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Dynamic power management in energy-aware computer networks and data intensive computing systems

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HIGHLIGHTS

- Dynamic power management reduces energy consumption in computer networks.
- A control framework for reducing power usage in computer networks is proposed.
- An efficient algorithm for computing power status of network devices is developed.
- Simulations and testbed implementation confirm the efficiency of the control system.

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ABSTRACT

Energy awareness is an important aspect of modern network and computing system design and management, especially in the case of internet-scale networks and data intensive large scale distributed computing systems. The main challenge is to design and develop novel technologies, architectures and methods that allow us to reduce energy consumption in such infrastructures, which is also the main reason for reducing the total cost of running a network. Energy-aware network components as well as new control and optimization strategies may save the energy utilized by the whole system through adaptation of network capacity and resources to the actual traffic load and demands, while ensuring end-to-end quality of service. In this paper, we have designed and developed a two-level control framework for reducing power consumption in computer networks. The implementation of this framework provides the local control mechanisms that are implemented at the network device level and network-wide control strategies implemented at the central control level. We also developed network-wide optimization algorithms for calculating the power setting of energy consuming network components and energy-aware routing for the recommended network configuration. The utility and efficiency of our framework have been verified by simulation and by laboratory tests. The test cases were carried out on a number of synthetic as well as on real network topologies, giving encouraging results. Thus, we come up with well justified recommendations for energy-aware computer network design, to conclude the paper.

1. Introduction to energy-aware networks

The growing energy consumption in the ICT (information and communication technologies) sector is unquestionable. It is obvious that in order to support new generation network services and infrastructure, network operators and internet service providers need a large number of more sophisticated network devices able to perform complex operations in a scalable way and assure expected quality of service. This is one of the reasons for the rapid growth of the energy requirements of wired and wireless modern computer networks. Therefore, the energy consumption trends in the next generation networks have been widely discussed and the optimization of total power consumption in today's computer networks has been a considerable research issue [1–4]. New solutions both in hardware and software have been developed to achieve the desired trade-off between power consumption and the network performance according to the network capacity, current traffic and requirements of the users. The aim is to reduce the gap

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between the capacity provided by a network for data transfer and the requirements, especially during low traffic periods. In particular, the energy dissipated in a network can be minimized by switching off idle energy consuming components such as routers, line cards, and communication interfaces, and by reducing the speed of processors and link speed. In general, data transfers should be aggregated along as few devices as possible instead of balancing traffic in a whole computer network. Selectively shutting down routers and links in periods of low demand seems to be a good solution for reducing the energy usage due to the fact that typical networks are usually overprovisioned. The techniques developed for keeping the connectivity and saving the energy can be successfully used for energy-efficient dynamic management in LANs (local area networks) and WANs (wide area networks) as well as in computing centers.

Various activities and research projects aimed at developing energy-efficient networks and computing devices have been undertaken. Approaches ranging from "green" network devices and architectures to traffic engineering and routing protocols have been developed and investigated. Novel devices equipped with mechanisms for dynamic power management can operate in a number of modes, which differ in the power usage. Two common techniques for dynamic power management are utilized in energy-aware networks: smart standby and dynamic power scaling. *Smart standby* leverages on the concept of introducing idle mode capabilities, i.e., the whole device or its component is automatically switched off when it is idle — there is no data to transmit. *Dynamic power scaling* adopts the capacity (and thus power consumption) of the devices to the current load utilizing *adaptive rate* (AR) or *low power idle* (LPI) techniques. The AR method reduces the energy demands in a network by scaling the processing capabilities of a given device or the transmission or reception speed of the network interface. The LPI method allows reducing the energy requirements by putting the device or its component into a low power mode. While dynamic power scaling approaches often involve deep modifications in the design of software and hardware components of network devices, the smart standby method requires only coordination among networking nodes to carefully re-route the traffic that results from switching off selected devices or their components.

The control framework for resource consolidation and dynamic power management of the whole network through energy-aware routing, traffic engineering and network equipment activity control has been designed and developed by the ECONET consortium [5]. It can be used both for optimal power management in backbone networks and in data intensive computer systems. This control system implements algorithms to exploit both smart standby and dynamic power scaling capabilities of network nodes and links. The implementation of the framework provides the local control mechanisms that are implemented at the network device level and network-wide control strategies implemented at the central control level. In this paper we focus on the optimization algorithms used by the central dispatcher for calculating the optimal energy settings of all components of a network infrastructure and the optimal routing that minimizes the energy consumption, while ensuring all user quality requirements imposed on a network. We have developed several possible formulations of a network energy saving optimization problem with continuous and discrete variables. The work starts from the complete network management problem assuming full routing calculation and energy-aware state (EAS) assignment to all links in a network, stated in terms of binary variables. Due to the numerical complexity of the complete problem formulation we applied some simplifications. Finally, we proposed to employ heuristics to calculate the optimal energy settings of the devices for more realistic size of networks. The developed control scheme has been validated for various network systems and traffic engineering using Multiprotocol Label Switching (MPLS) [6] and RSVP-Traffic Engineering (RSVP-TE) [7] protocols through simulations and the testbed implementation. We compared the performance of all proposed solutions due to the energy saving and efficiency, while providing for adequate transmission quality.

The paper is structured as follows. In Section 2 we discuss the selected approaches to power control in computer networks provided in the literature. The description of the control framework that can operate in two variants (centralized and hierarchical) is reported in Section 3. In Section 4 the basic formulation of network-wide optimization of energy consumption and its relaxation and transformation to the simpler problem are presented. The scalability of proposed optimization schemes is discussed in Section 5. The results of simulations and experiments in the testbed are presented in Sections 6 and 7. Finally, conclusions are drawn in Section 8.

2. Related work

The problem of reducing energy consumption of telecommunication networks has been studied in recent years by many researchers. First the power needs of networks were assessed and some basic models built [8–11], then some elementary local strategies, using AR and LPI techniques have been proposed — see e.g. [12,13]. The industry standard implementing some of these ideas is IEEE 802.3az [14] providing energy efficient Ethernet interfaces.

Apart from improving the effectiveness of network equipment itself, it is possible to adopt energy-aware network-wide control strategies and algorithms to manage dynamically the whole network and reduce its power consumption by appropriate traffic engineering and provisioning. Recent studies concerning networks of internet service providers suggest that such an approach can significantly decrease the energy consumption of a network [1,3].

The rationale behind this solution is that network load varies periodically and may be predicted with reasonable probability while network resources stay constant. Furthermore, typically infrastructure is to some degree redundant to provide the required level of reliability. To mitigate power consumption some parts of the network may be switched off or their performance may be decreased during off-peak periods. To attain a multi-commodity flow an optimization problem may be formulated and solved. Such a formulation resembles traditional network design problems [15] or QoS (quality of service) provisioning tasks found in e.g. [16,17], but with energy consumed by all components of the network being major part of the performance index. As energy states of particular devices must be computed and flows routed resulting problems include a large number of integer or binary variables and may be solved only for networks of limited size so linear models are preferred to reduce complexity [8,18–21]. Some authors try to exploit properties of the optical transport layer to scale link rates by selectively switching off fibers composing them [22,23] or even build a two level model with an IP layer set upon an optical devices layer [24]. Similar decomposition may be found in [25,26] where switching off the idle devices and modulation of the power supply in computational grids is analyzed.

The major drawback is complexity which has roots in NP-completeness of flow problems formulated as mixed integer programming (MIP). Furthermore, energy consumption models are often non-convex making even continuous relaxation difficult to solve and introducing instability of suboptimal solutions [11]. Also, while some authors – e.g. [19] – assume only two states of network equipment — active and switched off, it must be remembered that future green network devices will have the ability to independently adapt the performance of their subcomponents by setting them to one of a number of energy-aware states. Modeling such a situation implies not only larger dimensionality of the problem