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Conclusions

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21.1 Summary

This book is divided into two main parts: In the first part, the wireless network aspects of green communication are addressed, including the fundamental, that is, categorization of the concepts, trade-off between energy efficiency and other efficiency metrics, the scales of achieved energy efficiency and the relationship between the embodied energy and the energy saving potentials of the current networks. It also covers not only base station considerations, network planning and management, but other emerging paradigms, such as vehicular networks and Internet of Things (IoT). In the second part, we focus on the energy efficient design and management approaches for wired networks, where Ethernet and optical networks are also discussed. The application, transport and network layer solutions are presented and the standardization efforts are introduced. Generally speaking, almost every individual aspect of green communications from wired and wireless perspectives is touched.

21.1.1 Green Communications in Wireless Networks

Three fundamental approaches for energy saving are identified: introduction of new energy-efficient network elements, improvement of dynamics of the network and employment of sleep mode. However, most of the strategies stemming from these basic approaches only consider the operating energy consumption but the manufacture energy is ignored. In this regards, an extended energy consumption model is proposed, where energy consumed by all the production processes of a network element, also referred as embodied energy, is taken into consideration [1].

Once a comprehensive energy model is defined, the metrics to evaluate the energy efficiency by the research communities are presented. The energy efficiency metrics can be categorized

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into three main classes: facility-level metrics, equipment-level metrics and network-level metrics [2–4]. Then the trade-off between energy and other costs is discussed from a variety of perspectives because energy efficiency can only be achieved by spending more on the other "costs," which can be spectrum efficiency, deployment efficiency and so on.

For wireless networks, today's existing various established and emerging system capabilities (features) towards green communications can be generally classified into three different elemental areas:

- **Radio component level**. A network node, such as a base station, comprises lots of sub-systems including radio unit, antennas, main power supply, baseband processing unit and cooling equipments. Solutions for reducing energy consumption of radio components exploit the potential of adapting to the load situations. In medium or low traffic load, some of the components can be deactivated, such as radio unit and power amplifier and some components can apply power scaling enablers to scale their power consumption according to the traffic load [23]. Other potential energy efficiency improving methods include reconfigurable antennas, where the antenna parameters are adaptive specifically according to spatial changes in traffic situation and changes in traffic load, and low loss antennas, where new foam substrate is used to improve the energy efficiency of the printed antenna structure [24]. Furthermore, antenna muting in smart MIMO systems, where the number of active antennas is adaptive by switching on antennas only when motivated by traffic load, is able to reduce energy consumption. Discontinuous transmission in time domain in radio part of a transmitter is also an enabler for energy efficiency improvement when there is not data to transmit [25].
- **Network elements level**. For each network element, the ability of sensing its environment gives the possibility of controlling the transmitting power, obtaining better management of interference. Recent research in cognitive radio exploits this possibility and addresses the potential of delivering green network nodes. A cognitive radio node exploits and uses the free spectrum available and power efficient modulation whenever possible. By doing this, power efficiency can be improved with little or no compromise on data rate [26]-[27]. In addition, the ability of dynamically adapting its resource usage according to the traffic level allows to reduce the energy consumption.
- **System architecture level**. Recent research on energy-aware system topology models and approaches for cellular networks focuses on two aspects: management issues such as switching on and off network elements based on the variation of traffic and radio planning issues such as deployment strategies and heterogeneous networks. Green Communications implements distributed and centralized algorithms, and network virtualization. Distributed algorithms allow for network management in different nodes so that each individual node is capable of taking a decision alone to reduce its energy consumption without degrading network performance. Centralized algorithms enables the operations and maintenance (O&M) to supervise and control network elements. Virtualization offers the possibility to share the same physical hardware to multiple instances of network services [28]. Heterogeneous networks (HetNets) are also proposed as a solution to improve overall energy efficiency, especially for cellular networks, where a mixture of Macro cells and small but agile cells is deployed [29]. In addition, the network management feature, i.e. node-activation/deactivation, has been proposed in order to improve energy efficiency.

Recent advances in the area of self-organized network (SON) reveals its potential to provide higher performance but also more efficient O&M [30]. SON offers main features such as self-configuration, self-optimization and self-healing and is part of the move to the next-generation of radio technology, aiming to leapfrog to a higher level of automated operation in mobile networks. It adapts itself to the fast changing traffic pattern in cellular networks and quickly and autonomously optimizes itself to sustain both network quality and a satisfying user experience.

These aforementioned green communication solutions/enablers can be regarded as a toolbox, meaning that it is unnecessary to apply all of them simultaneously because they are targeting various application scenarios. Actually, some of the solutions are not compatible with each other, thus cannot be employed at the same time. An integration of a carefully chosen subset of available solutions should be tailored based on applicable scenarios to achieve maximum reduction of energy expenditure.

21.1.2 Green Communication in Wired Networks

Network design and planning should consider the physical placement of devices, network topology, Quality of Service (QoS) and resilience. The design of converged networks that combine different transport technologies via network virtualization by introducing fewer network devices and network sharing is shown to be energy efficient in Ref. [5] and references therein. In addition to optimized network design, the network management with adaptability for new applications and paradigms in the network can further improve energy efficiency. One of the most promising solutions is software-defined networks, which allow for administration of network services more easily through abstraction of lower level functionality into virtual services and features the separation of the network elements' control plane to a central external entity [6]. An energy-efficient SDN-based network architecture with a newly defined Green Abstraction Layer (GAL) is presented for the power management of an individual device, where three main control plane processes are used including LCPs, NCPs & monitoring and OAM [7].

Besides the approaches in network level, the network devices can also be adaptive in modularity and rate. For the most common computer networking technology – LAN, the energy efficient enhancement of Ethernet is introduced, that is Energy Efficient Ethernet, also known as green Ethernet [8, 9]. The concept was presented in 2005 and substantially developed into IEEE 802.3az in 2007 [10]. In energy-efficient Ethernet, some network devices are put into sleep mode during the period of low data rate and they are only activated when the data is due to be sent.

In addition to computer networks, the study of energy-efficient strategies for optical networks is also important, as they are the backbone of core networks and an evolving solution providing high speed access. Optical networks are evolving into complex interconnected circuit-switched networks due to the continued growth in high-bandwidth applications. New cluster-based architecture, in which the nodes of the optical backbone network are divided into disjoint sets, is being discussed as a potential solution to improve the energy efficiency [11]. Each set consists of more than one node to form a single cluster. These clusters can be set to adopt a sleep mode initiated by the optical control plane (OCP) to save energy in low traffic scenarios.

An overview of energy-aware routing algorithms traffic engineering methods in backbone networks is also provided. Two potential approaches are identified: *switch off* and *energy proportional*. In the first approach, some devices are put into sleep mode to save energy. For instance, the routing algorithms and traffic engineering methods that perform aggregation of the current network load into as few paths as possible during off-peak periods are proposed to power off underutilized router/switches and links [12]. A solution named Table Lookup Bypass (TLB), based on the deactivation of forwarding functionalities inside a router line card, is elaborated in Ref. [13]. On the contrary, the second approach adapts to the speed and capacity of the devices to the actual load over relatively short timescales [14].

One of the most essential parts in today's backbone infrastructure is the modern data centres whose energy consumption can be decoupled into data server/storage power, network infrastructure power and cooling facilities power. These three main targets can be individually or jointly optimized to save a data centre's energy consumption. The state-of-the-art solutions to improve the energy efficiency of a data centre are focused on the computing and storage power mainly from three perspectives: dynamic link rate adaptation, link and switch sleep mode and improvement of the network topology [15–19]. Most importantly, these various approaches can be combined to be jointly optimized subject to some constraints on the network performance to achieve further energy efficiency improvement.

The energy consumption can be divided into two parts for core networks and edge devices, that is user equipments in homes and offices, respectively. In core networks, a continuous increase in traffic by a factor of 10 every 5 years has made TCP/IP-based core network suffer from severe scalability problems with respect to power. The current transport protocols can also be modified to become more energy efficient. For the TCP protocol, efforts have been made to make TCP aware of burst error, which is a major cause of packet loss, and act in a more energy-efficient manner [20]. The retransmission protocol can be further optimized to limit unwanted retransmission to save the wasted energy. Besides, the headers of protocols can be compressed to minimize the energy consumed for transmission of headers [21]. For edge devices, several energy saving protocols are introduced including *on-demand wakeup*, *proxying*, *content-aware power management* and *power-aware protocols*, each addressing the energy saving problem for edge devices from different perspectives.

From the perspective of Internet, the content delivery network (CDN) plays an important role in saving energy by resorting to location and mobility content update. However, CDN might not be efficient if the intended content for the user is not stored in the server nearby. Since users are more interested in obtaining the contents and do not care the establishment and maintenance of the connections, content-centric future Internet architecture is instigated, where the routing is influenced by the content request and the request is sent to the closest server to the user [22].

21.2 Green Communication Effects on Current Networks

Global warming has become a more and more serious challenge across the whole world in the past century mostly caused by human activities that increase concentrations of greenhouse gases in the atmosphere. Some scientific findings reveal that the CO_2 emission of the Information and Communications Technology (ICT) industry has contributed to a considerable percentage to the world energy consumption budget and global warming [31, 32]. In order to meet the exponentially growing demand, nearly 120,000 new base stations are deployed every year, each consuming an average power of 1 KW and using a total of 8,800 KW-hours each year. A typical medium-sized network constituting 12,000–15,000 cell sites, each equipped with two technologies (2G and 3G) and around three antennas per technology, accounts to an energy use of 736,000 MW-hours [33]. 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 [SBI Bulletin] SBI Bulletin: energy efficiency technologies in information and communication industry 2005-2015. Apparently, this revolutionary growth will be accompanied by a huge increase of the energy consumed by the telecommunication industry.

Other than the CO_2 emissions, there are other metrics to evaluate the energy expenditure of dissimilar components, individual network nodes and the whole network. In the node level, the Energy Consumption Index (ECI) can be used to measure the energy efficiency of a network node [25]. In the network level, consumed power per unit area is a common measurement metric.

The current research on green communication has successfully created innovations to dramatically reduce the energy consumption as well as the CO_2 emissions by bringing the current networks closer to its practical energy efficiency limit. The new developments in hardware have defined new innovative architectural concepts and are proved to be able to reduce the energy consumption of a network node by more than 40%. From the network perspective, the network optimization and management in the individual node level and in the system level, respectively, bring additional 30% energy savings all together in terms of consumed energy per information bit [25]. These analysis and values reveal the effects that the state-of-the-art green communication technologies bring to the current implemented networks. In the following section, we will exploit its future developing path.

21.3 Future Developments

Wired/wireless communication proliferates into nearly every aspect of life, leading to exploding traffic demands due to meteoric growth of static/mobile broadband services and as such is an essential driver for economic growth and improvement of welfare and well-being. For operators, equipment suppliers and service providers, it is becoming more and more challenging to achieve revenue growth in the same pace of the traffic growth. In this regard, the design of future communication systems not only needs to address the capacity crunch but it also has to deal with ecological concerns to reduce the cost per bit.

21.3.1 Future Network Requirements

As a consequence of the evolving global trends for advancing the efficiency of wired/wireless communication networks beyond the established state-of-the-art ones, the following objectives are broadly identified in order to enhance the sustainability of the future networks:

1. *Improved spectral and energy efficiency*. Since the current growth in traffic demand and the number of connected user terminals is inevitably limited by spectrum and energy consumption, a primary goal to be addressed by future communication networks is to provide an economic communication network with increased spectral and energy efficiency due to flexible infrastructure.

2. *Improvement of quality of experiences (QoE).* High bandwidth-demanding applications such as HD-video and 3D-video are becoming more and more popular. The actual throughput experienced by every individual user is essential and needs to be improved. In addition, users have increasing expectation in terms of quality of experience including transfer rate, responsiveness, accessibility, integrity, usability and so on. However, the increased QoE should be subject to the cost constraint and not bring huge energy expenditure.
3. *Reduction of cost of ownership and operation.* Huge investments are expected to deploy new networks in order to grantee satisfactory coverage and QoS for all customers. For example, in the radio access network side, it is expected that nearly 120,000 new base stations are deployed every year, let alone the associated core network enhancements. Since most of the telecommunication markets all over the world are shared by several main operators, it is compelling to share the network infrastructures for reduced total cost of ownership. Joint infrastructure sharing agreements between operators also reduces the operation cost in terms of energy consumption.
4. *Fusion of new and legacy networks.* Current deployed legacy networks employ different paradigms, spectrum bands and technologies from future networks. However, it would be a great waste to completely abandon these legacy networks. Network operators should ensure backwards compatibility, while exploiting multiple technologies and spectrum bands to establish an integrated interface across both legacy and future networks to support customers with different requirements.

21.3.2 Towards Holistic Energy Efficient Networking

There might be more potentials and objectives unveiled in addition to the aforementioned ones. For instance, improving the signalling efficiency is becoming increasingly important for wireless networks due to the dramatic increase of small data traffic. These objectives provide a direction where the current industry trends and research should be aligned with. It is an enormous challenge taking into account every aspect but the following topics/areas are considered as the most promising ones:

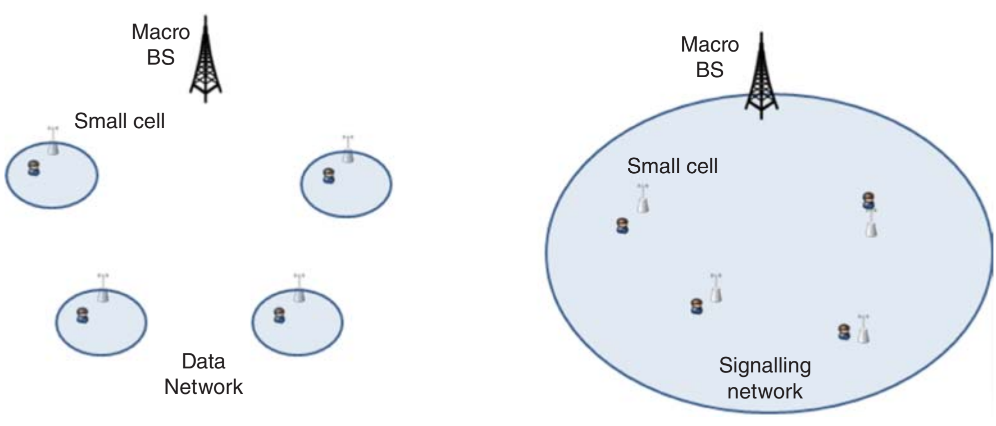

Figure 21.1 Splitting data and signalling

- *Architecture evolution*. Most of the aforementioned green technologies are built upon current enhancements networks and standardizations, which could be bottlenecks to constrain the architecture and functionalities. Revolutionary architecture enhancements without legacy network dependence needs to be studied to provide 10-fold or even more capacity improvement along with increased efficiency. Heterogeneous networks (HetNets), where large cells and small cells are mixed, have been studied to handle the traffic growth with densified spectrum reuse [34, 35]. However, the disadvantages of HetNets are obvious: Firstly, the constant association changes of a moving user generate mobility problems; secondly, inter-cell interferences are increased; thirdly, high densification of cell deployment causes additional energy consumption requiring a tighter alignment, i.e. a joint coordination, with the backhaul. As shown in Figure 21.1, innovative adaptable splitting between signalling and user traffic via their association to different cells is proposed to differentiate functionalities and remove the capacity and energy bottlenecks [25, 36]. The essence of this concept is to allow the terminals to exchange signalling traffic with large cells and data traffic with small cells, respectively. It provides a new degree of freedom to optimize and decouple the connectivity from the capacity. The mobility management can be easily handled by the large cells. Since the signalling is taken care of by the large cells, small cells are dedicated for data transmission and no longer need periodic signalling exchange, new network management schemes can be applied to put the small cells into “deep sleeping” status to save energy.
- *Extreme agile networks*. Agile networks with intelligence capabilities offer great adaptation and reconfiguration opportunities and make possible an unprecedented improvement of the energy efficiency through an extremely agile management of network elements and radio resources [37]. The agile efficient management is built upon context awareness and cognition of the network and comes at the cost of a higher complexity with respect to traditional systems. The context on which the network takes decision is not stable, but is rapidly changing. The agile management is based on a context-aware approach that makes use of a set of information elements creating a context framework and it includes the selection and activation of data access points, the dynamic and coordinated management of sleep modes, traffic balancing, and mobility and traffic variations management, taking into account different degrees of signalling and data access separation. In order to perform agile management, the following three steps need to be employed: First, identify, define and classify the set of information elements that can be used for creating the context in the network, identify possible information sources and define mechanisms for extracting information and making it available. Second, define context elaboration algorithms that allow obtaining high-level information from raw data exploiting historical traces, data caching, environment models and so on. Third, design algorithms and high-level signalling protocols for the activation of data sessions and the management of terminal mobility, and design optimization algorithms for energy-efficient, dynamic and automatic configuration of the network.
- *Orchestration*. An orchestration framework for a holistic and inclusive situation-aware management across cell sizes, wireless and backhaul technologies, spectrum opportunities and operators has been proposed to constitute the "brain" and "memory" of a network. This framework is designed to optimize the infrastructure behaviour across all current and foreseen scenarios for global handling of data/signalling traffic, mobility, interferences and so on. This framework considers both the network management transparent to the terminals and necessary interfaces between the terminals and the network(s). The framework itself should

consist of orchestration enablers including context-gathering, multi-technology and virtualization for both infrastructure and spectrum. The Orchestration intelligence exploited by multiple operators at a time is the core part and consists of situation awareness, knowledge, memory, reasoning and optimization.

- *Service-tailored network programmability*. Enable a network programmability allocating a resource slice that is tailored to optimize the energy consumption for a particular service by virtualizing and flexibly placing core network and radio functions at selected locations. This aims to facilitate a joint energy optimization of the radio, backhaul and core networks, while at the same time providing resource efficient and energy aware cloud, Over-The-Top, social applications and other emerging services. The main technologies for supporting this approach are the Network Function Virtualization (NFV) and Software Defined Networks (SDN) that can enable additionally the support for network sharing and multi-tenancy. SDN can also bring the advantage of considering the energy efficiency for using the underlying transport and backbone networks and forward requests towards the appropriate data center optimizing energy consumption.
- *Network federation*. Federating networks means to share resources among multiple independent networks in order to optimize the use of those resources, improve the quality of network-based services and/or reduce costs [38–41]. The sharing concept introduces management functionalities for transparently mapping logical networks (each associated with one operator) to (a) physical network(s). The management functionality will offer optimal cost reduction in combination with ample opportunities for competition through service level differentiation between operators, while guaranteeing fairness and security. For the users, this leads to transparent access to the shared physical networks. The sharing concept will enable fundamentally new business models for infrastructure and resource sharing (and federations thereof), including new business roles and actors in networks and services. The network segments can be jointly owned by several operators and each network segment covers a subset of the area can be owned by one operator, and is open to other operators.
- *Reconfigurable hardware*. The low power, load adaptive and reconfigurable hardware are essential to implement any of aforementioned solutions. The new generation hardware should go beyond state-of-the-art and possess the capability of adapting themselves to different activity levels and optimizing their performance with finer granularity, which facilitate seamless transitions between different network operation states and maximize the energy efficiency improvements.

There will be more directions for green communication with the continuously evolving markets. These no-stopping researches will guide us to the inspiring new generation of products and networks and eventually change the world as well as our lives significantly.

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