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Mixed Integer Non-Linear Programming models for Green Network Design

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ABSTRACT

The paper focuses on Network Power Management in telecommunication infrastructures. Specifically, the paper describes four energy aware network design problems, with the related mathematical models, for reducing the power consumption of the current and future Internet. Each problem is based on a different characterization and power awareness of the network devices, leading to either Mixed Integer Linear Programming or Mixed Integer Non-Linear Programming models. We have assessed the effectiveness of the proposed approaches under different real core network topology scenarios by evaluating the impact of several network parameters. To the best of our knowledge, this is the first work that deeply investigates the behavior of a pool of diverse Network Power Management approaches, including the first Mixed Integer Non-Linear Programming model for the Power Aware Network Design with Bundled Links.

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1. Introduction

Saving energy has become one of the most important challenges of the twenty-first century, both for environmental and economical reasons. Following to the explosive growth of Information and Communication Technologies (ICTs), energy saving policies and techniques have ineluctably entered also into the pool of design objectives of ICT infrastructures. Thus, if the major focus of the "old" ICT market was on performance and cost, the present and future ICT market regards as crucial the improvement and maintenance of today's performance jointly with minimizing the power consumption and the carbon footprint.

In this scenario, the research community is studying a set of approaches for improving the energy efficiency of the future Internet. Detailed and up-to-date surveys on the different strategies for energy efficient networking are presented in [1,2]. These studies are based on the consideration that current networks are widely overprovisioned and network equipment is not energy aware, i.e. it always consumes the same energy irrespective of its utilization factor. By taking into account these issues, recent works on energy efficient networks have defined energy aware problems and have proposed solutions for two relevant aspects: the *Network Device Design* (*NDD*) and the *Network Power Management* (*NPM*). NDD consists in formulating energy efficient mechanisms to be implemented in the various network apparatuses that allow to build energy aware network devices [3,4]. NPM is expressed by methods aimed at achieving further energy saving by means of strategies that exploit the power consumption features of energy aware network devices.

The development of optimization models for the design of communication networks and traffic routing is an important subject for both researchers and practitioners [5–7]. In particular, several different forms of network design problems have been investigated in the literature, depending on the specific application context under consideration. However, despite the huge number of models and methods suggested in the area of telecommunication networks, very few optimization techniques have been proposed so far for NPM. Aim of this paper is to partially fill this gap, by investigating optimization models and related approaches for such a challenging area of research.

More in detail, we focus on NPM by describing four problems, of increasing complexity, aimed at reducing the power consumption of current and future networks composed of energy-aware devices:

1. Power Aware Routing (PAR).
2. Power Aware Network Design (PAND).
3. Power Aware Routing and Network Design (PARND).
4. Power Aware Routing and Network Design with Bundled Links (PARND-BL).

In this way, a hierarchy of NPM models is defined and studied, having *PARND-BL* at the top, *PAR* and *PAND* at the bottom, and *PARND* at the intermediate level. Each problem is based on a different characterization and power awareness of the network

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devices, leading to either a Mixed Integer Linear Programming (MILP) model or a Mixed Integer Non-Linear Programming (MINLP) model.

In addition to building a mathematical formulation for the power aware design and routing problems, a crucial issue is to solve them within the time limits dictated by the application environments. Therefore, a further contribution of this paper is to report the results of a wide computational experimentation, aimed at investigating the efficiency of the proposed power-aware approaches when applied to several real network topologies. The efficiency has also been measured from various perspectives, such as the reduction of the overall network power consumption, the characteristics of the computed solutions (expressed in terms of powered-off links and PICs), and the time required to get the optimal solutions. To obtain the problem solutions, we have used commercial optimization solvers, which in some cases yielded an optimal solution, and in other cases an approximated one. The power aware methods have been compared to the reference routing algorithm named Shortest Path Routing (SPR). In fact, as described in Section 5, SPR represents a widely used approach in core networks where no specific administrative or cost constraints are present. To the best of our knowledge, no other author has so far addressed such a general NPM problem as PARND-BL, nor has deeply investigated the behavior of diverse NPM approaches under real network topologies.

The paper is structured as follows. Section 2 presents the NPM in more detail. Section 3 reviews the main literature on the subject. Section 4 introduces the power aware problems, together with the related formulations that are the focus of the paper. Section 5 reports the network scenarios considered for the simulations. Section 6 presents the simulation settings and discusses the computational results. Finally, the conclusions are drawn in Section 7.

2. Network Power Management (NPM)

Generally speaking, NPM consists in finding the design and the routing strategies that minimize the overall power consumption of a network by taking into account the power consumption of the network elements and the traffic demand among the nodes. Therefore, two critical issues can be devised in NPM: the time horizon of the traffic demands and the power behavior of the network devices.

Regarding the first issue, we can observe that in actual deployments the traffic matrix presents significant changes mostly between two periods: peak and off-peak. Just relatively small variations are usually registered within each period. Therefore, the time scale of the NPM approaches could safely be based on peak and off-peak traffic periods only. If we assume that the duration of the two periods is that of day and night, the maximum acceptable time for computing an NPM solution can be set in the order of 6/12 h.

As for the second issue, the energy characterization of the network devices determines what can be exploited to minimize the overall network consumption. In this work, we have used a general power consumption model of a router, which is made of three main components [8]:

- Chassis.
- Physical Interface Cards (PICs).
- Route processor.

The chassis can be powered off (i.e. it works in a low power mode); hence, the power consumption can be assumed to be constant if the chassis is powered-on, and zero otherwise.

To model the power profile of the PICs, we have to dissect the communication process in more detail. The energy for transferring a bit from a node u to a node v can be ascribed to various components, such as the power consumed by the transmitting PIC in u and the receiving PIC in v. To make the tractation easier (and without loss of generality), when dealing with the traffic sent from u to v we will associate all the power consumption and the related capacity with the PIC at node u. Obviously, in the reverse direction we will associate them with the PIC at node v. Worth noting is also the fact that the network operators tend to deploy similar devices in their core networks. Thus, we can assume that the power consumption and the capacity of the PIC used to transmit along (u,v) are equal to the ones of the PIC transmitting along (v,u). Similarly to the chassis, the PICs can be powered off too. Therefore, there is a constant, non-zero power consumption when the PIC is powered-on, and a zero power consumption when the PIC is powered-off.

Another aspect that will be included in the analysis, is the fact that in modern core networks pairs of routers are typically connected, for each traffic direction, by multiple PICs that form one logical bundled link [9]. This technique is called link aggregation and is standardized by IEEE 802.1AX [10]. Link aggregation is widely diffused because it allows to easily upgrade the link capacity by adding new PICs, and to reach link capacities bigger than those available even using the fastest available technology. For example, a 40 Gb/s bundled link may be set up with four OC-192 PICs having a 10 Gb/s capacity each. Therefore, in our model, we assumed that links are composed of multiple PICs, and that each PIC of the bundled links can be independently powered off.

As for the route processor, its power consumption generally depends on the traffic load of the router in a non-linear way (see [11]).

Based on the energetic and technological characterization of the network devices described above, we can list four basic NPM problems, which will be investigated hereafter:

- *PAR*—Given the traffic demands associated with the nodes, PAR consists in determining the traffic routing strategy that minimizes the overall power consumption of the network by taking into account only the power absorbed by the route processor.
- *PAND*—Given the traffic demands associated with the nodes, PAND consists in determining the traffic routing strategy that minimizes the overall power consumption of the network just by powering off entire links and/or nodes.
- *PARND*—Given the traffic demands associated with the nodes, PARND consists in determining the traffic routing strategy that minimizes the overall power consumption of the network by jointly considering the power absorbed by the route processor and the possibility of powering off entire links and/or nodes.
- *PARND-BL*—Extends PARND by exploiting also the possibility to power off single PICs of bundled links.

Note that only the first three problems have already been addressed in the literature on NPM, whereas defining and solving PARND-BL is an original contribution of this paper.

3. Literature review

Starting with the seminal work on power efficient network devices presented in [12], many efforts have been recently devoted to define strategies for reducing the power consumption of the whole network infrastructure.

A first set of activities has been aimed at defining models for the PAND problem. In particular, [13] presents at first some

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