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RESEARCH ARTICLE

GREEN NETWORKING

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ABSTRACT

Green networking is the practice of selecting energy-efficient networking technologies and products, and minimizing resource use whenever possible.
Green networking practices include:

- Implementing virtualization.
- Practicing server consolidation.
- Upgrading older equipment for newer, more energy-efficient products.
- Employing systems management to increase efficiency.
- Substituting telecommuting, remote administration and videoconferencing for travel.

Although investing in green networking may require an initial cash outlay, the products and practices involved typically save money once put in place.
This paper focuses on optical networking as an energy efficient solution in green networking.

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INTRODUCTION

Green networking is a broad term referring to processes used to optimize networking or make it more efficient. This term extends to and covers processes that reduce energy consumption, as well as processes for conserving bandwidth or any other process that will ultimately reduce energy use and, indirectly, cost. The issue of green networking has many important applications, especially as energy becomes more expensive and people become more conscious of the negative effects of consolidating devices or otherwise optimizing a hardware setup. Software virtualization and efficient server use can contribute to this general goal. Green networking could also include such diverse ideas as remote work locations, energy use in buildings housing hardware, or other peripheral aspects of a network infrastructure. Ideas associated with green networking also address tech services or user relationships that may ultimately be built on a network. This includes green search or studies of the energy use of search engines, along with many other kinds of analysis of modern networks and tech system.

Key challenges to green networking: As a leader in telecommunications, Alcatel-Lucent recognizes the important role our industry must play in the global effort to address environmental issues such as climate change. This article highlights some of the corporation's major research and development initiatives.

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Alcatel-Lucent products are thoroughly evaluated for energy efficiency to ensure they support service providers' efforts to reduce the carbon emissions of new and existing networks. As part of its efforts to create exceptional value for its customers, Alcatel-Lucent committed itself to improving the energy efficiency of key products by at least 20% by the end of 2010 compared with 2008. In addition, Bell Labs scientists and engineers are creating innovative solutions and services that provide significant environmental benefits in a variety of business sectors, including smart metering, smart buildings, smart transport and tele-working. Alcatel-Lucent uses an end-to-end approach to energy efficiency in access, transport and core networks. For example, solutions for eco-sustainable wireless networks address all hardware, software, site and subsystem levels. As a result of this holistic strategy, customers benefit from tangible business and environmental benefits, including dramatically reducing their electricity bills, minimizing their carbon footprint, developing new revenue-generating opportunities through the availability of affordable alternative energy, and potentially expanding their business opportunities with carbon-reducing communication services. In February 2009, Alcatel-Lucent announced the Dynamic Power Save feature on its GSM/EDGE mobile networking portfolio. This new feature reduces power consumption when traffic drops, with real-time reactivity that guarantees no impact on service quality. This reduces average power consumption by 25-30% and can be installed on all of the 500,000 Alcatel-Lucent base stations deployed since 1999, thus protecting mobile operators' investments and making existing networks more energy efficient.

Alcatel-Lucent pioneered the combining of different types of wireless base stations to help customers save energy. The arrays of small coverage area (pico) base stations, strategically combined with a few large coverage area (macro) base stations in mixed deployments can be significantly more energy efficient than networks based on a single technology. Researchers have determined that the total network energy consumption can be reduced by up to 60% in urban areas for high data-rate user demand based on today's technology. Benefits could be as high as a 70% reduction in energy consumption as both technologies mature and the demand for high data rates increases. In July 2009, Alcatel-Lucent introduced the industry's first 100 Gigabit Ethernet service routing interface for the edge, to help service providers around the world meet massive bandwidth demands. Service providers must minimize space and power requirements if they are to contain costs and maintain an environmentally friendly operation. Alcatel-Lucent's FP2 silicon innovations and improvements in thermal efficiency reduce power consumption to levels approaching four watts per gigabit with the new 100 Gigabit Ethernet interface modules, a significant improvement compared to the 10 Gigabit and 40 Gigabit alternatives widely deployed today.

With 300 solar-powered wireless sites, Alcatel-Lucent has established an industry-leading Alternative Energy Programme. The programme's goal is to develop the world's first integrated, mass-produced, alternatively powered wireless base stations, making it possible for operators to extend the reach of their wireless services to access a huge population of potential new subscribers for its customers – the more than one billion people living in areas not served by an electrical grid. Intended for worldwide deployment, these hybrid stations powered by wind, solar and bio-fuel cells will be available as turnkey offerings, with faster delivery times and a higher return on investment than can be achieved with the fragmented, site-by-site solutions currently available on the market. The programme brings together the benefits of Alcatel-Lucent's experience in integration and implementation, the power efficiency of its base stations and its professional services. The operational launch of the world's first alternative energy laboratory and pilot site, located on the Bell Labs research site in Villarceaux, France, was announced in June 2009. Alcatel-Lucent Bell Labs is also researching new ways to improve thermal management performance while reducing the energy required to cool the equipment. These include thermal interface materials to conduct heat, vapour chambers to spread heat and heat sinks to dissipate heat into the air stream. Through its participation in the European research cooperation framework, Alcatel-Lucent is a key partner in the EC FP7 ADDRESS Integrating Project (IP). This project is working on a technical and economic solution to 'active demand', which means enabling consumers to proactively interact with the power system market, by means of real time interaction based on price and volume signals and by promoting the exploitation of sources of renewable energy and the development of a distributed generation model. Alcatel-Lucent Bell Labs is currently coordinating the preparation of the major EC FP7 EARTH IP, (EARTH: Energy Aware Radio and neTwork tecHnologies) addressing 'Green Networking'. The target of the project is to cut the energy use of mobile cellular networks by a factor of at least two. The project will investigate the energy efficiency limit that is theoretically and practically achievable whilst providing high capacity and uncompromised quality of service. The project is primarily focused on the future 3GPP mobile cellular systems LTE and LTE-A (Long Term Evolution-Advanced), where the potential impact on standardization is envisaged, but will also consider currently deployed 3GPP technologies (UMTS/HSPA) for immediate impact. The project will mobilize a consortium of major stakeholders to develop a new generation of energy-efficient products, components, deployment strategies and energy-aware network management solutions. The tangible results of the research project will include (i) energy-efficient deployment strategies, (ii) energy-efficient network architectures, (iii) new network management mechanisms that adapt to varying loads, (iv) innovative component designs with energy-efficient adaptive operating points, and (v) new radio and network resource management protocols for multi-cell cooperative networking. The new techniques will be validated using sophisticated simulation tools and in a mobile network test plant. The project will provide valuable and timely contributions to standardization and regulations process.

Recent studies indicate that Information and Communication Technology is responsible for a significant fraction of the world electricity consumption, ranging between 2% and 10%, with the twofold effect of contributing to global warming, through greenhouse gases release, and threatening sustainability of the growth of demand of Internet applications and services. For these reasons, energy efficient and sustainable networking, often simply referred to as Green Networking, has become a hot topic in the last few years. All aspects of Information and Communication Technology are under investigation, from energy-saving design of individual devices, to strategies that consider the entire network's energy consumption in the design, planning, and management phases, to new paradigms for long-term sustainability of the networks, that include reformed attitudes of users' as well as smart energy harvesting techniques. This paper on Green Networking aims at providing innovative contributions to the research and development of energy-efficient networking solutions and approaches for network sustainability. Possible topics include, but are not limited to:

- Energy efficiency for wired, wireless and mobile networks
- Energy efficiency for the core network
- Energy efficiency for data centers
- Energy efficiency for content distribution architectures and applications
- Measurements and models for energy consumption of networks and networks' elements
- Prototype, test beds, experimental results
- Zero grid-electricity networks
- Use of renewal energy in the networks
- Life-cycle assessment of networks and network components

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% . Lange *et al.* 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 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*. propose a regression approach to address the problem.

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 . Chabarek *et al*. 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*. propose a congestion control technique coupled with a physical layer re-source/power management primitives which results in a new access router functionality design (coined as the green router). In a follow-up paper , 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 consump-tion (assuming adaptive rate scaling) to match the minimum of the available capacity and user requirements QoS targets can be met with minimum energy consumption. Vasi´c and Kosti´c 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.Survey on green networking Aleksi Penttinen: be lowered to save energy. The authors report 21% and 16% sleep ratios for links and routers, respectively. Xia *et al*. 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*. 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 net- work in a series of two papers, . The approach represents the ideal case where the energy consumption is limited only by the Shannon bound on receiver sensitivity and depends on modu- lation 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. Tucker studies the energy-efficiency i.e., the energy per bit transmitted and show that the energy consumption is minimized by locating repeaters appro-priately. 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. Ac-cordingly, 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 . 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.

Access Networks

Wired access: The case of local area networks di□ers 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. Tsiaflakis *et al*. 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.

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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 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. . Karray 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 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*. 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 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.

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. 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 .

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 or 1.5% of the total U.S. energy consumption illustrate the enormous scale. In a data center virtually all the input electrical power eventually ends up as heat. 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 . Naturally also the energy-efficiency considerations of data centers emphasize the facility view- point. Major international e□orts are on-going to harmonize the energy efficiency metrics for data

Survey on green networking Aleksi Penttinen: IT Equipment 47 % Chiller 23 % CRAC/CRAH 15 % UPS 6 % PDU 3 % Humidifier 3 % Lighting / aux. devices 2% Switchgear / generator 1 % centers to enable the owners of data centers to assess and improve their performance. The Green Grid is a global consortium of IT companies and professionals seeking to improve energy ef-ficiency 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 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 con- sumption and it reflects the overhead of supporting components, especially cooling. A value 1 is perfect, whereas 1.7 is regarded as high . Google reports the PUE of its data centers (those with actual IT load above 5MW) already below 1.2 . 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) . 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) , and Data Center Energy Productivity (DCeP) Proxies . 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) , Carbon Usage Effectiveness (CUE) , and On-site Energy Generation Efficiency (OGE) and Energy Carbon Intensity (ECI) . Recent research has already addressed various aspects of improving the energy efficiency of data centers. Energy management schemes include low-power CPUs, efficient power supplies, water cooling (or even outdoor air cooling, , switching off network elements 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

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Survey on green networking Aleksi Penttinen 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.* 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 . The authors 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 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 .

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 (Barroso, 2007), 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 (Lachlan, 2010). 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 (Matthew Andrews, 2011) 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 utilize simple models to assess energy savings in a two-operator scenario and 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 examines the energy consumption of optical networks in detail and Karray 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*. .

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 require- ments?

At a more detailed level, future research will be seeking advances through piecemeal and dis- ruptive 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 im- portant 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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