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Introduction

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1.1 Origins of Green Communications

Climate change and energy crisis are not just a vague future problems, as their effects are becoming apparent at a rapid pace. Greenhouse emissions, such as CO_2 and methane, cause global warming with catastrophic consequences on planet and on the human society as documented in Ref. [1]. The Kyoto protocol to the United Nations Framework Convention on Climate Change (UNFCCC) established in 1997 indicates that mainly the developed countries are responsible for the current levels of greenhouse gases, followed by a strong objective to take action against global warming. In the Conference of the Parties (COP) 17 climate change conference in Durban, 2011 scientists raised concerns that the measures taken so far are not sufficient to avoid global warming beyond 2°C (a limit established in the G8 meeting in L'Aquila in June 2009 to avoid unpredictable environmental damage) and more urgent action is needed. Besides environmental concerns, the energy crisis becomes apparent with claims stating that approximately 50% of the world petroleum resources are already exploited [2], creating major obstacles for power supply with negative consequences on the economy. In general, energy pricing influenced by fuel prices is showing an increasing trend according to the forecast study performed by the Energy Information Administration (EIA) of the US Department of Energy [3].

As the use of Information Communication Technology (ICT) becomes an essential part of human daily lifestyle allowing social and business interaction on a local and global scale, the pace of development and integration of new technologies is performed on an accelerating rate. According to ITU estimations, Internet users reached around 2.7 billion by the end of 2013, almost 40% of the world's population, whereas mobile cellular subscribers approach 7

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Table 1.1 Traffic projections between 2010 and 2020 for the mobile access, wireline access and core networks modeled by GreenTouch for the Mature Market segment [7]

Year	Mature market traffic projections (PB/month)		
	Mobile access	Wireline access	Core network
2010	161	7,727	10,707
2015	3,858	33,879	45,402
2020	14,266	74,462	103,085
2020/2010	89x	9.6x	9.6x

billion, with the mobile broadband being the most dynamic market with 2.1 billion subscribers globally [4]. Effectively, such enormous adoption of ICT is accompanied by a massive growth of the number of user devices, wireless, indoor, transport, core and data center networks and services, raising significant cost and sustainability concerns. In particular, ICT across a wide range of applications currently accounts for 5.7% of the world's electricity consumption and 1.8% of CO_2 emissions [5], stressing the need for enhancing energy efficiency in ICT products. Data from different telecommunication operators globally confirms their huge consumption of electricity as summarized in Ref. [6].

To comprehend the energy consumption of modern telecommunication systems considering the expected scale of increase, a summary of historic and near-future global traffic volumes for the mature markets over the decade 2010–2020 regarding mobile access, wireline and core networks is illustrated in Table 1.1 [7]. From the traffic growth projections, it becomes evident that there is a significant increase on mobile access, but with the wireline access and core networks still carrying the majority of user traffic. Multimedia applications and particularly video is one of the main contributors of such significantly higher traffic volumes, with Cisco Internet traffic projection forecasting that in 2015 the video consumption will reach one million video minutes per second, which is equivalent of 674 days [8]. Such tremendous data growth also as a consequence of the increasing population of users that can afford ICT services, raises new economic and sustainability challenges for network operators, which face the need of expanding their deployed network infrastructure in order to cope with the continuously increasing traffic volumes. Furthermore, the introduction of novel architectures and technologies, for example, machine-to-machine communications, smart grid, automotive, social media, smart cities, adds an extra degree of complexity to the network design, generating a compulsory need for holistic end-to-end approaches for the network operation.

The telecommunication networks' greenhouse emissions growth rate is expected to continuously increase as illustrated in Figure 1.1. Wireless and wireline networks accounted for an equal share on greenhouse emissions between 2002 and 2011 with a footprint of 0.13 and 0.20 gigatons of CO_2 equivalent ($GtCO_2e$), respectively. However, the remarkably high data volumes in the mobile communications sector and the launch of fourth-generation (4G) long-term evolution (LTE) networks have the consequence of increasing the wireless greenhouse footprint to 0.16 $GtCO_2e$ compared to a wireline equivalent of 0.14 $GtCO_2e$ anticipating the adoption of fiber optics that significantly lower the energy consumption.

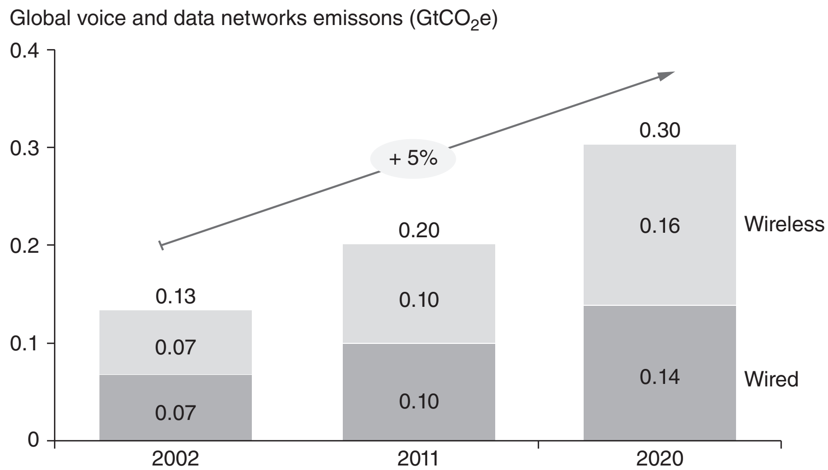

Figure 1.1 Telecommunication system emissions between 2002 and 2020 showing wireless and wireline contributions [9]

Besides economic and environmental matters, energy efficiency in telecommunication systems is particularly crucial for developing countries providing a means for bridging the digital divide. In such cases, cost is the main barrier and hence energy efficiency may reduce the operational expenses provisioning affordable ICT services. In addition, green communications relying on alternative energy sources may provide the means of equipping remote areas without or with limited power supply creating an environmental friendly ICT adoption in developing countries. Furthermore, energy efficient mechanisms and practices could prove critical for telecommunication systems in disaster situations, where the power generation or the distribution infrastructure is damaged. Specifically, network equipment that supports a low-power mode may sustain a basic operation available only for critical services.

1.2 Energy Efficiency in Telecommunication Systems: Then and Now

The problem of energy efficiency in telecommunication systems is not entirely new. Indeed, energy efficiency has always been a significant issue for maximizing the battery lifetime of handheld devices and wireless sensor nodes that operate autonomously without a power grid supply. Early solutions considering the field of cellular and portable communications focus on wireless and mobile terminals, notebooks, and personal digital assistants (PDAs). The main objective was to establish power saving modes or states, in where devices either operate with minimal power consumption or simply sleep, that is, freeze their prior operating state. Common examples are the idle mode of global system for mobile (GSM) communication devices or the hibernate/standby mode of laptops and PDAs.

Similarly, studies on ad hoc and wireless sensor networks have devoted major efforts on energy optimization with the goal of extending the entire system lifetime. A plethora of different energy saving techniques including device sleeping patterns, clustering and head selection for minimizing the energy expenditure of the ad hoc or sensor system as well as energy-aware routing and data aggregation protocols have been extensively analyzed [10, 11]. However, these studies concentrated primarily on the energy management of each device considering the ad hoc or sensor network in isolation. Probably the most widely studied energy problem concentrates on the transmission efficiency considering medium access control (MAC) protocols, error correction, and radio channel gain techniques [12]. Again the focus concentrates on the device energy efficiency since transmission and radio optimizations simply reduce the device processing and forwarding.

These early efforts attempt to extend the lifetime of devices without a power supply. Fundamentally, this is different from the current trend of green communications and energy efficiency in ICT, which seeks solutions to reduce the energy consumption and the CO_2 footprint of network equipment and ICT systems irrespective of power supply limitations usually at off-peak time or when equipment are not in use. Effectively, strategies, mechanisms, and protocols, which stretch along home and enterprise networks, wireless access and cellular networks, transport, and the Internet, are considered with the goal to introduce adaptive operations based on load variations and new equipment design and system architectures with reduced the energy consumption needs.

Such a green communication vision has also got momentum within ICT government and regulatory bodies, especially since the launch of the Kyoto protocol, which aimed to create policies and recommendations for developing and using ICT equipment and systems. Early efforts from the US environmental Protection Agency concentrated on energy efficiency of personal computers (PCs), peripherals, and monitors, establishing a voluntary labeling program referred to as Energy Star in 1992. The European Commission (EC) recognized since 1999 the need for further actions toward energy efficiency and green communications, introducing the code-of-conduct [13] to drive policies and recommendations for reducing CO_2 emissions considering power supplies, digital TV, broadband equipment, and data centers. A number of different government acts and industry initiatives on green ICTs are documented in the survey by the Organisation for Economic Co-operation and Development (OECD) in Ref. [14]. Out of over ninety proposals only 20% suggest measurable targets, with government programs driving the majority of them. A representative example illustrating different targets and initiatives regarding green communications and energy efficiency from various telecommunication operators around the globe is shown in Figure 1.2.

Besides encouraging the adoption of green ICT, government and regulation policies drive energy efficiency standardization efforts by inquiring key standards organizations to provide indications for upper bound power limits of network equipment. The goal of such efforts is to develop power saving features, mechanisms, and protocols; examples are the mandate M-462 introduced by the EC that was communicated to European Telecommunication Standardization Institute (ETSI), European Committee for Standardization (CEN), and European Committee for Electrotechnical Standardization (CENELEC) [15]. Apart from standards, the EC has initiated the ICT for Energy Efficiency (ICT4EE) forum [16] since 2010 to address green communications and energy saving, bringing together high-tech industry from Europe, Japan, and America including the DIGITALEUROPE, Global e-Sustainability Initiate (GeSI), the Japanese Business Council Europe (JBCE), and Tech America Europe.

Furthermore, green communications and energy efficiency in ICT has motivated important initiatives, such as GreenTouch [7], a consortium of industry, academic, and nongovernmental research bodies and experts sharing a vision of increasing the total energy efficiency of ICT by the scale of 1000. The goal of the participants is to transform data and wireless communications as well as the Internet to reduce significantly the CO_2 footprint of network equipment, system

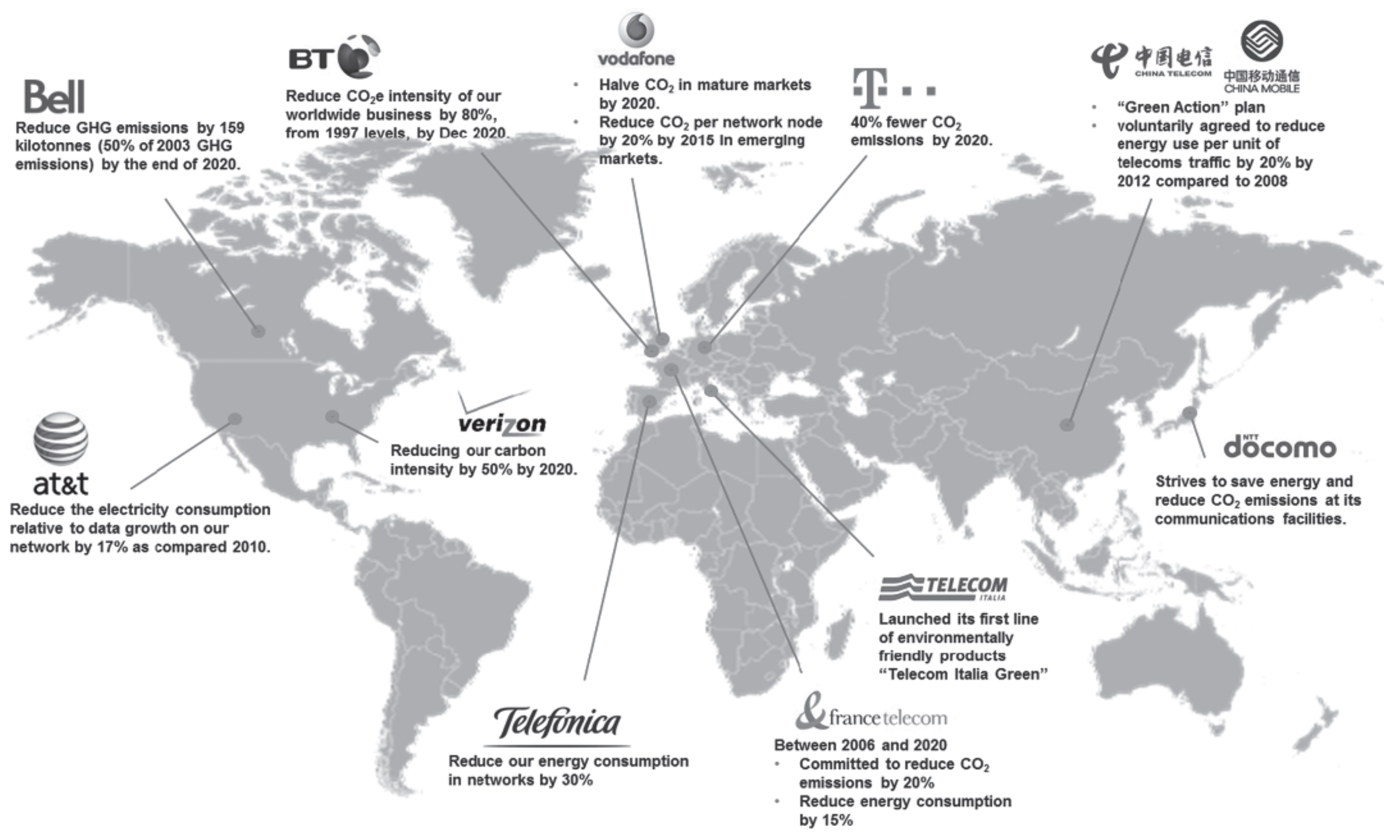

Figure 1.2 Green and energy efficiency ICT targets introduced by the major telecommunication operators around the globe

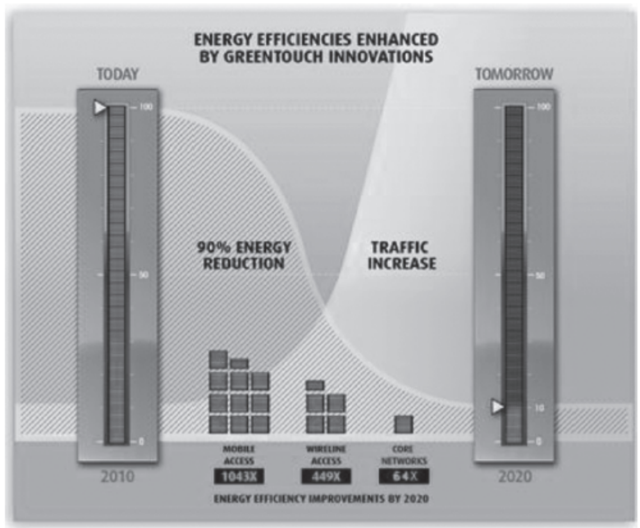

Figure 1.3 Energy efficiency forecast by GreenTouch innovation [7]

platforms, and networks, employing novel, smart, and sophisticated architectures, mechanisms, protocols, and algorithms.

In particular, GreenTouch recently announced the potential of reducing the net energy consumption in communication networks up to 90% by 2020 [7]. This dramatic net energy reduction in wired and wireless networks, despite the foreseen increase in traffic, is fueled by significant improvements in the energy efficiency of network equipment and the component networks as illustrated in Figure 1.3. Hence, it becomes clear that energy efficiency should be studied in a holistic end-to-end network perspective, taking into account all the network layers, and corresponding mechanism and protocols considering a variety of possible network architectures.

1.3 Telecommunication System Model and Energy Efficiency

As mentioned, telecommunication networks need to carry exponentially increasing data traffic while avoiding a similar increase of energy consumption. A telecommunication system is structured into multiple network parts or regions which employ a diverse set of technologies, each posing different challenges for reducing energy consumption. Figure 1.4 shows the architecture of a telecommunication system including the different type of networks, which comprise the subject of this book. The access network provides connectivity to the end users through either fixed network or wireless network technologies including digital subscriber line (DSL) technologies, optical fiber, cellular systems such as Universal Mobile Telecommunications System (UMTS) or wireless broadband technologies such as IEEE 802.11 (Wi-Fi), IEEE 802.16 (WiMAX), or 3GPP LTE. Wireless broadband technologies allow access for mobile end user terminals such as laptops, mobile handheld device, smartphones and tablets, or sensors.

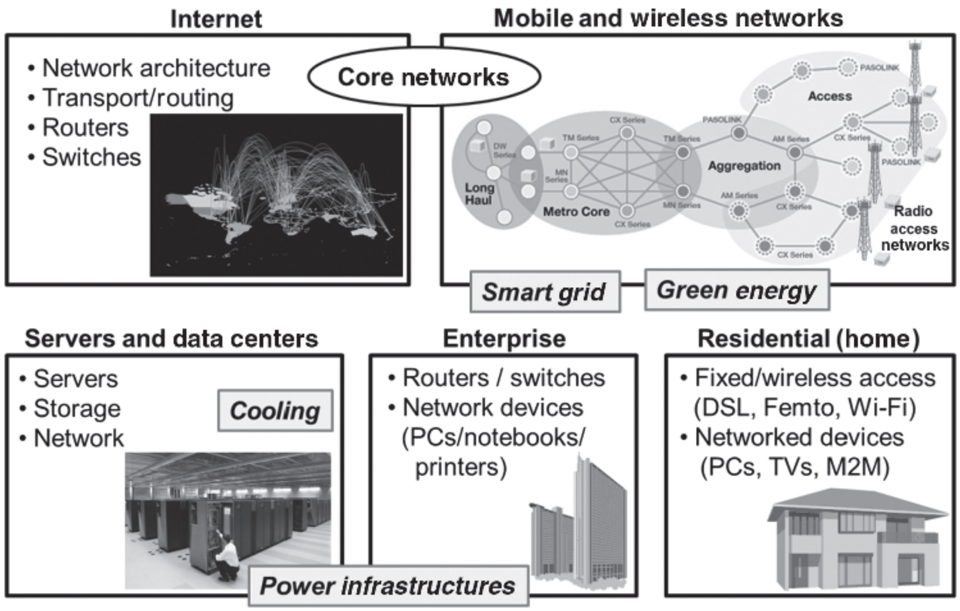

Figure 1.4 Telecommunication system model

Fixed access networks provide connectivity to residential and enterprise networks, which support a number of devices including PCs, peripherals, sensors and Wi-Fi access points, user-deployed femtocells, or operator-deployed base stations. Data offloading solutions or indoor networks employing Wi-Fi or picocells, for example, in shopping malls or train station, as well as coverage extensions via small cells or capacity booster cells can enhance the access providing service diversity for mobile and fixed operators.

Traffic from the access network is aggregated at different stages usually in a tree-structured network which is referred to as backhaul network. It is difficult to draw a clear line between access and aggregation network, for example, if an end user deploys a Wi-Fi access point, the DSL connection may also be part of access network or already part of the aggregation network. The aggregation network is connected to the metro network, which provides connectivity between the individual network equipment within a metropolitan area. Usually, such a network has a ring structure and provides eventual access to the core network. The size of a metro network may vary significantly from a few ten kilometers up to a few hundred kilometers. In metro networks, either optical technologies, such as synchronous optical networking (SONET)/synchronous digital hierarchy (SDH) or wavelength division multiplexing (WDM), are deployed or high-throughput Ethernet technologies such as Carrier-Ethernet.

Finally, the core and backbone network connects different metro networks nationwide, and it connects the telecommunication network with the Internet as well as other telecommunication networks. It is composed of switching and routing equipment, gateways as well as subscriber information, authentication, policing, mobility, charging, and Operations Administrations and Management (OAM) functions. Data centers are typically a part of the core and backbone networks, hosting network services and user applications. Core networks can vary significantly in their degree of centralization, whereas the backbone network can be a purely optical network due to the immense amount of data that needs to be transported.

Every network layer and even each element within a network layer contributes differently to the energy consumption, for example, routers and data centers mainly consume energy due to data processing, large-scale switches mainly consume energy due the maintenance of their link interfaces, and wireless infrastructure consumes a major portion for their radio front end and its cooling. Furthermore, each part of a network is subject to different traffic characteristics, that is, access networks usually carry more time-variant traffic which becomes more bursty as the number of users decreases. More centralized and aggregated traffic gains from statistical multiplexing and may be less time variant. This is of interest for fixed networks such as Ethernet as well as for wireless networks where the cell size has a major impact on the traffic characteristics. In addition, traffic patterns and data load may change during the course of the day.

Besides the network as a whole, transmission technologies, deployment sites, as well as individual devices and network equipment need to be taken into account when considering the energy efficiency of a telecommunication network. Access networks, in particular wireless access networks, are characterized by a large number of devices and sites. By contrast, metro and core networks are built upon a small number of sites and data centers. Although each of these core network equipment and data centers consumes significantly more energy than a single site in the access network, the access network outnumbers the core network in total energy consumption.

In Ref. [6], the energy expenditure of the access is estimated to account 70% of the entire network consumption, whereas the transport and core is responsible for the remaining 30%, despite the fact that the access network equipment consume around 1000 W/hour, whereas the transport and core consume six and ten times more, respectively. Therefore, the energy efficiency of devices and sites within the individual network layers needs to be considered differently. Another major challenge for energy efficiency is to scale the energy consumption to the actual demand for resources. Many networks consume significant energy resources for being ready to provide peak throughput although only a fraction of it is used.

End-user terminals, such as PCs and handheld devices as well as network peripherals and wireless sensor devices, compose the first layer. As stated already, an improvement of energy efficiency for terminals by introducing a sleep or idle state rather improves the lifetime of wireless devices and operational cost of fixed ones than having a major impact on the overall energy consumption of the telecommunication network. Similarly, proxy devices are used in fixed-line networks, which take care of the network communication and keep connections alive while the host computer or other peripherals are turned off or hibernated. In the access network, the main challenge is the interaction of wireless network infrastructure with the mobile backhaul network. Both use different technologies and require continuous protocol signaling exchange. This complicates turning off a wireless access point as it needs to be re-initialized both on the air interface and toward the backhaul and core network. Similarly, in reducing the power consumption of router and switches, there is a need to perform the corresponding protocol updates for coordinating the network topology.

In general, wireless access networks are less energy efficient in terms of throughput per Joule than wired networks, but wireless networks allow for more deployment and usage flexibility. Furthermore, deploying one wireless access point allows for connecting a large number of end users, whereas trenching new cables for a wired may be more expensive and energy intensive, at least in the short term. This relation is considered by a concept called embodied energy [17], which not only accounts for the energy consumed during the operation but also to build and deploy a communication technology. Apparently, this complicates the evaluation of energy efficiency and makes it very specific to individual scenarios.

Metro and core networks are increasingly adopting optical technologies, alongside asynchronous transfer mode (ATM), Internet Protocol (IP), and Carrier-Ethernet. Optical transport consumes the least energy during operation because of reduced data processing and forwarding effort. Such efficiency alongside the very high data rates makes optical technology a good candidate for highly reliable and high-throughput networks. The largest part of energy consumption in optical networks is caused by the conversion from optical to electrical domain and back, that is, from optical to IP routing or vice versa. Therefore, purely optical switches or cross-layer optimization solutions are of particular interest in the research community and industry as they significantly reduce the overall energy consumption. Data centers constitute an elementary part of telecommunication networks but are rather in scope of computing energy efficiency, for example, higher silicon integration. A promising option for data centers is to use renewable energy in order to reduce the CO_2 footprint. In this book, data centers' internal architecture is not in focus, but only the networking related issues such as routing and network topology, which provide access and connectivity to data centers.

Within each network type, energy efficiency can also be considered on the individual Open Systems Interconnection (OSI) protocol layer, being subject to different constraints and causes of energy consumption. For instance, on PHY layer, energy efficiency has been of particular interest in the area of wireless networks. In wireless networks, the radio front end and the baseband processing consume a major portion of the energy. In fact, more than 50% of the energy at a base station is consumed by the power amplifier, most of it as dissipated heat. Hence, engineers and researchers are investigating ways to improve the amplifier efficiency, to introduce micro-sleeps during which the radio front end is turned off, alongside cooperative algorithms, advanced multi-antenna schemes, and encoding/decoding algorithms, which have already received significant attention. Similarly for fixed networks, managing the power of particular interfaces by applying sleeping either on a temporarily, regular, or event basis is significant for the energy consumption of switches, routers, and other core network equipment.

On data link and network layer, scheduling, packet segmentation as well as feedback algorithms are subject of investigation for improving energy efficiency. For instance, in the area of wireless networks, intercell interference coordination, load balancing, and efficient segmentation processes may have a significant impact on the energy efficiency. For wired networks, the primary focus is on developing routing and switching protocols and algorithms to handle energy efficiency on network equipment while taking care of synchronization and service performance issues.

Considering the transport and application layer the main energy saving efforts concentrate on transport protocols, for example, Transmission Control Protocol/Internet Protocol (TCP/IP), content distribution, codecs and digital signal processing (DSP) as well as on context adaptation and location information. Finally, besides individual improvements on each protocol layer, cross-layer considerations have an even stronger impact on energy efficiency, for example, switching off access points is only possible if efficient protocols on higher layers are available which allow disrupting connections.

1.4 Energy Saving Concepts

When analyzing energy saving and green communications it is important to firstly understand what characterizes a communication system as energy efficient or green. Energy efficiency is associated with the provision and operation of resources that enable a service corresponding to a user demand, with reduced energy consumption. It is typically defined as the ratio of a functional unit to the energy required to deliver such a functional unit, with higher values indicating greater energy efficiency [18]. Network equipment and communication systems are typically provisioned to handle peak-time traffic demands, which differ significantly from the average load during other times. In fact, even when idle, that is, not in use, ordinary nonenergy aware network equipment and communication systems consume a significant amount of power, unless energy efficient mechanisms are employed.

In principle, reducing the energy consumption of telecommunication networks can be achieved in the following five fundamental ways:

- *Network planning*: optimize the physical placement of resources and enable the potential to power off network equipment.
- *Equipment re-engineering*: introduce low-energy network equipment and devices; redesign internal equipment architectures to accommodate energy saving requirements.
- *Network management*: optimize the operation of network equipment as well as network-wide protocols and mechanisms by adjusting network resources based on the users' demand.
- *Renewable energy*: reduce the energy consumption from power grid by supplying energy from alternative sources, for example, solar and/or wind, which are also environmental friendly.
- *Social awareness*: educate users to avoid wasting energy.

Network planning is an offline activity, a first step that aims to accommodate energy saving by considering the dimension of the network topology, equipment, and deployment aspects. For instance, the consideration of small cells and heterogeneous networks within the network planning phase can increase the spectral efficiency of a wireless system, while reducing power amplifier needs and cooling for network elements, therefore improving the network-wide energy efficiency. Similarly for wireline networks, energy efficiency can be realized by provisioning nodes, that is, switches or routers, and links forming a network topology by considering also the deployment strategy in terms of the transport technology, for example, fiber, microwave, etc., and the corresponding routing policy. Additional opportunities for energy saving in network planning are obtained via network virtualization and node consolidation, which can achieve significant savings through the use of overlay networks by integrating functions and services into less network equipment.

Energy efficiency in telecommunication systems relies mainly on the power consumption of individual components that comprise them and on the way that different components and mechanisms influence one another. For instance, new power operations on network equipment may affect and introduce new features on communication protocols. Perhaps the most fundamental issue is to consider energy-efficient hardware improvements on the devices and equipment, which may allow an operation with reduced power. The use of advanced materials may reduce cooling, whereas new technologies, for example, fiber optics, can cut down significantly data processing and forwarding power. In addition, enhancing the internal equipment architecture design to accommodate energy saving needs is another important hardware attribute, which can contribute to scale down the need of the power amplifier, a component that consumes a high portion of energy. It can also enhance energy efficiency in data processing, by improving the energy usage profile of equipment hence achieving energy proportionality, that is, scaling the energy consumption with profitable use.

Hardware advancements may also create opportunities for a more efficient energy saving management of devices by controlling the energy state of equipment reflecting traffic dynamics according to the following two fundamental mechanisms:

- Power off where equipment is not operational:
  - (i) A cyclic-operation of being powered on and powered off during particular time periods.
  - (ii) A soft-sleep or dossing where equipment maintain a minimal components or devices operational to allow rapid wake-up.
  - (iii) An extended or deep-sleep where equipment need a significant amount of time to become fully operational again.
- Slow down the operation of equipment:
  - (i) Modular where selected functions are reduced, while the equipment is partially operating.
  - (ii) Rate adaptation reducing the operational rate of processing and/or forwarding traffic.

In managing the energy operations, it is important to ensure that network equipment are profitably under a power saving state or mode for a sufficient time period avoiding oscillations and the associated costs (i.e., signaling, power, computation) for changing the power state or mode of network equipment. Hence, monitoring of network traffic load is essential as suggested in Ref. [19] to identify long-term off-peak time periods and avoid local traffic load minima as illustrated in Figure 1.5.

Such traffic load monitoring assists the network management operation which can control the energy state or mode of individual network equipment considering a network-wide view. The corresponding energy control actuators may reside locally on network equipment or can be centralized.

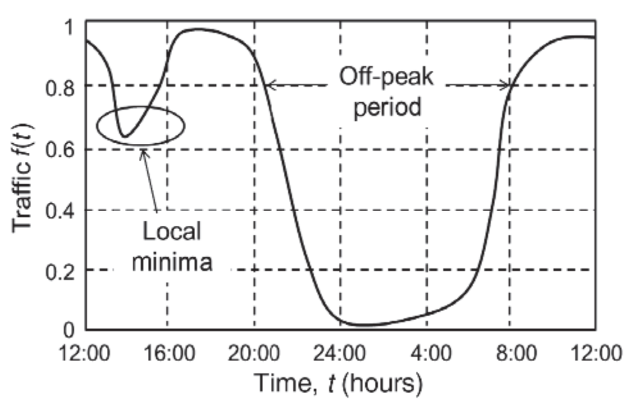

Figure 1.5 Example of normalized traffic variation over a daily period

Network-wide mechanisms that rely on network management decisions can mainly influence traffic shaping and steering realizing the following energy saving opportunities:

- Regulating traffic forwarding between selected network equipment allowing a soft-sleep or dossing within particular time periods, for example, discontinuous transmission (DTX) in LTE, Energy-Efficient Ethernet (EEE), and fast sleep in passive optical networks (PONs). In addition, scheduling or filtering may shape traffic volumes reducing the network resource utilization providing energy efficiency.
- Traffic aggregation in selected routes or parts of the network allowing underutilized network equipment, for example, base stations, routers, switches, interfaces, to enter or maintain a reduced power consumption operation. Cell zooming and energy partitions are common examples for wireless communications, whereas routing, traffic steering, and transport mechanism may achieve the equivalent for wireline systems.

Additionally, network-wide protocols and content applications can further improve the energy efficiency associated with network resources and operations via:

- Reducing the volume of traffic across the backhaul and core networks, enabling users to retrieve content at closer locations by introducing content distribution network (CDN) and cache mechanisms at selected edge positions. Similarly, the use of information centric networking (ICN) may reduce the data traffic processing and forwarding on network equipment within the backhaul and Internet, while peer-to-peer and location aware applications may provide more efficient information exchange for both wireless and wireline communications.
- Introducing lightweight protocols, which require less control plane signaling and protocol advancements that result in reduced energy consumption, for example, MAC protocols, or adapt considering power saving states or modes of network equipment.

A critical attribute when providing energy efficiency in networking is the effect on service level agreements (SLAs) bound to particular users and applications. Typically, it is desired to maintain SLAs, irrespective of network power conservation circumstances and hence this is a significant design requirement for energy saving mechanisms and processes. Mechanisms which can assist energy conservation maintaining a continuous service on behalf of sleeping equipment, for example, proxying, are particularly useful for applications and other network services. When SLAs are relaxed and quality of service (QoS) is not critical, further energy conservation can be obtained. For instance, delay tolerant network (DTN) mechanisms enable users to store, carry, and forward traffic on behalf of other users allowing certain base stations to maintain low-energy consumption. Similarly, data offloading policies and mechanisms may steer non-QoS critical traffic directly to the Internet bypassing the operator's core network in where energy saving can be realized.

In practice, it is desirable to differentiate data traffic in order to customize energy saving policies with respect to the user and application type. This can prove to be useful to determine when it is worth re-empowering a network element, for example, a base station considering the application type and user mobility, or for how long a network element should sleep considering the delay caused in relation with a certain application. The user context information may further enhance energy saving considering the user activity/behavior and movement, for example, a home base station may only operate when the user initiates an application or a user's movement away or toward his premises may power off or re-empower his home base station. Similarly, enterprise networks can manage efficiently the energy of printers, PCs, wireless access points, and so on, based on information about the incoming users' profiles and permissions. Evolving applications, such as proximity services and social applications, may optimize device communication considering location information allowing energy saving in radio and core network.

Nevertheless, as energy efficiency may reduce the operational costs of telecommunication networks making networking commodities cheaper, the user may consume higher amounts of services and applications creating a rebound effect as suggested by the Khazzoom–Brookes postulate [20]. Hence, it is also of utmost importance to raise social awareness, introducing policies that reward users who conserve energy on behalf of the network operator. Charging models may also reflect energy consumption to a certain extend encouraging users to saving while receiving better bills.

1.5 Quantifying Energy Efficiency in ICT

The definition of quantitative metrics for the characterization of the energy efficiency of network equipment is fundamental for comparing solutions and technologies, estimating their effectiveness, taking proper decisions. Moreover, metrics and indices to quantify energy efficiency can be used as variables in the internals of algorithms and strategies such as those devoted to resource allocation or resource sharing. However, despite the intense research and development activity performed in the field of energy-efficient communications, a definite established agreement on the most appropriate metrics is still open. The manifold aspects related to energy efficiency make the definition of proper metrics so complex that the efficiency of a given system cannot be described only by a single energy-efficient indicator but has to be expressed as a set of metrics or a hybrid metric that relate in different ways the work done by the system, in terms of the amount and quality of a provided service, with its cost in terms of the amount of energy that is needed to produce that work.

Thus, several different metrics have been proposed that are specific of a system or scenario, depending on the kind of work or application that is provided. For example, indices that aim at measuring the efficiency of a processor unit relate the amount of executed operations with the amount of used energy; indices that target the efficiency of a transceiver system relate the emitted power with the power drained by the system; and for devices that carry telephone calls efficiency is measured in terms of the number of Erlang of carried traffic per unit of energy. Moreover, for the same device or system, depending on the specific interest and objective of an evaluation, the metrics might be different. For instance, in a wireless systems, the amount of power that must be drained to obtain a given transmitted power from the antenna might be relevant, as well as the energy needed to provide coverage of a given unit area.

For core network nodes, ETSI defines in Ref. [21] a general metric, referred to as energy efficiency ratio as the fraction of useful output, intended as the capacity of service of a core network node, to the requested power. The useful output is then, depending on the functions of the node, expressed as the number of Erlang, for a device targeting voice calls, or as packets per second, or number of simultaneously attached users. The measure can then be derived for different load levels and for various traffic mixes. More complex is the definition of proper energy efficiency metrics for wireless networks.

In these cases, the efficiency of the network devices themselves is not enough for many investigations. In fact, in addition to the quantity of capacity that is carried by a device, the concept of coverage and, hence, service provisioning, add a new dimension to the space of the possible metrics. When two technologies are compared, for example, the planning strategy, in terms of number and kind of devices deployed in a given area, can make an important difference; similarly, the need to cover areas even if the carried traffic is negligible can really change the evaluation of the efficiency of a solution. In Refs. [22, 23], the following main metrics are proposed for wireless access networks:

- The *energy per information bit* [J/b] or [W/bps] represents the energy needed to transfer a bit of information.
- The *power per unit area* [W/m^2] relates the average power used by a device that provides connectivity to the size of the covered area.

For cellular systems, the first metric is particularly relevant for urban areas, where traffic is high, and cellular networks are capacity limited. In these cases, one of the most important characteristics of a system is the possibility to provide high capacity; the amount of work corresponds to number of bit transfers that can be done with a unit of energy. For this reason, this metric is widely used to evaluate and compare transmission techniques over an individual link. This metric is less relevant for systems under low traffic conditions, when the work that is actually needed by the system is low. In these cases, the second metric, the power per unit area, is more suited, since it targets the energy needed to provide service provisioning, regardless the actual usage of the service itself. This metric allows also to consider different system configurations. For example, given an area, the coverage might be provided by different kinds of devices, with different coverage and, thus, the metric is also well suited to give a view of heterogeneous network scenarios.

In Ref. [24], ETSI proposes two metrics that introduce, besides service provisioning, the concept of quality with which the service is provided:

- The ratio between the throughput of users obtaining a minimum specified (service-dependent) QoS within the served area and the total power consumed by the base stations offering service in the same area [b/J].
- The ratio between the number of users obtaining a minimum specified QoS within the served area and the total energy consumed by the base stations offering service in the same area during the observation time [J^{-1}].

QoS is then defined based on the kind of considered service. For circuit-switched services, like voice or constant bit rate data, blocking and dropping are the only QoS measures. For data services, an additional QoS metric is the throughput that is further distinguished in guaranteed throughput for streaming-like services and best effort.

The efficiency of devices alone does not include the efficiency of the site infrastructure that is needed to operate the device. If the perspective of a study is the overall consumption of a network node, the evaluation should therefore include also some aspects related to the site itself. Derived from the case of data centers, where the physical layout of the site, with the need of a power-hungry cooling infrastructure, backup power supply and other support systems, has a large impact, a measure of the efficient use of the energy in the whole site is the power usage effectiveness (PUE) defined by the ratio of the amount of power entering a site (or a data center) over the power needed to run the site.

The source of energy that empowers ICT is also significant since it has a different effect toward the environment. Usually a variety of energy sources is available, for example, coal, hydro, geothermal, nuclear, solar, and are typically mixed when empowering a system. Hence, a metric that can capture the CO_2 emissions per transmitted data volume may provide an insight of the environmental impact related to the corresponding energy source.

Finally, measuring the energy consumption of ICT systems is significant to gain understanding of their efficiency. Obtaining energy measurements is challenging in terms of accuracy, timeliness, overhead, and so on and can be performed instantaneous or with a degree of aggregation, either directly on network equipment or through a model-based approach [25]. Direct measurements can be carried out on hardware using power meters, by software means via Application Program Interfaces (APIs) or using management protocols such as Simple Network Management Protocol (SNMP), for example, in the case of power over Ethernet. Model-based approaches monitor certain traffic and equipment characteristics in order to derive the energy consumption and similarly to direct measurements can be carried out on hardware, for example, on a switch that may monitor the packet rate or traffic volume of an attached network equipment, by software, for example, PC's CPU load obtained via Windows Performance API or through SNMP queries, for example, querying the CPU load of a switch. A framework for monitoring and managing the energy consumption of network equipment including internal devices is detailed in Ref. [26] presenting an information model, which specifies energy objects and the means to monitor and control them.

1.6 Conclusions

Energy efficiency and green communication is getting momentum due to environmental and cost reasons, with government bodies creating energy regulations and policies for network equipment and systems. However, energy efficiency is not a new problem, but currently it is considered in relation with telecommunication systems and network equipment, not merely for user devices or sensor networks. Providing energy efficiency is a complex process that should consider all operational aspects and parts of a system in coordination providing a holistic approach. Network equipment should support one or a combination of energy saving features being able to power off, slow down, and regulate traversing traffic. Communication systems are expected to adopt energy efficiency in the planning and deployment phase as well as in network management, which ensures that network equipment are profitably saving energy. Besides equipment and systems, energy-aware protocols can handle communications, steer traffic, and retrieve content with minimum energy consumption, while considering the expected user QoS. However, the contribution and effect of these aforementioned methods and mechanisms is not quantified unless the appropriate metrics and measurements process are not in place. Hence, it is important to create such metrics and processes for measuring energy efficiency with respect to particular network equipment and specific system deployment scenarios.

This book aims to provide a detail insight into energy efficiency methods and mechanisms considering different operational layers and part of a telecommunications network. It initially explores wireless communications starting from a review of the fundamental aspects in Chapters 2–4, which contain a categorization and modeling of energy efficiency, an analysis of energy metrics, performance trade-offs, and the embodied energy consumption considering the system life cycle. The following four chapters are then considering the different aspects of a cellular system starting from the base station, the fundamental elements of a radio access network in Chapter 5, the network planning and design in Chapter 6, the radio considerations in Chapter 7, and the network management perspective in Chapter 8. The next three chapters explore energy efficiency studying specific wireless networks, with Chapter 9 concentrating on home and enterprise networks, Chapter 10 on delay tolerant and vehicular networks, and Chapter 11 on machine type communications (MTC) and Internet of Things (IoT). Finally, the last chapter for the wireless communication part, Chapter 12, overviews the current state of standards analyzing the efforts of 3rd Generation Partnership Project (3GPP), European Telecommunications Standards Institute (ETSI), and IEEE 802.11/Wi-Fi Alliance.

The remaining of the book analyze energy efficiency in wireline communications, considering in the first four chapters the typical technologies for fixed networks, with Chapter 13 concentrating on routing, switching, and transport, Chapter 14 on Energy Efficient Ethernet, Chapter 15 on optical communications, and Chapter 16 on data center routing and networking. The next three chapters consider different system attributes with Chapter 17 concentrating on network management, emphasizing the use of the emerging software-defined network (SDN) and network function virtualization (NFV) technologies, Chapter 18 analyzing energy aware communication protocols including TCP/IP, peer-to-peer, proxying, and context aware power management, and finally Chapter 19 considering content-based networking and ICN. The last chapter of the wireline communication part, Chapter 20, overviews the standardization efforts considering the Internet Engineering Task Force (IETF), Institute of Electrical and Electronics Engineers (IEEE), Broadband Forum (BBF), ETSI, and Alliance for Telecommunications Industry Solutions (ATIS). Finally, Chapter 21 provides the conclusions of the book and also presents the vision for energy efficiency in future deployments analyzing the evolving service requirements and analyzing the most promising areas for saving energy.

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