rate [31–33]. The ALR concept can be generalized by the notion of *multi-line rate* (MLR) [34].

2.2. Routing and transport protocols

Routing protocols have a major impact on traffic engineering techniques, and therefore on the energy management polices that can select traffic routes to reduce the consumption or to put to sleep some nodes or links (line cards).

In IP networks, we identify two main classes of routing protocols, i.e., flow based and shortest path based. When routing is flow based, like in the case of network based on Multi-Protocol Label Switching (MPLS), each traffic demand (identified by source and destination pair) is routed along one or multiple dedicated paths [35]. In this case, traffic engineering is very flexible because each routing path can be selected independently from the others by the network administrator.

When shortest-path routing is adopted, as with classical IP destination based forwarding, the shortest paths are determined according to link weights [36]. Therefore, traffic engineering approaches aiming at modifying routing to divert traffic from sleeping nodes, thus minimizing energy consumption, can be performed by just adjusting the link weights. However, since packet forwarding is based on destination address only, not all combinations of paths can be selected and all paths to the same destination must be on a tree.

Note that both flow based and shortest path routing can be either based on single path or multiple paths (per flow or destination, respectively).

A new idea that has been recently proposed is to use multi path TCP (MPTCP) to improve the energy efficiency of the network. Given that MPTCP is particularly adapted to wireless net-