Green Networking - A Literature Survey

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Green networking is a rapidly expanding area of research. This survey browses through the recent green networking literature with two aims. First, the survey attempts to sketch the main ideas in the research on different parts of communications networks. Second, the aim is to recognize areas where mathematical modeling approaches are applied.

Contents

1 Introduction

Research on energy-efficient communications networks[1], especially with respect to environmental concerns is commonly referred to as *green networking.* First efforts towards green networking can been traced back to the papers by Gupta and Singh [22] and Christensen et al. [10], but during the last three years the interest has increased tremendously. This development is clearly visible in the number of publications made on the topic, cf. the recent surveys [4, 7], and the number of conferences and workshops organized in this field indicate that the interest has not even peaked yet (see, e.g., [19] for an updated list). Whereas the research community has traditionally aimed at maximizing performance of communication systems[2], the paradigm is now rapidly shifting towards how to produce sufficient performance with minimum energy cost. Indeed, overprovisioning and redundancy – positive qualities in the traditional network design – are inherently conflicting objectives with green networking. Alongside with the research also the standardization and regulation bodies are gearing up for the energy-aware communications technology of the future. Thus, the development will fundamentally change the way communication and networking research is conducted: The viewpoint of sustainability will be present in almost *all* the future research.

The importance of the area is also recognized within EU. Key projects within FP7 framework are EARTH [11], OPERA-Net [40] and ECONET [12], and there is also a Network of Excellence TREND [50] dealing with the energy-efficient communications and networking. European Institute of Innovation and Technology (EIT) ICT Labs has a thematic action line coined as Smart Energy Systems & Green ICT [49] in which also the Department of Communications and Networking (Aalto ELEC) participates actively.

This survey explores the recent developments in the field of green networking. The aim is to capture the central ideas and approaches to different parts of the networks rather than provide a comprehensive account of all research. Despite the interest in this field has surfaced only recently, the amount of work is quickly becoming overwhelming. Focus here is on developments since 2010 with an emphasis on wired networks (there exists a separate account on energy efficiency in wireless access networks at Comnet). Also several surveys that cover the older work are briefly discussed.

2 Surveys on green networking

Green networking is still at its infancy but it has already received considerably attention. Accordingly, there are several extensive surveys from slightly different viewpoints that summarize the prior work related to the concept.

A recent survey by Bianzino et al. [4] provides a comprehensive treatment of recent green networking techniques focusing on wired networking. They classify the existing research into four categories; (i) adaptive link rate, (ii) interface proxying, (iii) energy-aware interfaces, and (iv) energy-aware applications. Adaptive link rate studies approach energy savings by scaling down the transmission speed of an interface (even to zero, i.e. to a sleep mode). Interface proxying refers to attempts to "outsource" network operations from CPUs and such to low-power devices on, e.g., network interface card or – in a case of a LAN – to a external device, closer to the physical network. Energy-aware infrastructure is related to the design and management of networks. This includes

[1]The environmental impact of network equipment arises from energy consumption during usage phase, although manufacturing plays also a significant role (e.g., [48]).

[2]With the sole exception of prolonging the battery life of wireless end devices in the context of wireless networks, see [29] for a survey.

clean-slate designs and retrofitted approaches. The last category, energy-aware applications, calls for energy-efficient software designs.

Another survey focusing on energy efficiency in the future Internet infrastructure [7] reviews a representative selection of projects and standardization activities that are ongoing in the area in addition to providing a detailed account of green networking papers. In their taxonomy, they have identified three categories of research; (i) re-engineering, (ii) dynamic adaptation, and (iii) sleeping/standby. Re-engineering aims at dimensioning and optimizing the network elements or devising completely new efficient equipment designs. Dynamic adaptation refers to modulating the capacities of packet processing engines and of network interfaces to meet actual requirements. The last category, sleeping/standby, considers the case where the network elements (or parts of) are switched off to a sleep state.

A comprehensive survey on the topics in optical networks is provided by Zhang et al. [59]. They review the recent literature over different domains where optical technology is applied; core, metro, and access networks. In addition, standardization efforts toward energy efficiency are summarized.

3 Energy consumption and measurements

In a typical ISP/telco network configuration the core network represents about 30% of the power consumption while access networks weigh 70% [7]. Lange et al. [34] attempts to predict the future energy consumption distribution of a universal network operator's broadband telecommunications (wireline) network. While the home networks are currently responsible for the most part of the energy consumption, it is envisaged that IP/MPLS core networks and data centers will dominate the growth in the future.

Measurement of energy efficiency is not necessarily an easy task. The authors in [6] survey the different energy-efficiency metrics proposed in the literature and show that the results may substantially depend on the chosen metrics. Measurement of legacy equipment is challenging as the equipment are not designed to allow measurements and invasive approaches would be require lot of work and cause interruptions in service. Phillips et al. [43] propose a regression approach to address the problem.

4 Core and optical networks

General approach to save energy in the Internet core is to route the traffic around some routers during low traffic periods and put the respective routers or line cards to sleep [22]. Chabarek et al. [8] argue that energy awareness should be taken into account already in the design phase in deploying the routers over a set of point-of-presences. They suggest that power-consuming packet processing operations should be limited to a subset of routers that allow energy efficient operation.

Panarello et al. [41] propose a congestion control technique coupled with a physical layer resource/power management primitives which results in a new access router functionality design (coined as the green router). In a follow-up paper [35], the authors improved the functionality of the approach by adding a measurement mechanism where the router estimates the minimum available capacity from source-destination path in the Internet. By scaling the power consumption (assuming adaptive rate scaling) to match the minimum of the available capacity and user requirements QoS targets can be met with minimum energy consumption.

Vasić and Kostić [54] present a traffic engineering approach that balances the traffic in the network so that links and routers can be put into a sleep state or, alternatively, the link rates can be lowered to save energy. The authors report 21% and 16% sleep ratios for links and routers, respectively. Xia et al. [55] present a traffic engineering approach to optical backbone networks. Traffic grooming and optical bypassing are discussed in the context of reducing the energy cost of the network. In addition, they model the power consumption of a network by an auxiliary graph that captures transmission/amplification costs as well as conversion costs between optical and electronic domains and devise a power-aware scheme that produces improved results compared to plain traffic grooming.

Fisher et al. [16] recognize that in the core network many of the physical links are actually bundles (e.g., a 40 Gbps link may consist of four OC-192 cables 10 Gbps each). Although the present technology does not support quick sleep modes for individual line cards (or bringing sleeping interfaces back up) it is envisaged that such features become commonplace in the near future. Such a degree of freedom could be utilized to shut down many cables in the bundles during the off-peak hours resulting in considerable energy savings. The optimization model of the problem is NP-complete, but the authors propose LP-based heuristics resulting in 79% energy savings on the Abilene backbone.

Tucker presents a comprehensive analysis of the minimum energy consumption in optical network in a series of two papers, [52, 53]. The approach represents the ideal case where the energy consumption is limited only by the Shannon bound on receiver sensitivity and depends on modulation format, fiber losses, system length, and noise in optical amplifiers. The first paper focuses especially on deriving a lower bound for optically amplified transport systems, while the second studies the network equipment. In [52], Tucker studies the energy-efficiency i.e., the energy per bit transmitted and show that the energy consumption is minimized by locating repeaters appropriately. He derives a lower bound for energy efficiency and points out that the difference of the practical equipment in use and the bound can be explained by inefficiencies in the equipment. Accordingly, the key to improving the energy efficiency lies in reducing these inefficiencies. The article contains also models for spectral efficiency of optical communications and detailed descriptions on component energy usage. It is expected that as technologies improve, the optimum repeater spacing becomes as large as 10000 km which highlights the need to minimize the number of instances where conversion is made between optical and electrical formats. The network perspective to optical equipment energy consumption is considered in [53]. Various switching devices are described by quantitative models and it is concluded that the energy cost of the switching infrastructure is much larger than that of transport infrastructure. Consequently, the switches and routers should receive priority in devising energy-efficient technologies.

5 Access Networks

5.1 Wired access

The case of local area networks differs from WANs by the fact that the recent hardware designs (e.g., by Intel and Broadcom) allow operation in low-power idle modes. In WANs the power usage remains largely independent of the load as the chassis and the line cards draw the most power. In the Ethernet low-power mode the idle periods can be optimized, see e.g. [21].

Tsiaflakis et al. [51] model DSL power allocation under crosstalk interference and consider optimization models to attain four different fairness notions. Also an optimization algorithm (subgradient type) is proposed to solve the problems.

5.2 Wireless access

Energy efficiency in wireless access networks has been studied intensively. Originally the focus was on battery life considerations and multihop wireless networks. Jones [29] provided a comprehensive survey on energy efficient network protocols for wireless networks already in 2001, but the line of research is still very active today, cf. [28].

Karray [30] derives analytical models for spectral efficiency and energy efficiency of OFDMA network. The models allow studying the efficiencies as a function of various parameters such as propagation exponent and cell radius.

Marsan and Meo [38] study energy savings obtained through coordination of two overlapping cellular access networks (e.g., of different operators) during the daily peak hours both networks can be on, but one could be switched off during low traffic and the users of that network roam in the other. In a related paper, Marsan et al. [37] the authors consider the case in where several WLAN access points have overlapping coverage. The authors develop a model that can be used to assess the effectiveness of different policies used to switch off access points. They also propose two simple policies based on the number of associated and active users, respectively.

While not strictly access networks, Koutitas [32] studies planning of wireless broadcasting networks (DAB and DVB-T). The transmitter locations were optimized using a genetic algorithm. He shows that significant energy (and CO_2 emission) savings can be obtained in a mountainous scenario when the network is planned explicitly using a green strategy.

6 User end

In [5] the authors study PC web-browsing and identify significant power consumption related to e.g. flash players and tabbed browsing. It is likely that there will be further focus on web content energy consumption and usage behavior. The area of mobile device energy consumption is studied intensively by several Finnish research groups, cf. [39, 57, 33].

In certain environments even power availability causes problems. In such environments, innovative energy generation means can be applied together with delay/distruption tolerant networking to provide network access in a sustainable fashion [45].

7 Server end

Massive data centers, facilities used to house servers and associated components, have been built during the last few years to provide various Internet services and applications. Rising energy prices and environmental concerns have prompted the industry and governments to scrutinize the energy consumption of the centers due to their global significance: Although there are no recent ratings available, older estimations such as 1% of the world energy consumption [31] or 1.5% of the total U.S. energy consumption [15] illustrate the enormous scale.

In a data center virtually all the input electrical power eventually ends up as heat. A typical high-availability dual power path data center with N+1 CRAC units operating at a typical load of 30% design capacity exhibits the power flows shown in Table 1 [46]. Roughly half of the energy consumption comes from the IT load and the other half from facility functions such as cooling. While the servers use the most of the IT equipment power share also the network equipment connecting the servers plays a major role [24].

Naturally also the energy-efficiency considerations of data centers emphasize the facility viewpoint. Major international efforts are on-going to harmonize the energy efficiency metrics for data

IT Equipment	47 %
Chiller	23 %
CRAC/CRAH	15 %
UPS	6 %
PDU	3 %
Humidifier	3 %
Lighting / aux. devices	2%
Switchgear / generator	1 %

Table 1: Power flow distribution in a typical data center [46]

centers to enable the owners of data centers to assess and improve their performance. The Green Grid [18] is a global consortium of IT companies and professionals seeking to improve energy efficiency in data centers and business computing ecosystems around the globe. The consortium participates also in a taskforce together with, e.g., U.S., European and Japanese authorities which has achieved the first steps towards standardized energy-efficiency metrics. The recent memo [17] describes the progress and identifies a general need for the following metrics:

- IT energy efficiency
- Facility and infrastructure energy efficiency
- Effect of energy re-use and sustainable energy technology

The harmonization attempts have been successful in the second category. The recent agreement promotes power usage effectiveness (PUE) as the main metric assessing the facility level energy efficiency. PUE is defined as the total energy of the data center divided by the IT energy consumption (see measurement details in [17]) and it reflects the overhead of supporting components, especially cooling. A value 1 is perfect, whereas 1.7 is regarded as high [20]. Google reports the PUE of its data centers (those with actual IT load above 5MW) already below 1.2 [25]. The inverse of PUE is referred to as Data Center Infrastructure Efficiency (DCiE) and it is generally given as a percentage value (i.e. 100 % being ideal) [18].

The work in the first and the third categories, however, is still on-going. Several metrics are in consideration, but so far a general consensus has not been reached. Examples of the IT efficiency metrics include IT Equipment Efficiency (ITEE) and IT Equipment Usage (ITEU) [26], and Data Center Energy Productivity (DCeP) Proxies [23]. The key challenge in defining the IT energy efficiency is to define what is considered as "useful work" by the IT Equipment, i.e., the what is the output that could be compared against energy consumption. Examples of the metrics addressing renewable technologies and energy re-use include, Energy Reuse Effectiveness (ERE) [14], Carbon Usage Effectiveness (CUE) [13], and On-site Energy Generation Efficiency (OGE) and Energy Carbon Intensity (ECI) [27].

Recent research has already addressed various aspects of improving the energy efficiency of data centers, see [58] for a recent survey. Energy management schemes include low-power CPUs, efficient power supplies, water cooling (or even outdoor air cooling, cf. [42]), switching off network elements (e.g., [24], [47]) and improved software (e.g., virtualization). A common technological problem is the current designs are not energy proportional and do not allow addressing the performance/power trade-off efficiently for varying loads. Ideally equipment would consume no energy at zero load and reach full power only at maximum load [3]. Dynamic voltage and frequency scaling has been a successful energy-saving technique on laptop computers. In a networked setting, e.g., in data centers, usage of DVFS is more challenging as it may have crucial impact on the response times. Chen et al. [9] propose means of predicting the response times enabling performance-aware DVFS for multitier applications.

In data center networks the servers and cooling account for 70% of the energy budget. The network of the center consumes 10-20% of the its total power. The energy consumption of the switches is typically such that most of the consumption can be associated with the switch being powered on and increasing the traffic from zero to maximum load has only a minor effect [36]. The authors in [24] propose an active power management scheme for data center networks which results up to 50% power savings by switching network elements on and off. In [47] a formal model of energy-aware routing in data centers is established and solved using efficient heuristics.

Computer systems manufacturers participate in various consortia which aim at standardizing the performance benchmarks used in trade. In light of recent development in energy costs and energy-awareness, organization such as Transaction Processing Performance Council, Standard Performance Evaluation Corporation, and Storage Performance Council have developed test to measure the energy consumption in computer systems [44].

8 Analytical work and models

One of the starting points of this survey was to study what kind of mathematical modeling work has been done on the topic. One of the key topics is related to speed scaling, which may turn out to be important feature in the future communications equipment that are scalable, or energy proportional [3], in the sense that when the service rate is scaled down also the energy consumption goes down proportionally.

In this field, important work has been done with respect to queueing models. The trade-off between response time optimality, fairness and robustness of such systems has been addressed in detail in [1]. The authors shortest-remaining-processing-time (SRPT) and processor sharing disciplines in a setting where jobs have random lengths and energy costs the weighted sum of which is attempted to minimize. Robustness refers to models that utilize known parameters of future traffic - such a model becomes inherently vulnerable if the parameter values are not correct. Along the same lines [2] address the question that what is the minimum energy that is required to keep the network stable? They assume that speed scaling can be used to reduce the link rates to save energy. They devise different policies for servers to increase the rate according to the queue length and show scalability results on the maximum queue size. In particular, the worst-case models are addressed in this body of work.

Besides speed scaling some modeling work has been done in the context of wireless access networks. Marsan and Meo [38] utilize simple models to assess energy savings in a two-operator scenario and in [37] overlapping WLANs are considered. However, the models attempt to illustrate the benefits of the proposed schemes on a coarse scale rather than aim at accurate analysis.

Finally, there are some studies that shed light on the energy consumption in a way that they support mathematical modeling tasks. Tucker [52, 52] examines the energy consumption of optical networks in detail and Karray [30] develops analytical models for spectral and energy efficiencies in OFDMA networks (e.g., LTE). A short general review of energy consumption models at different levels is given by Xu et al. [56].

9 Concluding remarks

With wireless end devices most of the low-level network operations are well developed already and it seems that optical networking is currently best aligned towards development of energy savings in the near future. With optical networks the whole energy consumption chain is quite well understood as a whole. Furthermore, optical core connections can be generally viewed as bit pipes which simplifies the energy efficiency considerations.

Other areas of communications and networking are, however, more fragmented from the green networking point of view. Piecemeal advances are made on various layers on the protocol stack with sometimes unclear, or even incompatible, assumptions on other layers both above and below the focus of development. Such development of particular technology may induce additional difficulties in some other part of the stack. What is more, the technologies close to the user end have to respond to more diverse needs and varying conditions compared to optical networking. The effects of user behavior cannot be neglected as eventually it is the users that generate the traffic.

The problem on green networking should be viewed from a rather general perspective to truly get to the roots of energy consumption. A holistic approach on energy-efficiency could attempt to address following questions:

- What information needs to be communicated?
  - ”Is that ad *really* necessary, does it *really* need a flash player?”
- What are the requirements for the information to be communicated?
- How the information is communicated with minimum energy but still meeting the requirements?

At a more detailed level, future research will be seeking advances through piecemeal and disruptive approaches. Legacy equipment poses a problem that will take a long time to disappear. Backward compatibility requirements will cast a shadow over the green networking even longer and limit the scale on which improvements can be made. Piecemeal advances within well-understood functionalities are welcome as they are most easily implemented in practice. However, it is important to ensure that the developments do not have side effects in other parts of the energy consumption chain.

Another promising direction of research is to find out is there a possibility to save energy by completely new disruptive ideas. This line of research could be approached through mathematical modeling. With the exception of speed scaling there is almost no work done on this field so far. A good starting point could be to address the fundamental building blocks of communications, i.e. queueing and server models to gain understanding on energy-performance trade-off and to devise energy-optimal operational policies. The challenge lies in determining the relevant energy consumption models.

Finally, whereas many of the green networking improvements aim at utilizing the temporal variations of user needs the spatial component has yet to be addressed. This question has a resemblance to problems in logistics; it is more beneficial to store products locally than deliver them one-by-one from overseas. By local replication of services and multicasting technologies also the energy consumption could be addressed.

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