J Supercomput
DOI 10.1007/s11227-011-0632-2

Energy-efficient networking: past, present, and future

Sherali Zeadally · Samee Ullah Khan · Naveen Chilamkurti

Abstract The twenty-first century has witnessed major technological changes that have transformed the way we live, work, and interact with one another. One of the major technology enablers responsible for this remarkable transformation in our global society is the deployment and use of Information and Communication Technology (ICT) equipment. In fact, today ICT has become highly integrated in our society that includes the dependence on ICT of various sectors, such as business, transportation, education, and the economy to the point that we now almost completely depend on it. Over the last few years, the energy consumption resulting from the usage of ICT equipment and its impact on the environment have fueled a lot of interests among researchers, designers, manufacturers, policy makers, and educators. We present some of the motivations driving the need for energy-efficient communications. We describe and discuss some of the recent techniques and solutions that have been proposed to minimize energy consumption by communication devices, protocols, networks, end-user systems, and data centers. In addition, we highlight a few emerging trends and we also identify some challenges that need to be addressed to enable novel, scalable, cost-effective energy-efficient communications in the future.

S. Zeadally
Department of Computer Science and Information Technology,
University of the District of Columbia, Washington DC, USA
e-mail: szeadally@udc.edu

S.U. Khan (✉)
Department of Electrical and Computer Engineering, North Dakota State University, Fargo ND, USA
e-mail: samee.khan@ndsu.edu

N. Chilamkurti
Department of Computer Science and Computer Engineering, La Trobe University, Melbourne, Australia
e-mail: N.Chilamkurti@latrobe.edu.au

Published online: 31 May 2011

Keywords Cellular · Efficiency · Energy · Green networking · Performance · Protocols · Wireless

1 Introduction

Recently, a committee of the National Academy of Engineering identified 13 Grand Challenges of Engineering for the twenty-first century. Among these challenges, three of them focus on *energy-related* issues namely, making solar energy more economical, providing energy from fusion, and the development of carbon sequestration methods [101]. All these Grand Challenges demonstrate the importance of energy issues and they share common goals which include reducing the cost of energy and reducing the emission of CO_2—a major contributor to global warming. Over the last two decades, we have witnessed an explosive growth in the use of Information and Communication Technologies (ICTs) equipment in all spheres of life that include the industrial, commercial, and residential sectors. ICTs have now become an integral part of our daily lives and our society has become heavily dependent on it.

In the past, a major focus of ICT equipment was on performance and cost. Little attention was given to the power consumed by ICTs and their impact on the environment. New trends such as rising costs of electricity, resource constraints, and increasing emissions of carbon dioxide (CO_2) are changing this focus making these trends global issues for governments and businesses. Figure 1 shows an estimate of CO_2 emissions for each ICT category. It is more than likely that energy consumption and carbon emissions will continue to increase in coming years. According to the SMART 2020 study, CO_2 emissions from ICT are increasing at a rate of 6% per year and with such a growth rate they could represent 12% of worldwide emissions by

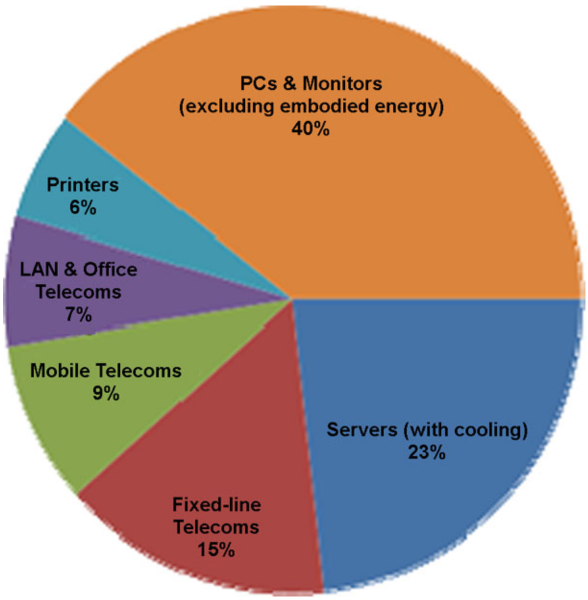

Fig. 1 ICT CO_2 emission estimate [99]

2020 [6]. To address this issue, it is crucial that we seek to improve and maintain the performance of ICTs while minimizing their energy consumption and their carbon footprint. ICT energy efficiency is not just about the amount of energy consumed by various ICT equipment and operations alone. A comprehensive energy-efficient ICT solution needs to take into account the entire product life cycle spanning from manufacturing to operation to disposal and recycling [100] of end-of-life products. A detailed discussion of the entire life-cycle of ICT energy issues is beyond the scope of this article. In this work, we focus primarily on the energy consumed by current commodity networking technologies, such as wired/wireless networks, communication protocols, end-user devices, and communication protocols and their environmental impact in terms of CO_2 emissions because these are the most widely used and deployed worldwide as part of the Internet infrastructure.

The rest of the paper is organized as follows. In Sect. 2, we present some of the motivations behind energy-efficient networking technologies. Section 3 describes recent techniques that have been proposed to enable energy-efficient networking and communications. In Sect. 4, we present some of the issues and some challenges that need to be overcome to enable energy-efficient solutions to be implemented and deployed to improve environmental and economic sustainability. Finally, we make some concluding remarks in Sect. 5.

2 Motivations for energy-efficient for information communication technologies (ICTs)

As mentioned previously, we have witnessed a drastic shift in priority in the information technology industry when it comes to ICTs in recent years. This shift and emphasis toward supporting the ICT needs by consuming less energy and minimizing carbon emissions in various sectors (industrial, commercial, residential) are being driven by various factors which include: (a) environmental issues such as global warming, (b) increasing demand for more power to support current and new ICT equipment, (c) the growing cost of energy, (d) increasing awareness of national energy security. A recent study showed that the increase in energy consumption and the corresponding CO_2 emission caused by ICT equipment is doubling every five years Daniels et al. [97]. The overall impact on the energy budget as a result of energy consumed by ICT equipment has been demonstrated in Matthews et al. [98] where it was shown that ICT consumes about 35–50% of the total energy consumption at an academic institution. Today, ICT is often one of the largest consumers of energy in residential homes of many industrialized countries.

It is worth pointing out that industry sectors, such as transportation and generating power (electricity production from coal-powered electrical generating stations), heating, and industrial processes directly generate CO_2. In contrast, ICT generates CO_2 indirectly by using electric power for ICT equipment and infrastructure (including cooling). It is this production of electric power from fossil-based fuels (in the US, over 50% of the electricity generated comes from coal) that leads to CO_2 emissions. In this context, many of the energy ICT saving strategies deployed so far have been aimed at improving energy usage, efficiency, and management of ICT equipment and

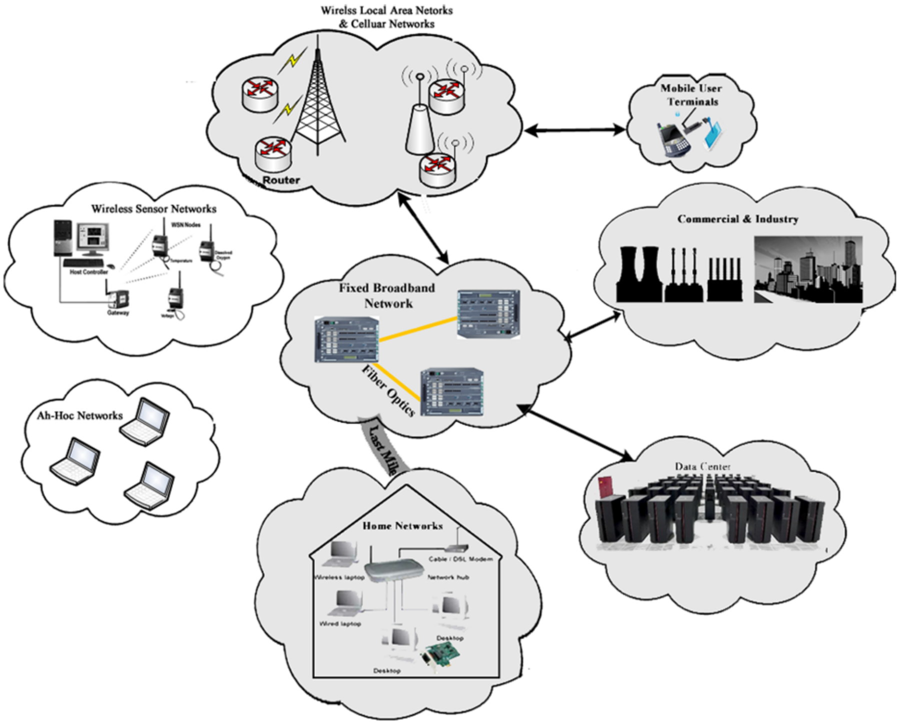

Fig. 2 Major networking areas of focus in this work with wireless sensor networks and ad-hoc networks excluded

infrastructures. The hope is that, through these strategies, we will be able to not only reduce the environmental impact of ICT use but also help energy providers, business, and residential users to improve long-term profitability.

In this paper, the scope of this work is restricted to energy-efficient schemes and strategies that are closely related to commodity networking technologies and devices that are currently most widely deployed and used within ICTs. Figure 2 shows some of the major networking components and technologies (excluding wireless sensor networks and ad-hoc networks) that we focus on in this work. Energy-efficient issues that address the entire product life cycle (material extraction, production, use, transport, and waste management) of ICT equipment and ICT hardware components (processors, memory, etc.) are beyond the scope of this paper.

The deployment and adoption of a wide variety of next generation wired/wireless and cellular networking technologies are causing a dramatic increase in the energy consumption. Currently, server farms and telecommunication infrastructures consume around 3% of the world's electric energy and this is increasing at the rate of 16–20% per year. Cellular networks consume 0.5% of the world's electrical energy with end-user terminals and the network consuming 1% and 99% of the total cellular energy consumption, respectively [96]. It is anticipated that the energy costs to run the cellular network will triple in the next seven years with 80% of the energy consumed by base station sites. Another dominant factor that is exacerbating the energy consumption in the telecommunication sector is the continued growth of the Internet which is being fueled by the growing number of different types of networks, the number of Internet users (using various types of mobile devices (some sort of handheld device such as a smartphone), personal computers (desktops and laptops), etc.) and the emergence of high bandwidth applications such as video conferencing, video-on-demand, remote visualization, video game consoles (Xbox and PlayStation), high definition TV, etc. all of which contribute to increased energy consumption. In the US alone, Internet uses 9.4% of the electricity produced [95] and this Internet electricity cost keeps increasing every year.

A recent study conducted by researchers at Rice University, Houston, TX, USA concluded that CO_2 emissions related to personal computers accounted for 48% of the total global ICT emissions in 2009. They predicted that the CO_2 emissions related to personal computers, mobile devices, and gaming consoles will experience more than a four-fold, four fold, and three-fold increase in carbon emissions, respectively, by 2020 compared to 2009 [94]. Various reports have been published in recent years demonstrating the need to develop energy-efficient networking infrastructures and technologies. In [93], the authors report that the energy consumption of Italy's telecommunication network came close to 1% of the total Italian energy demand and experienced a sharp increase of 7–12% from previous years. In 2007, another report from the Ministry of Internal Affairs and Communications in Japan revealed that networking equipment and devices (including routers, PCs, servers, etc.) consume about 4% of the total electricity generated in Japan with an increase of 20% over the past five years [28]. The BT Group, a major telecommunications and broadband Internet provider in the United Kingdom is one of the largest consumers of electricity using around 0.7% of the UK's total electricity consumption [92]. In developing nations such as India, the predicted rise in energy consumption (by almost 30% by 2014 [91]) stems primarily from the growing computing infrastructure such as personal computers, monitors, and mobile devices. Similar trends exist with other telecommunication and service providers in other countries to cope with increasing traffic demand and the ability to support emerging services. User mobility and the expectation of users to access information anywhere, anytime, from any device also require the availability of mobile communication networks and infrastructures to support such communications. The advent of fourth generation (4G) networks will also result in a dramatic increase in energy consumption. CO_2 emission is expected to grow by a factor of three by 2020 [89].

It is therefore in the interest of network designers, telecommunication equipment manufacturers, and service providers to build novel networking technologies, wireless transmission techniques, and network architectures and protocols that can scale cost-effectively not only in terms of their performances but are also highly energy-efficient during their operations in order to lower their operational costs [90].

3 Energy-efficient networking approaches

Research on energy-efficient networking has been going on for several years. With the growth of the Internet (including wired networks) and the emergence of wireless networks such as wireless sensor networks, multi-hop networks, mesh networks, ad-hoc networks, many studies have explored the topic of energy-efficiency of these networks, and protocols and applications running over them. Various energy-related issues have been thoroughly investigated covering a wide range of topics (routing, cross-layer designs, coverage protocols, spectrum allocation, Media Access Control (MAC) protocols, resource allocation, scheduling, etc.). It is not the intention of this section to present all these techniques covering these different types of networks. Such a survey is beyond the scope of this work. The goal of this section is to present some of the most recent advances that have been made specifically to improve the energy-efficiency of commodity-based networks (e.g., Ethernet, Wireless Local Area Networks (WLANs), cellular networks) rather than discussing related works for specialized networking technologies (e.g., sensor networks, ad-hoc networks, etc.) (as shown in Fig. 2).

3.1 Energy management for network equipment

3.1.1 Network adapter

Ethernet is the most popular wired technology for Local Area Networks (LANs) with over three billion network interfaces and millions of users worldwide. It is widely used in residential, commercial, and industrial sectors. Today, almost any desktop, laptop, or server manufactured has one or more Ethernet network adapters. Recently, many home appliances are also being equipped with Ethernet network interfaces. Ethernet data transmission rates have been improving over the years (from 10 Mbits/s to the latest 10 Gigabit Ethernet (10 GbE) technology that can support 10 Gbits/s). Higher data rates supported by recent Ethernet network adapters consume a much higher amount of power (e.g., a 10 GbEBASE-T transceiver consumes about ten times more power than a 1000BASE-T Ethernet transceiver).

Over the last five years, networking researchers and designers have been showing a lot of interests [86, 87] to improve the energy efficiency of Ethernet network technology. Their efforts led to the development of the IEEE 802.3az Energy Efficient Ethernet (EEE) standard [88] that was approved in 2010. The basic enhancement made by the EEE is the introduction of the Low Power Idle (LPI) concept. For high speed Ethernet (100 Mbits/s and above), a sender continuously transmits an idle signal that is used to maintain the alignment between the sender and the receiver (even when there is no data to transmit). The requirement to transmit this idle signal causes different parts of the transceiver of the network adapter to remain active and consume a significant amount of energy. The proposed LPI concept distinguishes between long periods of inactivity (during which no signal is transmitted and saves energy) and short periods of activity during which a signal is transmitted to refresh the receiver state. At least 50% energy saving is made over the traditional approach of using an idle signal [85]. Other approaches, such as the packet coalescing at the sender before transmitting them in a burst have also been investigated and demonstrated to minimize energy consumption of EEE while keeping packet delays within reasonable bounds for Internet-based applications [84]. It is anticipated that the adoption of EEE is likely to result in energy savings exceeding one billion dollars worldwide [85]. Another interesting energy-efficiency effort for Ethernet technology [102] evaluated current Ethernet encoding schemes and proposed a new energy-conscious encoding that is simpler to implement. The proposed technique yields around 18% and 60% improvements in transmission and encoding circuit energy, respectively.

Efforts to deploy energy-efficient network products also have recently been initiated by various networking equipment manufacturers such as D-link through their D-link Green Technology initiative. For instance, the D-Link's PowerLine Ethernet adapter saves energy by reducing the power delivered to it when it is not used. In 2009, D-Link released their 16-port Managed Gigabit Switch (the DSG-320-16 switch) that has the capability of automatically monitoring the status of the switch and minimizes power consumption by reducing the power delivered to ports that are not linked. D-link reports a maximum of 44% power savings with their energy-efficient switches [83]. Another feature of this switch is the inclusion of a smart fan equipped with heat sensors that can cause the fan to be switched on if the temperature of the switch increases beyond some level.

3.2 Network connecting devices—routers and switches

In addition to the dramatic increase in the bandwidth of communication links for wired networks mentioned in the previous section, another significant development over the last decade has been in the area of routers and switches that are widely used to connect different types of high speed networks that make up the Internet today. New packet switches and routers are being designed with increasing capacities and performance by exploiting recent improvements in the semiconductor technologies. The throughput capacities of many of these packet switches and routers have increased by several orders of magnitude in the last decade. As a result of these substantial improvements, the complexity of these switches and routers has also increased along with the power they consume. In addition, traditional solutions (such as the use of air cooling) used to cope with heat dissipation demands are becoming inadequate as well [81].

Unfortunately, the electronic components of these switches and routers are beginning to reach their physical limits primarily because of factors, such as maximum clock rate, maximum number of gates, and other hardware design limitations. The power density of the routers continues to increase, and at the same time, their power consumption also continues to rise with each new generation of switches and routers dissipating more heat than the previous generation.

To address power density issues, and reduce power consumption of electronic-based packet-switched routers, all optical router designs have been investigated for quite some time. In [82], it was shown that the power per bit required to switch the state of a semiconductor device is 100 to 1000 higher than that of a photonic device. Performing all of the processing, routing, buffering, and switching of packets in the optical domain continues to attract a lot of attention from router and switch designers [80]. Multi-rack (linecards that share a rack are connected by parallel optical links and a central electronic-based switch fabric) router designs have been proposed. Unfortunately, although such an approach reduces the power density, it increases the power consumption because more conversions are needed between the electrical and optical domain. To reduce power consumption, increase reliability and scalability, researchers from both academia and industry have been investigating the use of optical technologies (including the use of optical switching fabrics) to interconnect linecards [79].

Many energy-saving optimization techniques for devices (routers, switches, etc.) connecting networks are mostly based on (a) exploiting idle states (when no operations are being performed) by putting some switch/router components in low-power modes or turned off completely, (b) clocking the hardware at a lower speed, (c) adjusting the trade-offs between performance and energy during active periods (e.g., by reducing the link layer rate when the traffic generated is low) [73, 77, 78]. Several power management solutions in connecting devices have recently been proposed that use a variation of these techniques or some hybrid combinations of them. In [76], the authors proposed an algorithm that can selectively turn off some nodes and links of an IP-based backbone network during off-peak times. They demonstrated that an energy saving of at least 23% is possible for the total energy consumed by the backbone network. Many of the energy-saving solutions are also implemented at the hardware level or by changing configuration settings such as voltage and operating frequencies [75]. Software-level energy-efficient approaches that are based on open source freeware have also been used to take advantage of multi-core Commercial Off-the-Shelf Software (COTS) hardware [74].

It is worthwhile mentioning that hardware designers have also been investigating energy-efficient on-chip communication architectures and dynamic voltage and frequency scaling (a power management technique to reduce the voltage based on the frequency of the processor clock) techniques [71, 72] for several years and many solutions have been proposed in the literature. A discussion of these works is beyond the scope of this paper but can be found in [67–70].

The use of photonic technologies to alleviate energy consumption in routers/switches also is of great interest to designers because of their low power usage in interconnecting subsystems of routers. The key challenge for these photonic-based routers is to design board-to-board router backplanes that are based on optical interconnections instead of electrical interconnections [66]. The architectural trade-offs in designing high-performance, energy efficient routers based on the Network-on-Chip architecture paradigm have been investigated in [65]. By applying the technique of three-dimensional integration (3D) (an approach that minimizes the interconnect wire delay when several layers of silicon are stacked upon one another) to a Network-on-Chip-based (NoC-based) router (called MIRA), the designers were able achieve up to 67% reduction in power consumption in addition to significant latency improvements. Another recently proposed NoC-based router design is described in [64] where techniques such as adaptive channel buffers (which reduce the number of buffers required) and router pipeline bypassing (avoiding the router buffers and pipeline) are applied so minimize energy consumed by the router without sacrificing performance.

3.3 Energy-efficient communication protocols

There are two major characteristics of a protocol that can affect its energy-efficiency. The first is the overheads incurred to transmit the same amount of data. Higher protocol overheads make a protocol less energy efficient. The second major factor that can affect the energy efficiency of a protocol is the time overhead. The longer the time it takes to send data, the longer a radio interface should be active increasing the energy consumption [45].

In this section, we review energy-efficient techniques that have been recently proposed primarily for commodity networks and for the popular Transmission Control Protocol and the Internet Protocol (TCP/IP). There are numerous publications on energy-efficient communication protocols for wireless ad-hoc networks, wireless sensor networks, multi-hop wireless networks, and other specialized networking technologies in the literature. However, most of those publications have really focused on energy-aware routing, MAC techniques [63], and related performance issues. Jones et al. [62] present a survey of energy-efficient network protocols for wireless networks. Surveys of energy-efficient techniques for wireless ad-hoc and sensor networks are reported in [60, 61]. A thorough analysis and a discussion of energy-aware routing protocols for wireless sensor networks are given in [58, 59]. The basic idea behind many energy-aware routing protocols is to maximize the network lifetime (the interval between when the network starts and when the first node completely exhausts its energy). Other surveys on energy-efficient protocols for wireless sensor networks are given in [56, 57]. It is worthwhile mentioning that various energy-efficient MAC protocols for efficient power management control have also been extensively studied in the past. Given the large volume of published works that already exist for energy-efficiency for wireless and ad-hoc networks, we therefore do not cover these topics further in this paper. Instead, we focus on energy-efficiency for TCP/IP over commodity wired and wireless local area networks.

The rapid proliferation of TCP/IP-based applications has made TCP the *de facto* transport protocol for reliable communications over IP-based wired, wireless, and hybrid wired/wireless networks. Mobile users are becoming increasingly dependent on portable devices such as smart phones, laptops, cell phone, handheld many of which are powered by batteries. Many research works [39, 52, 54, 55] have been undertaken in the past to improve the performance of TCP over wired, wireless (including mobile wireless networks), heterogeneous wireless, heterogeneous wired/wireless networks. Most of the proposed approaches use one of the following techniques: link layer, end-to-end, split (by splitting a TCP connection into two: (a) one between the mobile host and the base station and the other between the based station and (b) the fixed host), cross-layer schemes, and various types of modifications to TCP congestion control algorithm). Most of them have focused on improving the performance (for performance metric such as throughput) of TCP when running over these IP-based networks. Despite the tremendous attention that has been given to improve TCP performance over wireless links, little consideration has been given to issues related to energy-efficiency of transport protocols such as TCP (and User Datagram Protocol (UDP)). Energy consumption associated with the execution of transport protocols at end systems (hosts) has become one of the important key performance issues that must be taken into consideration particularly for limited power mobile devices that have become so ubiquitous today.

One of the earliest studies on energy efficiency for TCP was conducted by Zorzi and Rao [51] in the late 1990s. They compared the energy consumed by several versions of TCP (OldTahoe, Tahoe, Reno, and New Reno). The main results derived from their analytical model demonstrate (a) that the congestion control implemented by TCP helps in saving energy (by simply avoiding transmissions when the channel conditions are poor); (b) the throughput and energy efficiency may be significantly improved by selecting the right choice of parameters for the TCP version used. Another study comparing the performance of energy/throughput tradeoffs of various TCP versions was conducted by Tsaoussidis et al. [50] who identified (using simulations) that the energy performances of various TCP flavors (they evaluated TCP Tahoe, Reno, and New Reno) are indeed fairly similar. The use of TCP segment caching as a technique to minimize energy consumption caused by expensive retransmissions was proposed in [49]. The main benefit of such an approach is that it does not require any changes to be made to the TCP protocol. However, it is hard to actually deploy this approach in portable devices because these devices are highly resource-constrained (for resources such as memory and processing power). Another interesting approach that improves energy efficiency of TCP is described in [48]. With this approach, the channel state (which can be in two states good or bad) of the wireless link is determined. If the channel state shows poor error characteristics the transmission stops and it resumes when the state becomes good. The state of a channel can be obtained by measuring the Signal to Noise Ratio (SNR) which is used to determine the link quality and the packet error rate. The proposed approach improves the energy efficiency of TCP by as much as 40% particularly for high-latency networks (e.g., Wide Area Networks (WANs)) and for networks with long durations of high error rates. Although the idea is simple and the simulation results show energy usage improvements, it is difficult to measure the SNR accurately making it hard to predict the channel state limiting its practical deployment.

One of the early protocols developed to improve TCP performance when packet loss occurs is the Partial Reliability Transport Protocol (PRTP) [47]. Unlike TCP which recovers from *all* lost/dropped packets, PRTP allows a certain *controlled* amount of packet loss which helps to improve energy efficiency and throughput as well as minimize delays. An energy-efficient version of TCP (E2TCP) was enhanced with PRTP and the impact of partial reliability on energy efficiency was demonstrated using simulations. E2TCP is used only on the last hop (the wireless link between the base station and the mobile host) for a wired/wireless connection and uses a combination of selective acknowledgments and a novel window management strategy aimed at reducing the time overhead [45]. It is worthwhile pointing out that the use of partial reliability is effective only for those applications that can tolerate a certain amount of packet loss, such as multimedia applications.

In [46], an energy-efficient TCP quick timeout technique was proposed for wireless local area networks that can improve energy efficiency by about five times over an unmodified TCP. The basic idea of this technique is for the MAC layer to provide feedback status of transmitted packets to the TCP layer, and for those packets dropped a quick timeout is triggered by the TCP layer. The net effect of this approach is to reduce the idle energy consumption.

A detailed study of the energy cost associated with different TCP functions is presented in [44]. Using hardware platforms such as laptops and handheld devices running FreeBSD and Linux operating systems, their experimental results revealed that TCP processing cost accounts for 15% (out of which 20–30% is used to compute TCP checksums) of the total computational energy cost incurred by host processing of network packets. The remainder of the computational energy cost incurred by a sender host is attributed to the energy used to perform user to kernel copy and kernel to network adapter copy. By minimizing these copies, the authors demonstrate they can achieve 20–30% energy cost reduction for TCP connections.

Other techniques for more specialized networks also have been proposed to improve the energy-efficiency of communication protocols. The use of novel scheduling algorithms described in [43] enable an energy-aware transmission schedule such as transmitting using a lower power but over longer durations leads to conservation of energy. In [42], a multi-threaded approach is proposed to integrate a simplified TCP/IP stack for resource-constrained systems such as those with highly energy-efficient microcontrollers with limited memory resources. The effects of data compression on energy consumption over wireless networks have been presented in [41] who found that up to 57% energy savings can be reaped depending on the compression tools (such as gzip, lzo, lzma) used.

3.4 Energy-efficient fixed and cellular networks

The explosive growth of mobile computing applications along with increasing mobility of users carrying all kinds of portable devices will continue to accelerate the demand for mobile wireless networks in the future. Mobile users will continue to expect high bandwidth and low delays from these mobile networks. All these user expectations and mobile infrastructures will lead to an increase in the energy consumption leading to higher emissions of CO_2. As shown in Fig. 3, the contribution of CO_2 by mobile networks is expected to almost triple in 2020 (181 Megatons of CO_2) from 2002 (65 Megatons of CO_2). This projection is motivating telecommunication operators to explore innovative solutions that can reduce the energy consumption by their mobile network infrastructures (such as fourth generation (4G) networks) and mobile devices of end-users.

As we mentioned previously, many mobile devices are being used by users for their mobile computing applications. These portable devices have limited battery

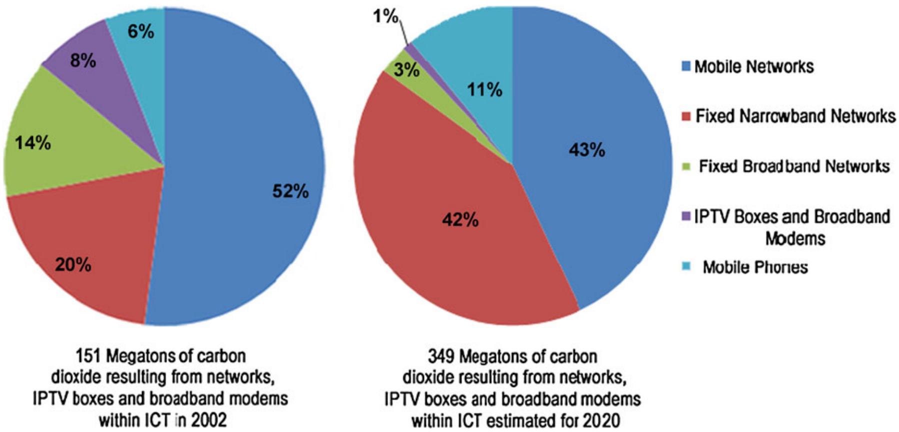

Fig. 3 CO_2 emission in 2002 and projected emission for 2020 [40]

power capacity. In this section, we briefly present some recent works that have focused on energy-efficiency issues for wireless local area networks and cellular networks. We have already covered protocol issues in the previous section; we will therefore discuss energy issues related to frequent mobile network operations (such as handover, network selection, etc.) in the following section.

3.4.1 Network selection and handoffs

Handoff is the process during which a mobile device keeps its connection active as it migrates from the coverage area of one network to another. Handoffs between homogeneous networks are termed horizontal handoffs whereas handoffs that occur between different networks are termed vertical handoffs. With the emergence of different types of wired/wireless networks (wireless local area networks, Generalized Packet Radio Service (GPRS), Worldwide Interoperability for Microwave Access (WiMAX), etc.), *vertical handoffs* are used to switch from one network type to a different one. The vertical handoff process is achieved by three basic steps: network discovery (the process by which a mobile device discovers reachable wireless networks), handoff decision, and handoff execution. Traditionally, network discovery and selection have been achieved based on criterion such as the received signal strength. The mobile device will connect to the access point that gives the strongest received signal strength. Today, with the availability of different types of networks, the network selection process (as part of the handoff process) has become more complex. This is because the choice of network to be selected needs to take into account several factors such as cost, Quality of Service (QoS) requirements of the user, QoS offered by the available networks, available services, and power consumption.

Traditionally, network discovery techniques assumed all network interfaces on a mobile device (assuming a mobile device has multiple network interfaces) are active all the time and these interface continuously scan for signals coming from one or more nearby wireless access points. The disadvantage of this approach is that it quickly drains the battery power of the mobile device. Past studies have demonstrated that the power consumption of network interfaces dominate the total system power consumption for mobile devices. One approach that can be used to save energy is to activate the network interfaces periodically instead of keeping them "alive" all the time. The power saved with such an approach is inversely proportional to the frequency of activations of the interfaces [53]. Chen et al. also proposed the use of a location-based wireless network discovery method using the Global Positioning System (GPS) technology. Such a solution is not practical because it requires embedding a GPS receiver in the mobile device increasing the cost and size. In addition, the accuracy of GPS results degrades in urban environments and it does not work well inside buildings. Joe et al. [38] proposed a handoff technique that takes into consideration the power consumption of network interfaces and the Quality of Service in available networks. Unfortunately, the authors do not describe how to determine those parameters in real networking environments.

Another network interface selection algorithm called WISE was proposed in [37] to achieve energy-efficient vertical handoffs and prolong the lifetime of mobile terminals. Nam et al. focused on handoffs between 3G networks (such as Code Division

Multiple Access 2000 (CDMA2000) and WLANs (such as 802.11b). Their motivations for investigating network interface selection for these two types of networks stem from the fact that a 3G network adapter (e.g., a CDMA2000 1× Evolution Data Optimized (EV-DO) adapter) for a mobile device in transmit mode uses about *twice* as much energy compared to a WLAN (Orinoco 802.11b) adapter. However in receive mode, the reverse is true (with the WLAN adapter consuming twice the energy) but close to nine times the energy used by the 3G network card when in idle mode (no data to transmit) [37]. By making use of a centralized entity called the virtual domain controller, the WISE approach dynamically switch between the 3G and WLAN network interfaces based on the amount of data traffic being exchanged to minimize energy usage by the mobile terminal. The design objective of WISE was to save energy but it is not entirely clear how throughput is affected when switching to networks such as a 3G networks with much lower bandwidth capacity compared to that of WLANs.

In [34], the authors proposed an energy-efficient discovery method based on a simple and inexpensive cell-id-based location management [33] technique. This approach not only avoids unnecessary network interface activation but also enables fast detection of wireless networks and does not require any upgrade of the network or the mobile device making it a highly practical solution. Empirical performance evaluation results of the aforementioned method gave a 19.1% energy usage improvement over the case when interfaces are active all the time and a 12.3% energy saving over the case when periodic activation is used.

In [35], the authors proposed the MxN architecture that uses a cost function to perform optimal network selection with high energy-efficiency. The energy consumed is kept to a minimum by enabling the device to reduce its frequency of scanning for available networks. This is achieved by using the information provided by the Information Service of the 802.21 standard [36] and it was also shown that the request rate for such information consumes little energy. In contrast to Siddiqui's work, the performance evaluation was based on simulation and a performance evaluation of an implementation of the $M \times N$ prototype still needs to be done to determine the practical performance that can be reaped with this approach.

3.4.2 Energy-efficient base stations

Mobile networks continue to be deployed at a fast pace to meet user mobility requirements. 4G networks (including network technologies such as LTE and WiMAX) promise higher data rates to end-users. These high data rates are also leading to an increase in the power consumption of the three basic components of mobile networks namely, user terminals (used by mobile users for data and phone calls), base stations (handles the radio interface between the network and the user terminal), and the actual core network (made up of core switches and routers used for switching, mobility and call connection management). As we discussed earlier, the communication protocols used also contribute to the end–end energy consumption for mobile network applications. A recent study [28] conducted on NTT DoCoMo, the largest telecommunication operator in Japan, found that the energy consumed (per day) by a user using the mobile network is about 150 times higher than the energy consumed by the user's mobile terminal. By optimizing the energy efficiency of base stations, Third Generation (3G) base stations over Second Generation (2G) base stations by about three times [31, 32].

3.4.2.1 Reducing energy consumption of base stations An interesting study on the life cycle of 3G network systems performed by Origuchi et al. [30] revealed that CO_2 emission from 3G networks was mostly from mobile terminals and base stations. 55% of the CO_2 is produced in the *usage* and around a slightly lower percentage is used in the *production* stage. The emissions that resulted from the usage portion mainly came from the base stations of mobile networks whereas terminals were responsible for emissions during the production stage. Given that the base station is a large contributor of energy (contributing 60% to 80% of the entire mobile network energy) consumed in a mobile network many recent efforts have been investigating novel techniques that can minimize the energy usage of base stations.

- *Improving hardware energy consumption of base stations:* one set of improvement techniques involve improving the hardware energy efficiency of the transceivers of the base station. The power amplifier is the component that uses the most power in the transmitter and its energy use depends on factors such as modulation used, the frequency band needed, and other operating conditions. To improve the energy efficiency of the power amplifier, different types of linearization methods, such as Cartesian feedback, digital pre-distortion and digital signal processing methods (used in Wideband CDMA) can be used [29].
- *Improving energy consumption used by system and software features of base stations:* one of the most common energy saving methods for base stations that has been used for quite some time by many mobile network operators is to turn off either some parts of the base station or the complete system when the traffic load for the base station site (cell) is low (e.g., during night time). This approach is commonly used for small cells (femto-cell and pico-cell) that are typically deployed for indoor sites [27]. Some site specific solutions have also been suggested and these include: (a) the deployment of indoor sites that use natural fresh air cooling instead of air conditioners, (b) having a base station design that brings the radio frequency transmitter closer to the antenna (which will reduce energy losses by the feeder cable and improve performance) in contrast to the traditional base station architecture where a coaxial cable runs between the in-building base station to the outdoor antenna. Such a design aimed at reducing the power consumption of the base station was recently demonstrated in [28] who proposed a distributed base station architecture using IP and Radio on Fiber (RoF) technologies and a novel Optical Feeder Transmitter and Receiver base station was proposed. The design makes use of IP and RoF technologies. RoF technologies can support highly scalable solutions through the use of distributed antennas and they do not suffer from the power loss that normally occurs with radio frequency co-axial cables. In contrast to traditional base station rooms which require air conditioning, this Optical-Fiber Transmission design can also be air-cooled naturally.

3.4.3 Reducing the energy consumption of cellular networks

The number of base station sites also has a significant impact on the total amount of energy consumed by the underlying cellular network. The tradeoffs among base station density, capacity, and energy consumption have also been studied by various researchers recently [23, 24, 26, 27]. Several centralized and decentralized power efficient algorithms have been proposed to make cells more energy-efficient. The centralized approach needs channel information, traffic requirements, etc. compared to the decentralized approach. In terms of energy consumption, the centralized approach performs better because the coverage area is small. The impact of other network factors such as load balancing and macrocell network topologies on energy saving by the base stations have also been explored recently [23–25].

3.5 Last mile access with fixed broadband networks

The "last mile" of many telecommunication networks often serves many residential and commercial users and it is a significant part of the Internet infrastructure. Wireless access networks (such as WiMAX) are also being widely deployed as a "last mile" network technology. Therefore, any reduction in energy consumption by these access networks will minimize the emission of CO_2. A novel architecture (called WOBAN) that was recently proposed in [22] combines an optical backhaul (a Passive Optical Network) with a wireless mesh access network as the front-end. The WOBAN architecture minimizes energy usage in both the wireless access part (by putting transceivers to sleep while maintaining connectivity, better coordination between nodes to reduce collisions, and lightweight protocol stack) and the optical backhaul (by putting some optical network units to sleep when the traffic load is low) as well as in the routing protocols used (with the goal of re-using routing paths previously used) [22].

In [21], the authors performed a life cycle assessment to study the carbon footprint of fixed broadband networks that include three types of FTTx networks such Fiber to the Cabinet (FTTC), Fiber to the Home (FTTH), Fiber to the Building (FFTB) for a dense urban area in Italy over a period of a year. The goal was to identify area of high-energy consumption for these network technologies. The worst case results show that all these network access technologies produce around the same amount of CO_2 a year. They also discovered that, in terms of energy savings, the customer equipment has the largest potential for improvements. By using existing infrastructure and smart power management schemes (such as low power mode for customer premise equipments and reuse of infrastructures), it is possible to reduce FTTH energy consumption by almost 80%. FFTH demonstrated the best result energy consumption when bandwidth is taken into consideration. The main energy consumption with FTTH comes from the use of home residential gateways, their production, and the use of diesel trucks during engineering civil works and trench deployment.

3.6 Data centers

Many dedicated facilities (also known as data centers) have been built recently to house large numbers of servers and storage systems. These data centers are being deployed to deliver different types of networked services offered by various businesses, governments, etc. Currently, the number of servers in data centers ranges from 10,000 to 100,000 with 150,000 servers emerging. Power density has grown so far from 10 kW/rack in 2004 up to the 55 kW/rack most recently [17]. It is estimated that around 50% of the total data center power consumption is used for cooling. Based on Arrhenius time-to-fail model [20] every 10°C increase of temperature increases the system failure rate by a factor of two. Energy management is therefore becoming increasingly important to deal with the operational temperatures and increase the reliability of computing resources in data centers.

The ever increasing electricity demands of data centers (the electricity consumed by data centers is doubling every five years in the US [19]) along with rising energy costs, inefficient power distribution systems, inefficient cooling systems and servers are strong catalysts pushing for more energy-efficient data centers with innovating cooling solutions. Techniques that have been proposed to improve the energy efficiency of data centers have focused on three specific areas: (i) effective cooling methods (such as the use of liquid cooling or fresh air cooling compared to the use of traditional air conditioning units), (ii) more energy-efficient servers (through more efficient microprocessor and chip designs that use less energy and power management strategies), storage systems, and power supplies, (iii) the deployment of highly efficient load balancing approaches that can maximize the usage of server resources. Virtualization software (using an encapsulating software layer (also known as a Virtual Machine (VM)) that provides the same inputs, outputs, and behavior that would be expected from physical hardware) is also being used as a promising technology that can maintain high utilization of servers [17, 18]. Server utilization rate can increase from 5–15% to 60–80% with virtualization. In addition, virtualization leads to fewer servers saving space and power.

To reduce cooling cost and power usage in data centers, a heat pipe based ice storage system is proposed in [16]. This system can be deployed in cold geographical areas where the temperature is low to enable the formation of ice and cold water. The criteria for choosing a data center location using this technology will depend on both the duration and temperatures below freezing. The ice storage system can be integrated with an existing chiller and serve either as a back-up or an alternate cooling system. In contrast to traditional water storage system which requires a dedicated room for storing cold water, the ice storage system is much more cost effective to build because it is located underground and therefore incurs much lower storage space and construction costs. By pre-cooling warm water coming from the servers using the proposed ice-storage system reduces the cooling load of the chiller, leading to a reduction in the overall power consumption used for cooling the data center.

In [13] and [14], the authors proposed various metrics to measure and quantify the performance of their data centers' air distribution systems. They also describe changes that they make to their cooling systems to improve air management to maintain cooling system effectively. The main drawback of these metric-based approaches is that they need to be rigorously tested and validated through extensive simulation tests before they can be implemented. However, once the metrics have been correctly validated and assessed, a major benefit is that the use of these metrics does not require major structural or new equipment changes. A more proactive approach based on novel sensing and measurement technologies that allow visualization of the temperature data in 3D and heat distribution in a data center is presented in [15]. This new technique will enable rapid diagnosis and identify existing cooling problems inside the data center and will help to improve its energy efficiency.

4 The future

4.1 The energy-efficient communications landscape

The area of energy efficient communications has been studied because half a century ago [12] by researchers and designers. However, the tremendous increase in interest in this area started in the late 1990s with the emergence of networking technologies such as wireless sensor networks and ad-hoc networks, along with the emergence of all kinds of portable devices with limited battery power. As mentioned earlier, most energy-related networking research efforts undertaken then have been focusing on techniques that can extend the lifetime of the network (including network nodes) and battery-operated networked, mobile user devices and appliances. Surprisingly, this strong energy interest from the networking research community remained almost flat for almost a decade afterwards during which researchers continued to explore energy efficient mechanisms for wireless sensor networks and ad-hoc networks specifically most probably because of their ubiquity. During that time, reducing the energy usage of commodity communication protocols, local area and backbone networks, and operating systems did not really receive a commensurate level of attention from the research community and manufacturers of networking products and systems. The situation changed dramatically in the last 2–3 years with efficient energy networking coming back as one of the emerging areas of intense research activity. Both academia and industry are now showing a renewed ever-increasing interest in energy consumption which is growing every year. There are many reasons for this sudden shift: the user base for personal computers and portable devices, and the number of different types of access networks, the use of IT equipment to meet the business computing needs all continue to grow at a rapid pace leading to an increase in the global energy consumption. The cost of energy also keeps increasing. Along with these two trends, environmental concerns (caused by CO_2 emissions) have also begun to receive a lot of attention from hardware/software manufacturers, various regulatory commissions, governments, and energy policy makers of various countries around the world. These trends are expected to continue in coming years.

4.2 Energy consumption of communication networks, protocols, and devices

The emergence of a standard such as IEEE 802.3az demonstrates a strong commitment of both industry and academia to deliver energy-efficient network adapters particularly for highly popular network technologies such as Ethernet. Given the ubiquity of network adapters in most end-user systems, optimizing their energy consumption can have a significant impact on the overall energy consumption of ICT. Most energy consumption optimization techniques that have been proposed to date for network adapters and switches have focused on primarily putting some adapter components to sleep or in some inactive state such that little or no power is consumed thereby saving energy. Significant energy savings have been demonstrated using these past approaches. However, it seems that all the optimizations are incorporated into the hardware (or firmware for the network adapter) at the design stage of the network adapters. This makes it difficult to optimize energy consumption further through software programmable functions. As a result, many of the proposed energy-efficient optimization solutions for network adapters are limited in their flexibility and scalability. Future network adapters and switches need to provide programmable low-level functions, such as device driver and user functions that can enable further energy optimization techniques to be explored if required.

Next generation routers and switches continue to improve their performances. Faster processing speeds consume more energy. To cope with the corresponding increase in energy requirement by many silicon-based routers, recent trends have focused on reducing the packet processing depth, and highly integrated designs. Best energy efficiency is obtained with routers that use a minimum packet processing depth in a highly integrated design using denser and faster silicon for routing and switching. Custom made silicon designs operate with the best power efficiency over complex silicon design [1]. However, one major shortcoming for specialized silicon is their inability to scale to support additional features in the future when new router functions become necessary. Besides, as mentioned earlier, current electronic switching fabrics used in most high capacity switches and routers have also reached their limits in terms of the large number of interconnections required, their energy usage, and heat dissipation. The current design trend for high capacity switches and routers is focusing on the use of optical technologies and optical switch fabrics which promise high capacity, better scalability and reliability, and reduced power consumption. However, this trend is still being hindered to some extent currently because of the lack of some of the optical components required to fully achieve this optics goal. More research in this area is needed to enable the design and development of inexpensive optical components that can be cost-effectively incorporated in future high-performance optical switches and routers.

Most of the related works on energy consumption for commodity protocol stack such as TCP/IP have focused mostly on improving its throughput with only a few of them which dealt with the protocol's energy-efficiency. These few efforts did not propose techniques that can optimize the energy efficiency of the TCP/IP stack. Instead, they focused on performance comparison studies of various flavors of TCP. The TCP/IP stack is used by every host connected to the Internet and there is significant room for improving the energy efficiency of this protocol stack when running over both wired and wireless networks. So far, work in this area has been slow and more efforts will be needed to improve the energy used by TCP-UDP/IP stacks in the future.

The number of mobile users worldwide is close to 5.3 billion with almost half a billion users accessing mobile Internet in 2009. This trend will continue and network designers and operators will need to support information access anywhere, anytime from any device as users roam around. Energy-efficient handoff has now become an important performance metric for network architectures supporting vertical handoffs among heterogeneous wired and wireless networks. While some cellular technologies (e.g., Global System for Mobile Communications (GSM)), have matured over the years with highly energy-efficient base station designs, energy-saving optimizations of base stations (through small, compact designs and the use of optical technologies) for various recent wireless technologies (e.g., WiMAX), Long Term Evolution (LTE), Wideband Code Division Multiple Access (W-CDMA)) still remain to be explored in the future.

The underlying operating system of the host system is part of the end-to-end communication path between the sender and the receiver. In this paper, however, we focus mainly on those components involved in network communications. New versions of Windows-based (e.g., Windows 7) and Linux-based (e.g., SUSE Linux Enterprise Desktop 11 from Novell) operating systems have been designed to be more energy-efficient by exploiting different types of smart power management techniques. An in-depth discussion of energy consumption design issues for operating systems is beyond the scope of this work but can be found in [11].

4.3 ICT energy consumption versus CO_2 emission

As we discussed earlier, the main source of CO_2 resulting from ICT comes from the production of electricity to power up networks, computers, servers, and storage devices (including the power needed for cooling and heat removal which continues to increase with higher power density of ICT equipment). In the US, almost two-thirds of the electricity produced by electrical generating stations comes from fossil fuels (i.e., coal, oil and natural gas) [10]. To reduce our dependence on fossil fuels, lower the carbon footprint, and improve energy security in the future for ICT, we need to focus on renewable energy sources such as wind, solar, geothermal, biomass, and water power. However, because most of our current communication infrastructures (including the Internet) heavily use electrical power to operate, it is imperative that any move to renewable clean energy ensures that we maintain a reliable and stable power supply. This implies that with intermittent energy sources such as solar or wind power we need to ensure high capacity energy storage facilities, such as the use of rechargeable batteries and ultra-capacitors that can continue to supply energy without interruption. This strategy of using renewable to power on the communication infrastructure can also be used to support rural areas of many developing nations where frequent interruptions of electricity is quite common [9].

4.4 Energy-efficiency at data centers

Various types of high-performance equipment are being deployed in data centers. To support these high performance requirements, data centers must provide more power for the equipment to perform efficiently and reliably. One of the strategies being investigated to improve energy use in data centers is the use of renewable energy sources to provide the required power need to operate the data center. Building data centers in those geographical areas with an abundance of renewable energy sources (solar, wind, etc.) is one option that has been explored. Another option is to avoid multiple conversions between Alternating Current (AC) and Direct Current (DC). The basic idea in this case is to do the conversion only once at the data center rather than doing it several times at various servers as is done currently [5]. The use of more power is also causing more heat to be generated by data center infrastructures. To address the heat issue, many cooling strategies are being investigated and developed. To quantify the power efficiency of data centers, a metric such as the Power Usage Effectiveness (PUE) has been proposed. The PUE is defined as the total power used by the data center divided by the total power consumed by the ICT equipment. PUE can be used to benchmark how much energy is being usefully deployed versus how much is wasted on overheads. Typical data centers today have a PUE of about 2 or higher. By carefully operating much of the current equipment in use and by using the latest hardware and software technologies, the Environmental Protection Agency (EPA) predicts this PUE number can be reduced to 1.7 and 1.2, respectively. Power and cooling efficiency improvements will continue to challenge the design of next generation, energy-efficient data centers. To achieve power efficiency, we need to develop solutions not only at the system level through well-known power management solutions but also through the careful integration of hardware solutions such as asymmetric multi-core microprocessor design, efficient packaging techniques, and energy-proportional hardware designs that focus on memory and disk subsystems which can reduce the power consumption of central processing units [2].

4.5 Energy efficiency measurement tools and performance metrics

As we mentioned before, PUE is a widely used metric to quantify the power efficiency of data centers. Today, energy efficiency has become an important metric that is being increasingly used to evaluate the energy consumption of devices, hardware, software, and various networking architectures, systems, and communication protocols. Many energy efficiency metrics for networking protocols and devices have been proposed in the past, but most of them have been specialized for specific networking software or equipment and are being used in an ad-hoc way. For instance, typical ones used in the literature include absolute power in watts, power per bit, and normalized energy consumption (sum of energy consumed by all components) to full-duplex throughput for networking devices [1]. Unfortunately, the lack of standard energy efficiency metrics makes energy performance comparisons for networking devices and protocols hard to achieve in practice. In the future, to help networking designers, implementers, application developers, and researchers better assess and evaluate the energy efficiency of their implementation prototypes, we need to standardize a set of energy-efficiency metrics with a finer granularity that takes into account diverse processing functions and configurations. Similarly, we found there is also a lack of energy performance tools that can be used to measure energy efficiency of networking devices, systems, protocols, and applications. There are a few commercial highly sophisticated power measurement tools available, but they are prohibitively expensive. A few cost-effective tools are also available on the market (e.g., the Kill A Watt EZ tool that can be connected to an appliance and measures its power usage). But they are of limited use for serious energy-efficiency research purposes given their coarse measurements of electricity used. Two freeware energy-measurement tools we recently experimented with include Joulemeter (estimates the power used by one's computer) from Microsoft Research and the Intel's Application Energy Toolkit (used to evaluate power consumption of software applications). We found that, while these tools are fairly easy to use and they do provide some basic power consumption information (e.g., battery usage, voltage, etc.), they are not user friendly as far the processed output results are concerned or sometimes even the output data would be corrupted and required the tests to be repeated, etc. In short, we need far more efficient, easy-to-use, low-cost energy performance tools that researchers and designers can easily use to conduct robust energy performance evaluations of their prototype systems.

4.6 Impact of energy-efficient information communication technologies (ICTs) on the economy and other sectors

ICT is expected to become one of the major contributors of CO_2 emissions by the end of this decade. But some interesting results recently published also revealed the tremendous positive impact that ICT will have on reducing the global carbon emissions by other sectors which are using ICT. Such a positive impact can be achieved through ICT use which: (a) makes current processes more efficient (e.g., improvements to vehicular technologies), (b) enables technologies (e.g., email communications) that improve business operations, (c) promotes the development of low-carbon solutions (e.g., fiber optic technologies) [8]. According to a recent Smart 2020 study [6], the adoption and use of ICT solutions could actually help reduce the carbon emissions by almost 15% by 2020 (almost five times the carbon emissions that could result from ICT itself by 2020). Another comprehensive study [7] explored the net energy impact of ICT on the overall energy consumption in the US. The study found that for every extra kilowatt-hour used by ICT, the US economy saved energy by almost a factor of 10.

The ICT sector (including laptops, personal computers, telecommunication networks, data centers and computer networks, mobile devices) continues to grow on a global scale and the momentum will increase in coming years as more ICT equipments are being deployed and used in various sectors of society. In 2009, the CO_2 produced by the ICT industry was around 2% of the global CO_2 emission which is comparable to that produced by the aviation industry [4]. This is estimated to increase to 3% of global emissions today by 2020 [3]. There is clearly a very strong need for the ICT industry to curb its CO_2 emissions which, in turn, will lead to further reduction of CO_2 emissions in many other sectors of society where ICT is ubiquitously deployed and used. In this work, we focused on some of the novel solutions that have been proposed to minimize the energy consumption of communication technologies and protocols that are major components of the ICT sector.

5 Conclusion

The reduction of operational energy consumption alone will not be sufficient to enable and maintain sustainability. We need a holistic approach that considers not only the energy consumption during the usage stage but the *entire* product life-cycle from production to usage to disposal/recycling. We presented various approaches that have been proposed to reduce energy usage in those technological areas. We also identified some future trends and a few challenges we still need to address in the future. Information and Communication technologies are strong catalysts that can help boost productivity and efficiency in many sectors of the economy. These benefits are currently being reaped at the expense of increasing emissions of CO_2 and the continuous depletion of fossil-based fuels used to generate the required electrical power needed to power ICT equipment. In addition, we are witnessing increasing energy costs year by year. To address these systemic challenges, we need to continue to develop innovative, cost-effective, and energy-efficient solutions that can minimize the energy consumption of ICT technologies and exploit renewable energy sources wherever possible. This can be achieved if power-awareness is fully taken into consideration in the design, implementation, deployment, and maintenance of ICT technologies. It is worth pointing out that various energy policies and standards will also continue to play a significant role in optimizing energy-efficiency of ICT equipment as well as their usage by the consumers. We do not cover these areas in this work. A detailed discussion of the impact of these efforts on energy efficiency is a subject of further study.

Acknowledgements We would like to thank Sean Golash and Rafine Ly for sharing their practical experiences on the energy performance tools. Sherali Zeadally was partially supported by a District of Columbia NASA Space Grant and an NSF TIP grant (Award Number 1036293) during the course of this work.

References

1. Ceuppens L, Sardella A, Kharitonov D (2008) Power saving strategies and technologies in network equipment opportunities and challenges, risk and rewards. In: Proceedings of international symposium on applications and the internet (SAINT), July, pp 381–384
2. Paleologo G, Benini L, Bogliolo A, De Micheli G (1998) Policy optimization for dynamic power management. In: Proceedings of design automation conference, June, pp 182–187
3. Harter G, Sabbagh K, Shehadi R, Karam D (2010) ICT for a low carbon world: activism, cooperation, innovation. In: World economic forum, Davos, Switzerland, Booz and Company, January
4. Fargo B, MacAvoy D (2010) A practical approach to greening the electronics supply chain results. In: Electronic industry citizenship coalition (EICC), 2009 EICC—carbon reporting system, pilot initiative, June
5. McKenna P (2008) Can we stop the Internet from destroying our planet? New Scientist, January 2008
6. The Climate Group, Smart 2020 (2010) Enabling the low carbon economy in the information age, 2008. http://www.smart2020.org/ (last accessed March 23, 2010)
7. Laitner J, Ehrhardt-Martinez K (2010) Information and communication technologies: the power of productivity, American council for an energy-efficient economy, February 2008, http://www.aceee.org/research-report/e081 (last accessed March 23, 2010)
8. UK Parliamentary Office of Science and Technology, ICT and CO2 emissions, Postnote, No. 319, December 2008
9. Raman B, Chebrolu K (2007) Experiences in using WiFi for rural internet in India. IEEE Commun Mag 45(1):104–110
10. US Department of Energy, DOE, http://www.energy.gov/energysources/fossilfuels.htm (last accessed March 23, 2010)
11. Zeng H, Ellis C, Lebeck R (2005) Experiences in managing energy with ECOSystem. IEEE Pervasive Comput 4(1):62–68

12. Potter N (1962) The reduction of energy consumption in deep space communications through transmitter programming. IRE Trans Commun Syst 10(4):441– 448
13. Tozer R, Salim M (2010) Data center air management metrics-practical approach. In: Proceedings of 12th IEEE intersociety conference on thermal and thermomechanical phenomena in electronic systems (ITherm), June, pp 1–8
14. Romadhon R, Ali M, Mahdzir M, Abakr A (2009) Optimization of cooling systems in data centre by computational fluid dynamics model and simulation In: Proceedings of innovative technologies in intelligent systems and industrial applications, July, pp 322–327
15. Hamann H (2008) A measurement-based method for improving data center energy efficiency. In: Proceedings of IEEE international conference on sensor networks, ubiquitous and trustworthy computing, June, pp 312–313
16. Cabusao G, Mochizuki M, Mashiko K, Kobayashi T, Singh R, Thang N, Xiao W (2010) Data center energy conservation utilizing a heat pipe based ice storage system. In: Proceedings of IEEE symposium components, packaging and manufacturing technology, Japan, August, pp 1–4
17. Hang Y, Kuo C, Ahmad I (2010) Energy efficiency in data centers and cloud-based multimedia services: an overview and future directions In: International conference on green computing conference, August, pp 375–382
18. Nathuji R, Schwan K (2008) VPM tokens: virtual machine-aware power budgeting in datacenters. In: Proceedings of the 17th ACM/IEEE international symposium on high performance distributed computing, Boston, MA, June
19. EPA, US Environmental Protection Agency, Report to congress on server and data center efficiency (Public Law 109-431), ENERGY STAR Program, August 2007
20. Hale P (1986) Acceleration and time to fail. Qual Reliab Eng Int 2(4):259–262
21. Griffa G, Radice L, Bianco C, Anders A, Zhu B, Han D, Gemma P, Luo S (2010) Carbon footprint of next generation fixed networks. In: Proceedings of the 32nd international conference on telecommunications energy, June, pp. 1–6
22. Chowdhury P, Tornatore M, Sarkar S, Mukherjee B (2010) Building a green wireless-optical broadband access network (WOBAN). J Lightwave Technol 28(16):2219–2229
23. Zhou S, Gong J, Yang Z, Niu Z, Yang P (2009) Green mobile access network with dynamic base station energy saving. In: Proceedings of MobiCom'09, Beijing, China, September
24. Marsan M, Chiaraviglio L, Ciullo D, Meo M (2009) Optimal energy savings in cellular access networks. In: Proceedings of IEEE ICC'09 workshop, GreenComm, June
25. Marsan M, Meo M (2009) Energy efficient management of two cellular access networks. In: Proceedings of GreenMetrics Workshop, in conjunction with ACM SIGMETRICS/performance. Seattle, WA, June
26. Jada M, Hämäläinen J, Jäntti R, Hossain MMA (2010) Power efficiency model for mobile access network. In: Proceedings of IEEE PIMRC'10 workshop, W-green, September
27. Jada M, Hossain A, Hamalainen J, Jantti R (2010) Impact of femtocells to the WCDMA network energy efficiency. In: Proceedings of 3rd IEEE international conference on broadband network and multimedia technology (IC-BNMT), China, October
28. Etoh M, Ohya T, Nakayama Y (2008) Energy consumption issues on mobile network systems. In: Proceedings of the 2008 international symposium on applications and the internet (SAINT 2008), Turku, Finland, July
29. Louhi J (2007) Energy efficiency of modern cellular base stations. In: Proceedings of 29th international telecommunications energy conference (INTELEC 2007), Rome, Italy, October, pp 475–476
30. Origuchi T, Maeda T, Yuito M, Takeshita Y, Sawada T, Nishi S, Tabata M (2006) Eco-efficiency evaluation of 3G services. In: Proceedings of 7th international conference on EcoBalance, Yokohama, Japan, November
31. Hikuma A, Fuke Y, Nakaminami N, Ohyane H, Kobayashi H (2006) Radio base stations equipments toward economical expansion of foma coverage areas. NTT DoCoMo Tech J 6(1):52–60
32. Ito Y, Fujimoto S, Kmura Y, Kijima M (2007) Outdoor booster equipment for 2 GHz FOMA. NTT DoCoMo Tech J 9(1):32–36
33. Trevisanai E, Vitaletti A (2004) Cell-ID location technique, limits and benefits: an experimental study. In: Proceedings of sixth IEEE workshop on mobile computing systems and applications, Lake District, UK, pp 51–60
34. Siddiqui F, Zeadally S, Elsayed H, Chilamkurti N (2009) A dynamic network discovery and selection method for heterogeneous wireless networks. Int J IP Technol 4(2):99–114

35. Huaiyu L, Maciocco C, Kesavan V, Low A (2009) Energy efficient network selection and seamless handovers in mixed networks. In: Proceedings of IEEE international symposium on world of wireless, mobile and multimedia networks & workshops (WoWMoM 2009), June, pp 1–9
36. IEEE P802.21/D13 draft standard for local and metropolitan area networks: media independent handover services, July 2008, ftp://thumper.research.telcordia.com/pub/world/yhcheng/P802-21-D13-0.pdf (last accessed March 23, 2011)
37. Nam M, Choi N, Seok Y, Choi Y (2004) WISE: energy-efficient interface selection on vertical handoff between 3G networks and WLANs. In: Proceedings of 15th IEEE international symposium on personal, indoor and mobile radio communications (PIMRC 2004), vol 1, Barcelona, Spain, September, pp 692–698
38. Joe I, Kim W, Hong S (2007) A network selection algorithm considering power consumption in hybrid wireless networks In: Proceedings of the 16th IEEE international conference on computer communications and networks, vol 13, Honolulu, Hawaii, pp 1240–1243
39. Chen W, Liu J, Huang H (2004) An adaptive scheme for vertical handoffs in wireless overlay networks. In: Proceedings of the tenth international conference of the parallel and distributed systems (ICPADS'04), Newport Beach, CA, pp 541–548
40. European Commission Joint Research Center, Climate Change: Commission welcomes final adoption of Europe's climate and energy package, EC Press release, December 2008
41. Le W, Manner J (2009) Evaluation of data compression for energy-aware communication in mobile networks. In: Proceedings of the international conference on cyber-enabled distributed computing and knowledge discovery, Zhangjiajie, China, October, pp 69–76
42. Glistvain R, Aboelaze M (2010) Bringing TCP/IP networking to resource limited embedded systems. In: Proceedings of the IEEE/ASME international conference on mechatronics and embedded systems and applications (MESA), Shandong, China, July, pp 239–244
43. Prabhakar B, Uysal E, El Gamal A (2001) Energy-efficient transmission over a wireless link via lazy packet scheduling. In: Proceedings of INFOCOM, Anchorage, AK, April
44. Wang B, Singh S (2004) Computational energy cost of TCP. In: Proceedings of 23rd annual conference of INFOCOM, March, vol 2, pp 785–795
45. Donckers L, Havinga P, Smit G, Smit L (2002) Enhancing energy efficient TCP by partial reliability. In: Proceedings of the 13th IEEE international symposium on personal, indoor and mobile radio communications, vol 5, Lisboa, Portugal, September, pp 2424–2428
46. Ci S, Turner S, Sharif H (2003) An energy-efficient TCP quick timeout scheme for wireless LANs. In: Proceedings of the 22nd IEEE international conference on performance, computing, and communications conference, Phoenix, AZ, April, pp 193–197
47. Brunstrom A, Asplund K, Garcia J (2000) Enhancing TCP performance by allowing controlled loss. In: Proceedings of SSGRR 2000 computer & e-business conference, L'Aquila, Italy, August
48. Lilakiatsakun W, Seneviratne A (2002) Enhancing TCP energy efficiency for mobile hosts. In: Proceedings of the 10th IEEE international conference on networks, pp 235–239
49. Ganesh S, Amutha R (2009) Energy efficient transport protocol for wireless sensor networks. In: Proceedings of the 2nd IEEE international conference on computer science and information technology, August, pp 464–468
50. Tsaoussidis V, Badr H, Ge X, Pentikousis K (2000) Energy/throughput tradeoffs of TCP error control strategies. In: Proceedings of 5th IEEE international symposium on computers and communications (ISCC), Antibes-Juan, France, pp 106–112
51. Zorzi M, Rao R (1999) Is TCP energy efficient? In: Proceedings of 1999 IEEE international workshop on mobile multimedia communications (MoMuC '99), San Diego, CA, November, pp 198–201
52. Elaarag H (2002) Improving TCP performance over mobile networks. ACM Comput Surv 34(3):357–374
53. Chen X, Zhai H, Wang J, Fang Y (2004) TCP performance over mobile ad hoc networks. Can J Electr Comput Eng 29(1):129–134
54. Holland G, Vaidya N (2002) Analysis of TCP performance over mobile ad hoc networks. Wirel Netw 8(2):275–288
55. Thangam S, Kirubakaran E (2009) A survey on cross-layer based approach for improving TCP performance in multi hop mobile adhoc networks. In: Proceedings of the international conference on education technology and computer (ICETC '09), Singapore, April, pp 294–298
56. Akkaya K, Younis M (2005) Energy-aware and QoS routing in wireless sensor networks. Clust Comput 8:179–188
57. Baranidharan B, Shanthi B (2010) A survey on energy efficient protocols for wireless sensor networks. Int J Comput Appl 11(10):35–40

58. Khan I, Javed M (2008) A survey on routing protocols and challenge of holes in wireless sensor networks. In: International conference on advanced computer theory and engineering (ICACTE '08), December, pp 161–165
59. Akkaya K, Younis M (2005) A survey of routing protocols in wireless sensor networks. Ad Hoc Netw 3(3):325–349
60. Nie J, Zhou Z (2004) An energy based power-aware routing protocol in ad hoc networks. In: IEEE international symposium on communications and information technology (ISCIT 2004), October, vol 1, pp 280–285
61. Mahfoudh S, Minet P (2008) Survey of energy efficient strategies in wireless ad hoc and sensor networks. In: Proceedings of 7th international conference on networking (ICN'08), Cancun, Mexico
62. Jones A, Sivalingam M, Agrawal P, Chen J (2001) A survey of techniques for energy efficient network protocols for wireless networks. Wirel Netw 7(4):343–358
63. Lin R, Wang Z, Sun Y (2004) Energy efficient medium access control protocols for wireless sensor networks and its state-of-art. In: 2004 IEEE international symposium on industrial electronics, vol 1, pp 669–674
64. Kodi A, Louri A, Wang J (2009) Design of energy-efficient channel buffers with router bypassing for network-on-chips (NoCs). In: Proceedings of the international symposium of quality electronic design, pp 826–832
65. Park D, Eachempati S, Das R, Mishra A, Xie Y, Vijaykrishnan N, Das C (2008) MIRA: a multi-layered on-chip interconnect router architecture computer architecture. In: Proceedings of the 35th international symposium on computer architecture, pp 251–261
66. Nishimura S, Shinoda K, Lee Y, Ono G, Fukuda K, Yuki F, Takemoto T, Toyoda H, Yamada M, Tsuji S, Ikeda N (2010) Components and interconnection technologies for photonic-assisted routers toward green networks. IEEE J Sel Top Quantum Electron PP(99):1–10
67. Raghunathan V, Srivastava M, Gupta R (2003) A survey of techniques for energy efficient on-chip communication. In: Proceedings of design automation conference, June, pp 900–905
68. Guang L, Nigussie E, Tenhunen H (2009) System-level exploration of run-time clusterization for energy-efficient on-chip communication. In: Proceedings of 2nd international workshop on network on chip architectures, NoCArc 2009, December, pp 63–68
69. Jose A, Shepard K (2007) Distributed loss-compensation techniques for energy-efficient low-latency on-chip communication. IEEE J Solid-State Circuits 42(6):1415–1424
70. Benini L (2005) Energy efficient NoC design. In: Proceedings of 18th symposium on integrated circuits and systems design, September
71. Pandey S, Glesner M (2006) Energy efficient MPSoC on-chip communication bus synthesis using voltage scaling technique. In: Proceedings of IEEE international symposium on circuits and systems (ISCAS), Island of Kos, Greece, May
72. Ruan X, Qin X, Zong Z, Bellam K, Nijim M (2007) An energy-efficient scheduling algorithm using dynamic voltage scaling for parallel applications on clusters. In Proceedings of 16th international conference on computer communications and networks (ICCCN 2007), August, pp 735–740
73. Bolla R, Bruschi R, Ranieri A (2009) Energy-aware equipment for next-generation networks In: Proceedings of 4th international conference on future internet technologies, New York
74. Bolla R, Bruschi R, Ranieri A (2009) Green support for PC-based software router: performance evaluation and modeling. In: Proceedings of IEEE international conference on communications, (ICC 2009), Dresden, Germany, June
75. Herbert S, Marculescu D (2007) Analysis of dynamic voltage/frequency scaling in chip-multiprocessors. In: Proceedings of the 2007 international symposium on low power electronics and design (ISLPED '07), Portland, OR, August, pp 38–43
76. Chiaraviglio L, Mellia M, Neri F (2009) Energy-aware backbone networks: a case study. In: Proceedings of the first international workshop on green communications (GreenComm09), IEEE international conference on communications, Dresden, Germany, June
77. Nedevschi S, Popa L, Iannaccone G, Wetherall D, Ratnasamy S (2008) Reducing network energy consumption via sleeping and rate-adaptation. In: Proceedings of 5th USENIX symposium on networked systems design and implementation, San Francisco, CA, pp 323–336
78. Gunaratne C, Christensen K, Suen S, Nordman B (2008) Reducing the energy consumption of ethernet with an adaptive link rate (ALR). IEEE Trans Comput 57(4):448–461
79. Cuda D, Gaudino R, Gavilanes G, Neri F, Maier G, Raffaelli C, Savi M (2009) Capacity/cost trade-offs in optical switching fabrics for terabit packet switches. In: Proceedings of the international conference on network design and modeling

80. McKeown N (2003) Optics inside routers. In: Proceedings of the European conference and exhibition on optical communication
81. Chabarek J, Sommers J, Barford P, Estan C, Tsiang D, Wright S (2008) Power awareness in network design and routing. In: Proceedings of the 27th conference on computer communications (INFOCOM), Phoenix, AZ, April, pp 457–465
82. Hinton H (1990) Photonic switching fabrics. IEEE Commun Mag 28(4):71–89
83. D-link, Green computing and D-link, http://www.graybar.com/docs/D-Link_Green_whitepaper.pdf, Whitepaper, February 2009 (last accessed March 23, 2011)
84. Reviriego P, Christensen K, Rabanillo J, Maestro J (2009) Performance evaluation of energy efficient ethernet. IEEE Commun Lett 13(9):1–3
85. Christensen K, Reviriego P, Nordman B, Bennett M, Mostowfi M, Maestro JA (2010) IEEE 802 3az: the road to energy efficient ethernet. IEEE Commun Mag 48(11):50–56
86. Gupta M, Singh S (2007) Using low-power modes for energy conservation in ethernet lans. In: Proceedings of the 26th annual IEEE conf on computer communications (INFOCOM), Anchorage, AK, May
87. Noguera J, Kennedy I (2007) Power reduction in network equipment through adaptive partial reconfiguration. In: Proceedings of the 2007 int conf on field programmable logic and applications (FPL 2007), August, pp 240–245
88. IEEE P802.3az, Energy efficient ethernet task force, http://grouper.ieee.org/groups/802/3/az, 2010 (last accessed March 23, 2010)
89. Blume O, Zeller D, Barth U (2010) Approaches to energy efficient wireless access networks. In: Proceedings of the 4th international symposium on communications, control, and signal processing (ISCCSP 2010), Limassol, Cyprus, March
90. Zhang H, Gladisch A, Pickavet M, Tao Z, Mohr W (2010) Energy efficiency in communications, guest editorial. IEEE Commun Mag 48(11):48–49
91. The Economic Times, http://economictimes.indiatimes.com/news/news-by-industry/energy/power/ICT-infrastructure-energy-consumption-to-grow-30-by-2014/articleshow/6391340.cms, August 22, 2010 (last accessed March 23, 2011)
92. British Telecom, http://www.commsbusiness.co.uk/News_Article_JS1.cfm?NewsID=3985&YearViewed=2007&Newsmonth=10&EndDay=31&StartDay=16&NoNews=0 (last accessed March 23, 2011)
93. Bolla R, Bruschi R, Ranieri A (2009) Performance and power consumption modeling for green cots software router. In: Proceedings of the first international conference on communication systems and networks (COMSNETS). Bangalore, India, January
94. Bronk C, Lingamneni A, Palem K Innovation for sustainability in information and communication technologies (ICT), Internal report, Rice University, http://www.rice.edu/nationalmedia/multimedia/2010-10-11-ictreport.pdf (last accessed March 23, 2011)
95. Nordman B (2009) What the real world tells us about saving energy in electronics. In: Proceedings of 1st Berkeley symposium on energy efficient electronic systems (E3S), CITRIS, June
96. Fettweis G (2009) ICT energy consumption, trends and challenges. In: Proceedings of ICC workshop on green communications, Dresden, Germany, June
97. Daniels G, Greene L, Carr S (2010) Planet Green, ICT for a low-carbon future, Decisive Media Limited, London
98. Matthews H, Hendrickson C, Chong H, Loh W (2002) Energy impacts of wired and wireless networks. In: Proceedings of IEEE international symposium on electronics and the environment, San Francisco, CA, May
99. Kumar R, Mieritz L (2007) Conceptualizing green IT and data centre power and cooling issues, gartner research paper No. G00150322, April 2007
100. Wang D (2008) Meeting green computing challenges. In: Proceedings of 10th electronics packaging technology conference (EPTC 2008), Singapore, pp 121–126
101. National Academy of Engineering, Grand challenges for engineering, 2008. http://www.engineeringchallenges.org/Object.File/Master/11/574/Grand%20Challenges%20final%20book.pdf (last accessed March 23, 2011)
102. Chen Y, Wang T, Katz R (2008) Energy efficient ethernet encodings. In: Proceedings of 33rd IEEE conference on local computer networks, Montreal, Canada