NIRWAN ANSARI AND TAO HAN

# GREEN MOBILE NETWORKS

## A NETWORKING PERSPECTIVE

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A Networking Perspective

*Nirwan Ansari*
*New Jersey Institute of Technology, USA*

*Tao Han*
*University of North Carolina, Charlotte, USA*

IEEE PRESS

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This edition first published 2017


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John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

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Library of Congress Cataloging-in-Publication data is available for this book.

ISBN 9781119125105 (hardback)

Cover Image: © Brandon Sillaro / EyeEm/Gettyimages
Cover Design: Wiley

Set in 10/12pt WarnockPro by Aptara Inc., New Delhi, India

Printed in Great Britain by TJ International Ltd, Padstow, Cornwall

10 9 8 7 6 5 4 3 2 1

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# Preface

Greening is not merely a trendy concept, but is becoming a necessity to bolster social, environmental, and economic sustainability. Naturally, green communications have received much attention recently. As mobile network infrastructures and mobile devices proliferate, an increasing number of users rely on cellular networks for their daily lives. As a result, mobile networks are among the major energy hogs of communication networks and their contribution to global energy consumption is increasing fast. Therefore, greening of cellular networks is crucial to reducing the carbon footprint of Information and Communications Technology (ICT). As a result, the field is attracting tremendous research efforts from both academia and industry.

This book is intended to provide a technical description of state-of-the-art developments in greening of mobile networks from a networking perspective. It discusses fundamental networking technologies that lead to energy-efficient mobile networks. These technologies include heterogeneous networking, multi-cell cooperation, mobile traffic offloading, traffic load balancing, renewable energy integrated mobile networking, device-to-device networking, and mobile content delivery optimization. The text is suitable for graduate courses in electrical and computer engineering and computer science. The authors have adopted some materials presented in this book for their graduate courses at New Jersey Institute of Technology[1] and University of North Carolina–Charlotte[2]. This book also includes many results and patented algorithms from our research, which makes this book a valuable reference for graduate students, practicing engineers, and research scientists in the field of green communications and networking.

The material is structured in a modular fashion with chapters being reasonably independent of each other. Individual chapters can be perused in an arbitrary order to the liking and interest of the reader, and they can also be incorporated as part of a larger, more comprehensive course. The first chapter provides an overview of existing networking technologies and solutions for greening mobile networks. The second to fourth chapters cover three major networking technologies in detail: multi-cell cooperation, green energy enabled mobile networking, and spectrum and energy harvesting. The fifth to ninth chapters present green mobile networking solutions including mobile traffic offloading, optimizing green energy enabled mobile networks, traffic load balancing, device-to-device networking, and content delivery optimization.

[1] ECE 639 Principles of Broadband Networks and ECE 788 Advanced Topics in Broadband Networks.
[2] ECGR 6120/8120 Wireless Communications and Networking.

## List of Abbreviations

| | |
|---|---|
| 3GPP | 3rd generation partnership project |
| ACE | Acknowledgment based on CWND estimation |
| AF; DF | Amplify-and-forward; decode-and-forward |
| AMC | Adaptive modulation and coding |
| ARQ; HARQ | Automatic repeat-request; hybrid ARQ |
| BA | Bandwidth allocation |
| BDP | Bandwidth delay product |
| BES | Base station energy sharing |
| BESS | Binary energy system sizing |
| BM | Battery minimization |
| BPO | Base station operation and power distribution optimization |
| BS | Base station |
| CAPEX; OPEX | Capital expenditure; operational expenditure |
| CBR | Constant bit rate |
| CELL_DCH | Cell dedicated channel |
| CELL_FACH | Cell forward access channel |
| CELL_PCH | Cell page channel |
| CF | Cluster formation |
| CH | Cluster head |
| CoMP | Coordinated multi-point |
| COS | Content owner selection |
| CR | Cognitive radio |
| CRE | Cell range expansion |
| CSS | Cooperative sensing scheduling |
| CW | Congestion warning |
| CWND | Congestion window |
| D2D | Device-to-device |
| DAC; ADC | Digital-to-analog converter; analog-to-digital converter |
| DC; AC | Direct current; alternating current |
| DCH | Dedicated channel |
| DRA | Dynamic resource allocation |
| DRB | Data rate bias |
| DSA | Dynamic spectrum access |

| | |
|---|---|
| EC-constraint | Energy causality constraint |
| EDR | Energy depleting ratio |
| EDS | Energy dependent set |
| EE | Energy efficiency |
| EH | Energy harvesting |
| ELLA | Energy loss and latency aware |
| EA | Energy Allocation |
| EPS | Evolved packet system |
| ESG | Energy saving greedy |
| ESM | Energy savings maximization |
| EST | Energy spectrum trading |
| EUTRAN (UTRAN) | Evolved UTMS terrestrial radio access network |
| FC | Fusion center |
| GALA, vGALA | Green energy aware and latency aware; virtual GALA |
| GAP | Green energy aware problem |
| GCB | Green content broker |
| GEO | Green energy optimization |
| GEP | Green energy provisioning |
| GESS | Green energy system sizing |
| GPRS | General packet radio service |
| GRA | Green relay assignment |
| GUA | General user association |
| HetNets | Heterogeneous networks |
| HTO | Heuristic traffic offloading |
| ICE | Intelligent cell breathing |
| ICT | Information and communications technology |
| IoT | Internet of things |
| ISP | Internet service provider |
| IT | Interference temperature |
| KKT | Karush–Kuhn–Tucker |
| LAP | Latency aware problem |
| LEM | Largest EDR minimization |
| LM | Latency minimization |
| LOEP | Loss of energy probability |
| LOLP | Loss of load probability |
| LTE | Long term evolution |
| MAC | Media access control |
| MBS | Macro base station |
| MDP | Markov decision process |
| MEA | Multi-stage energy allocation |
| MEB | Multi-BS energy balancing |
| MIMO | Multi-input-multi-output |
| MINLP | Mixed integer non-linear programming |
| MNO | Mobile network operator |
| MRC | Maximal ratio combining |
| MWBM | Maximum weight bipartite matching |

| | |
|---|---|
| NC | No cache |
| NLOS | Non-line-of-sight |
| NPS | Non-interfering prefetching system |
| NUA | Network utility aware |
| O-DSTC | Opportunistic distributed space-time coding |
| OFDM; OFDMA | Orthogonal frequency-division multiplexing; orthogonal frequency-division multiple access |
| P2P; P2MP | Point to point; point to multi-point |
| PBR | Power-bandwidth ratio |
| PBS | Primary base station |
| PCA | Provisioning cost aware |
| PCM; SPCM; HPCM; WPCM | Power consumption minimization; simplified PCM; heuristic PCM; weighted PCM |
| PDCP | Packet data convergence protocol |
| POMDP | Partially observable Markov decision process |
| PS | Processor sharing |
| QB | QoS bound |
| QoE | Quality of experience |
| QoS | Quality of service |
| RA | Resource allocation |
| RAN; RANC | Radio access network; RAN controller |
| RAT | Radio access technology |
| RED | Random early detection |
| RF | Radio frequency |
| RLC | Radio link control |
| RN | Relay node |
| RR | Round robin |
| RRC | Radio resource control |
| RSSI | Received-signal-strength-indication |
| RTO | Retransmission timeouts |
| RTT | Round trip time |
| SAM | System advisor model |
| SBS | Secondary base stations |
| SCBS | Small cell base station |
| SCN | Small cell network |
| SCS | Serving content selection |
| SD | Source-destination |
| SDR | Secondary data rate |
| SDU | Service data unit |
| SE | Spectrum, efficiency |
| SGSN; GGSN | Serving GPRS support node; gateway GPRS support node |
| SHA | Secure hash algorithm |
| SI | Side information |
| SINR | Signal interference noise ratio |
| SN | Source node |
| SNR | Signal to noise ratio |

| | |
|---|---|
| SoftRAN | Software-defined radio access network |
| SSF | Strongest signal first |
| TDMA; FDMA | Time division multiple access; frequency division multiple access |
| TOM | Traffic offloading maximization |
| UA | User association |
| UE | User equipment |
| UMTS | Universal mobile telecommunications system |
| URA_PCH | UTRAN registration area paging channel |
| URICA | Usage-aware interactive content adaptation |
| WBST | Wireless boosted session transport |
| WEM | Weighted energy minimization |
| WLA | Wireless loss alarm |
| WUA; AWUA | Weighted user–BS association; approximate WUA |
| X2 | Inter-eNode B interfaces |

# Part I

# Green Mobile Networking Technologies

# 1

# Fundamental Green Networking Technologies

As cellular network infrastructures and mobile devices proliferate, an increasing number of users rely on cellular networks for their daily lives. Mobile networks are among the major energy guzzlers of information communications technology (ICT) infrastructure, and their contributions to global energy consumption are accelerating rapidly because of the dramatic surge in mobile data traffic [1, 2, 3, 4]. This growing energy consumption not only escalates the operators' operational expenditure (OPEX) but also leads to a significant rise of their carbon footprints. Therefore, greening of mobile networks is becoming a necessity to bolster social, environmental, and economic sustainability [5, 6, 7, 8]. In this chapter, we give an overview of the fundamental green networking technologies.

## 1.1 Energy Efficient Multi-cell Cooperation

The energy consumption of a cellular network is mainly drawn from base stations (BSs), which account for more than 50% of the energy consumption of the network. Thus, improving energy efficiency of BSs is crucial to green cellular networks. Taking advantage of multi-cell cooperation, energy efficiency of cellular networks can be improved from three perspectives. The first is to reduce the number of active BSs required to serve users in an area [9]. The solutions involve adapting the network layout according to traffic demands. The idea is to switch off BSs when their traffic loads are below a certain threshold for a certain period of time. When some BSs are switched off, radio coverage and service provisioning are taken care of by their neighboring cells.

The second aspect is to connect users with green BSs powered by renewable energy. Through multi-cell cooperation, off-grid BSs enlarge their service areas while on-grid BSs shrink their service areas. Zhou *et al.* [10] proposed a handover parameter tuning algorithm and a power control algorithm to guide mobile users to connect with BSs powered by renewable energy, thus reducing on-grid power expenses. Han and Ansari [11] proposed an energy aware cell size adaptation algorithm named ICE. This algorithm balances the energy consumption among BSs, enables more users to be served with green energy, and therefore reduces on-grid energy consumption. Envisioning future BSs to be powered by multiple types of energy sources, for example, the grid, solar energy, and wind energy, Han and Ansari [12] proposed optimizing the utilization of green energy for cellular networks by cell size optimization. The proposed algorithm achieves significant main grid energy savings by scheduling green energy consumption in the time

*Green Mobile Networks: A Networking Perspective*, First Edition. Nirwan Ansari and Tao Han.

domain for individual BSs, and balancing green energy consumption among BSs for the cellular network.

The third aspect is to exploit coordinated multi-point (CoMP) transmissions to improve energy efficiency of cellular networks [13]. On the one hand, with the aid of multi-cell cooperation, energy efficiency of BSs on serving cell edge users is increased. On the other hand, the coverage area of BSs can be expanded by adopting multi-cell cooperation, thus further reducing the number of active BSs required to cover a certain area. In addition to discussing multi-cell cooperation solutions, we investigate the challenges for multi-cell cooperation in future cellular networks.

## 1.2 Heterogeneous Networking

The energy consumption of mobile networks scales with the provisioned traffic capacity. On deploying a mobile network, two types of BSs may be deployed. They are macro BSs (MBSs) and small cell BSs (SCBSs). As compared with SCBSs, MBSs provide a larger convergence area and consume more energy. SCBSs are deployed close to users, and thus consume less energy by leveraging such proximity. Owing to a small coverage area, in order to guarantee traffic capacity in an area, a very large number of SCBSs must be deployed. The total energy consumption of the large number of SCBSs may exceed that of the MBSs. Hence, in order to improve the energy efficiency of the network, a mixed deployment of both MBSs and SCBSs is desirable. In general, there are two SCBS deployment strategies: deployed at cell edges and at traffic hot spots.

- The users located at the edge of a macro cell usually experience bad radio channels due to excessive channel fading. In order to provide service to these users, MBSs could increase their transmit power, but this will result in a low energy efficiency. In a heterogeneous network deployment, SCBSs can be deployed at the edge of macro cells as shown in Figures 1.1–1.4. Depending on the traffic capacity demand, different SCBS deployment strategies can be adopted. For example, when the traffic capacity demand is relatively low, one SCBS may be deployed at the edge of a macro cell to serve the cell edge users as shown in Figure 1.1. As the traffic increases, additional SCBSs can

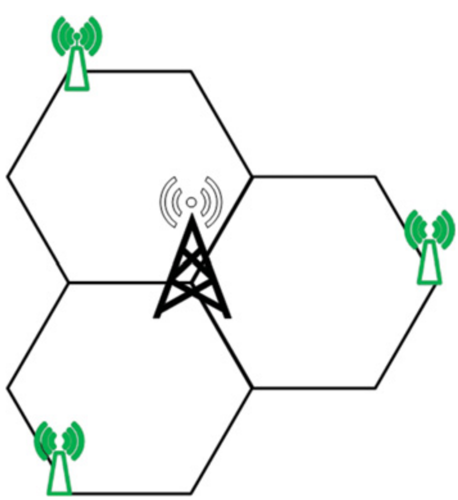

**Figure 1.1** Scenario 1: One SCBS per macro site.

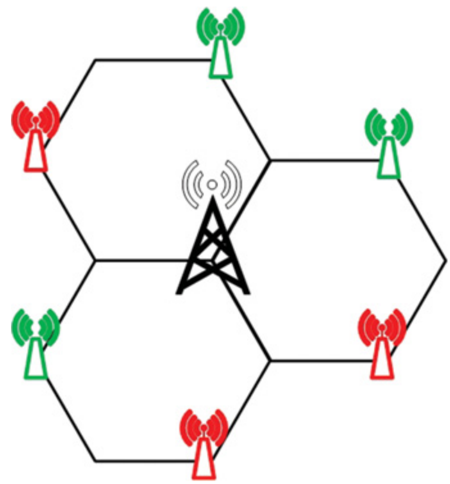

**Figure 1.2** Scenario 2: Two SCBSs per macro site.

be deployed at the cell edge as shown in Figs. 1.2 and 1.3. When the traffic capacity demand is very high, additional SCBSs should be deployed. For example, five SCBSs are deployed for enhancing the energy efficiency of serving cell edge users in Figure 1.4. The number of SCBSs that are deployed to enhance the energy efficiency of serving users located at the edges of macro cells should be optimized based on traffic capacity demand at the cell edge.

- When the traffic capacity demand in mobile networks is inhomogeneous, deploying SCBSs at the edges of macro cells may not be optimal. Instead, SCBSs can be deployed in areas where there is high traffic capacity demand such as shopping areas, stadiums, and public parks. We define such areas as *hotspots*. Owing to proximity to the users, SCBSs can provide very high capacity at hotspots and serve the traffic demand with low energy consumption. In order to deploy SCBSs at traffic hotspots to enhance energy efficiency, the distribution of traffic capacity demand should be understood from network measurements. In addition, the traffic capacity demand should be localized so that a large portion of the traffic demand can be offloaded to

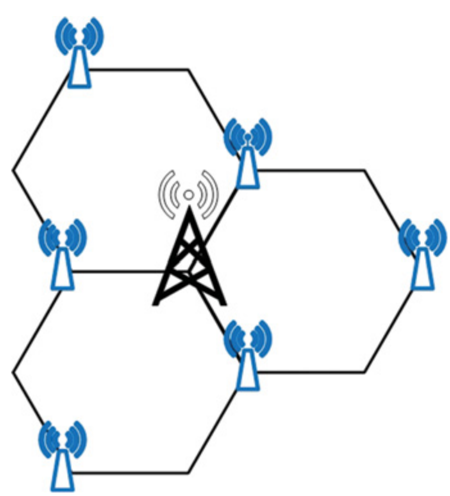

**Figure 1.3** Scenario 3: Three SCBSs per macro site.

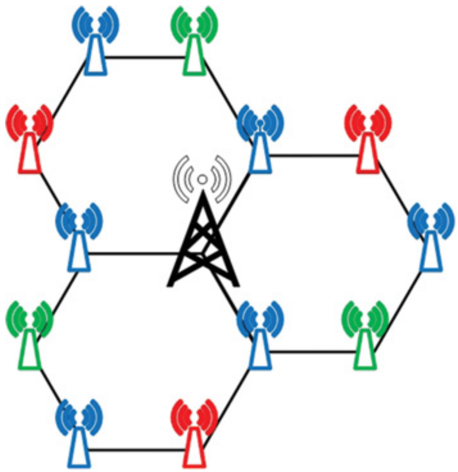

**Figure 1.4** Scenario 4: Five SCBSs per macro site.

SCBSs. In the ideal case, MBSs are only serving users with high moving speed while all the other users are served by SCBSs. If the high traffic demand occurs indoors, the indoor deployment of SCBSs can significantly enhance the energy efficiency of mobile networks.

## 1.3 Mobile Traffic Offloading

Mobile traffic offloading, which is referred to as utilizing complementary network communications techniques to deliver mobile traffic, is a promising technique to alleviate congestion and reduce the energy consumption of mobile networks. Based on the network access mode, mobile traffic offloading schemes can be divided into two categories. The first category is infrastructure based mobile traffic offloading, which refers to deploying SCBSs, for example, pico BSs, femto BSs and WiFi hot spots, to offload mobile traffic from MBS [14, 15]. SCBSs usually consume much less power than MBSs. Therefore, offloading mobile traffic to SCBSs can significantly enhance the energy efficiency of mobile networks [6, 16]. However, the lack of cost-effective backhaul connections for SCBSs often impairs their performance in terms of offloading mobile traffic and enhancing the energy efficiency of mobile networks. The second category is ad-hoc based mobile traffic offloading, which refers to applying device-to-device (D2D) communications as an underlay to offload mobile traffic from MBSs. By leveraging Internet of Things (IoT) technologies, smart devices within proximity are able to connect with each other and form a communication network. Data traffic among the devices can be offloaded to the communication networks rather than delivering through MBSs. Moreover, in order to reduce $CO_2$ footprints, mobile traffic can be offloaded to BSs powered by green energy such as sustainable biofuels, solar, and wind energy [17, 12, 10, 18]. In this way, green energy utilization is maximized, and thus the consumption of on-grid energy is minimized. In this section, we briefly overview the related research on mobile traffic offloading and the solutions for user–BS associations in heterogeneous mobile networks.

### 1.3.1 Infrastructure Based Mobile Traffic Offloading

In infrastructure based mobile traffic offloading, the mobile traffic is offloaded to either pico/femto BSs or WiFi hot spots. Deploying pico/femto BSs improves the spectral and energy efficiency per unit area of cellular networks, and thus reduces the network congestion and energy consumption of cellular networks. Traffic offloading between pico/femto BSs and the MBS is achieved by adapting user–BS associations. Kim *et al.* [19] proposed a user–BS association to achieve flow level load balancing under spatially heterogeneous traffic distribution. Jo *et al.* [20] proposed cell biasing algorithms to balance traffic loads among pico/femto BSs and the MBS. The cell biasing algorithms perform user–BS association according to the biased measured pilot signal strength, and enable traffic to be offloaded from the MBS to pico/femto BSs.

WiFi hot spots are also effective in terms of offloading mobile traffic. Lee *et al.* [21] pointed out that a user is in WiFi coverage for 70% of the time on average, and if users can tolerate a two hour delay in data transfer, the network can offload about 70% of cellular traffic to WiFi networks. Balasubramanian *et al.* [22] proposed to offload the delay tolerant traffic such as email and file transfer to WiFi networks. When WiFi networks are not available or experiencing blackouts, data traffic is quickly switched back to 3G networks to avoid violating the applications' tolerance threshold. Han and Ansari [15] designed a content pushing system which pushes the content to mobile users through opportunistic WiFi connections. The system responds to a user's pending requests or predicted future requests, codes the requested content by using Fountain codes, predicts the user's routes, and prelocates the coded content to the WiFi access points along the user's route. When the user connects to these WiFi access points, the requested content is delivered to the user via the WiFi connections.

### 1.3.2 Ad-hoc Based Mobile Traffic Offloading

Ad-hoc based mobile traffic offloading relies on D2D communications to disseminate content. Instead of downloading content directly from BSs, User Equipment (UE) may retrieve content from their neighboring UEs. Han *et al.* [23] proposed a mechanism to select a subset of UEs based on either UEs' activities or mobilities, to deliver content to them through cellular networks, and to let these UEs further disseminate the content through D2D communications to the other users. Mashhadi *et al.* [24] proposed a proactive caching mechanism for UEs in order to offload the mobile traffic. When the local storage does not have the requested content, the proactive caching mechanism will set a target delay for this request, and explores opportunities to retrieve data from neighboring UEs. The proactive caching mechanism requests data from cellular networks when the target delay is violated. To encourage mobile users to participate in the traffic offloading, Zhou *et al.* [25] proposed an incentive framework that motivates users to leverage their delay tolerance for cellular data offloading.

### 1.3.3 User–BS Associations in Heterogeneous Mobile Networks

Heterogeneous networking is a promising network architecture which may significantly enhance the spectral and energy efficiency of mobile networks. One of the most important issues in heterogeneous cellular networks is to properly associate mobile users with the serving BSs, referred to as the "user–BS association problem." In heterogeneous cellular networks, the transmit power of SCBSs is significantly lower than that of MBSs. Thus, mobile users are more likely to be associated with the MBS based on the strength of their received pilot signals. As a result, SCBSs may be lightly loaded, and do not contribute much to traffic offloading. To address this issue, many user–BS association algorithms have been proposed [19, 20, 26]. Kim *et al.* [19] proposed a framework for user–BS association in cellular networks to achieve flow level load balancing under spatially heterogeneous traffic distribution. Jo *et al.* [20] proposed cell biasing algorithms to balance traffic loads among MBSs and SCBSs. The cell biasing algorithms perform user–BS association according to biased measured pilot signal strength, and enable traffic to be offloaded from MBSs to SCBSs. Corroy *et al.* [26] proposed a dynamic user–BS association algorithm to maximize the sum rate of the network and adopted cell biasing to balance the traffic load among BSs. Fooladivanda *et al.* [27] studied joint resource allocation and user–BS association in heterogeneous mobile networks. They investigated the problem under different channel allocation strategies, and the proposed solution achieved global proportional fairness among users. Madan *et al.* [28] studied user–BS association and interference coordination in heterogeneous mobile networks, and proposed heuristic algorithms to maximize the sum utility of average rates.

## 1.4 Device-to-Device Communications and Proximity Services

The surge in mobile data traffic brings about two major problems to current mobile networks. The first problem is that the significant data growth congests mobile networks and leads to long delays in content delivery [14]. The second problem is that a continuous surge of mobile traffic results in a dramatic increase in energy consumption in mobile networks from provisioning higher network capacity [5]. By leveraging IoT technologies, smart devices within proximity are able to connect with each other and form a communication network. Data traffic among the devices can be offloaded to the communication networks rather than delivering through MBSs. For example, by enabling D2D communications, some UE downloads content from MBSs while the other UEs may retrieve the content through D2D connections with their peers. In this way, D2D communications alleviates traffic congestion and reduces the energy consumption of mobile networks.

D2D communications may, however, suffer from several disadvantages which impair its performance in terms of offloading mobile traffic. First, UEs are battery powered devices, and therefore the additional energy consumption may prevent UEs from participating in D2D communications. Second, the transmission range for D2D communications among mobile devices is limited by its low transmission power. For example, if a mobile device experiences a shortage of battery power, the mobile device may restrict its power usage in D2D communications. This leads to a reduced transmission range for the mobile device's D2D communications. Especially when mobile devices operate at millimeter wavelengths, the transmission range is further limited by the channel propagation characteristics. Third, D2D communications may require complicated radio resource management schemes implemented in mobile devices to avoid the introduction of extensive interference to mobile networks. This will further increase mobile devices' power consumption in D2D communications. Fourth, sharing content through

D2D communications may reveal users' privacy. Hence, mobile devices may not be willing to participate in D2D communications in order to protect their users' privacy.

Much effort has been spent studying the related problems in device-to-device communications. Bletsas *et al.* [29] proposed a distributed relay node selection scheme which selects relay nodes based on the instantaneous channel condition at the nodes. Zhao *et al.* [30] studied the performance of a cooperative communications system where a source node communicates with a destination node with the help of multiple relay nodes, and showed that choosing one best relay node is sufficient to maintain full diversity order. Wang *et al.* [31] proposed a game theory based relay selection algorithm for multi-user cooperative communication networks. Sharma *et al.* [32] studied the relay assignment problem in cooperative ad hoc networks, and proposed a relay assignment algorithm to maximize the minimum data rate among all the source destination (SD) pairs. While these works investigated the relay assignment problem with different network settings and optimization objectives, they all assumed that a relay node is assigned to at most one source SD pair. Yang *et al.* [33] extended the relay assignment problem to consider a relay node being assigned to multiple SD pairs. The authors proposed maximizing the summation of the data rates of all SD pairs, and proved that it is only necessary to assign one relay node to one SD pair in order to achieve the optimal solution.

## 1.5 Powering Mobile Networks With Renewable Energy

As green energy technologies advance, green energy such as sustainable biofuels, solar, and wind energy can be utilized to power SCBSs and MBSs [17]. Telecommunications companies such as Ericsson and Nokia Siemens have designed green energy powered BSs for cellular networks [34]. By adopting green energy powered secondary base stations (SBSs), mobile service providers may reduce on-grid energy consumption and thus reduce their $CO_2$ emissions. For instance, Orange, a French mobile network operator (MNO), has already deployed more than two thousand solar powered BSs in Africa [35]. These BSs serving over 3 million people saved up to 25 million liters of fuel and reduced about 67 million kilograms of $CO_2$ emissions in 2011 [35].

The design and optimization of green energy powered mobile networks is challenging. As shown in Figure 1.5, in addition to radio resource management, optimizing green energy enabled mobile networks involves the optimization of the utilization of green energy from both standalone power generators and green power farms. At the same time, smart grid techniques enable power trading among consumers via smart meters. As a result, power cooperation, which enables BSs to share their green power with each other, has been introduced to engineer green energy enabled mobile networks. The coupling of radio resource optimization and power utilization optimization introduces new research challenges on optimizing green energy enabled mobile networks. This chapter investigates the design and optimization issues involved in green energy enabled mobile networks.

## 1.6 Green Communications via Cognitive Radio Communications

The proliferation of wireless devices is driving the exponential growth of wireless data traffic over wireless and mobile networks. This leads to a continuous surge not only in

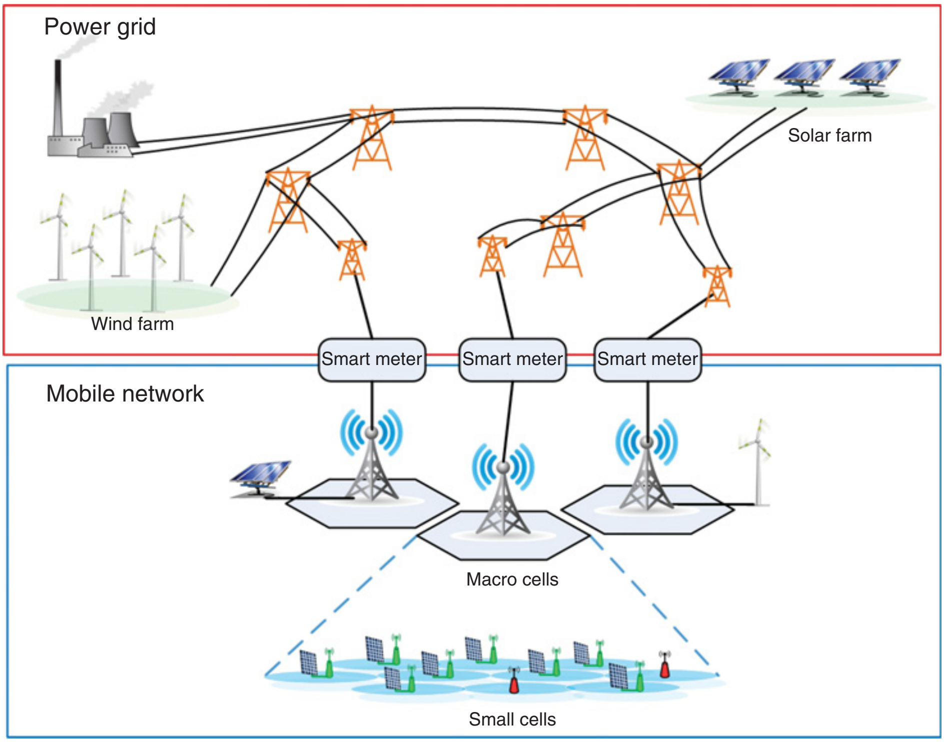


**Figure 1.5** Green energy enabled mobile networks. *Source:* Han 2014 [17]. Reproduced with permission of IEEE.

network capacity demands but also in network energy consumption. Since a wireless system is spectrum limited, the ever-increasing capacity demands result in a spectrum crunch. Deploying additional network infrastructure such as BSs is an effective approach to alleviate spectrum shortage [36]. Thus, SCBSs will be widely deployed. SCBSs can provide high network capacity for wireless users by capitalizing on their close proximity to the users. However, an SCBS has a limited coverage area. Thus, the number of SCBSs will be an order of magnitude larger than that of MBSs for a large scale network deployment. As a result, the overall energy consumption of cellular networks will keep increasing [5]. Therefore, current wireless access networks are eventually constrained by spectrum scarcity and energy consumption. It is desirable to amalgamate spectrum harvesting and energy harvesting technologies to liberate wireless networks from these constraints.

Greening wireless access networks can capitalize on the broad paradigm of spectrum harvesting technologies. Spectrum harvesting technology, which is also known as cognitive radio (CR)[1], has been defined thus: "A cognitive radio transmitter will learn from the environment and adapt its internal states to statistical variations in the existing radio frequency (RF) stimuli by adjusting the transmission parameters (e.g., frequency band,

[1] In this book, we use the terms spectrum harvesting technology and cognitive radio technology interchangeably.

modulation mode, and transmission power) in [a] real time and online manner" [37]. With the capability to detect available spectrum and the reconfigurability to dynamically access parts of the spectrum over which less fading and interference is experienced, the intelligent CR communications system enhances spectrum agility and energy efficiency.

In addition to current CR networks powered by reliable on-grid or un-rechargeable energy sources, continuous advances in green energy have motivated researchers to investigate green powered cognitive radio (green CR) networks. The concept of the energy harvester has been proposed to capture and store ambient energy to generate electricity or other forms of energy that is renewable and more environmentally friendly than that derived from fossil fuels. If the green energy source is ample and stable in the sense of availability, a CR network can be powered to opportunistically exploit the underutilized spectrum by harnessing free energy, without requiring an energy supplement from the external power grid or batteries.

## 1.7 Green Communications via Optimizing Mobile Content Delivery

Owing to imminent fixed/mobile convergence, Internet applications are frequently accessed through mobile devices. Given limited bandwidth and unreliable wireless channels, content delivery in mobile networks usually experiences long delays. Inefficient content delivery significantly increases the energy consumption of mobile networks. Many solutions have been proposed to accelerate content delivery in mobile networks.

To understand the performance of mobile networks, many measurement studies have been presented. These studies unveil the obstacles that delay content delivery in mobile networks, and shed light on the research directions for enhancing the performance of mobile networks. Noticing the shortcomings of mobile networks, many solutions have been proposed to reduce content delivery latency and enhance subscribers' quality of experience (QoE) in mobile networks. Figure 1.6 shows a classification hierarchy of available content delivery acceleration solutions. We classify these solutions into three categories, namely, mobile system evolution, content and network optimization, and mobile data offloading. The techniques are further classified within each category. Mobile communications system evolution is one of the major solutions to enhance content delivery efficiency in mobile networks. On the one hand, to meet the increasing demands for mobile data services, the 3rd Generation Partnership Project (3GPP) has established evolution plans to enhance the performance of mobile communications systems. 3GPP LTE (Long Term Evolution) Advanced is a mobile communications standard for next generation mobile communications systems featuring high speed and low latency. LTE Advanced networks adopt multi-input-multi-output (MIMO) and orthogonal frequency-division multiple access (OFDMA) to enhance both the capacity and reliability of wireless links, introduce the Evolved Packet System (EPS) [38] to reduce the amount of protocol related processing, and integrate CR techniques to expand the available bandwidth in the system. On the other hand, mobile networks and content delivery networks are being integrated to provide end-to-end acceleration for mobile content delivery [39].

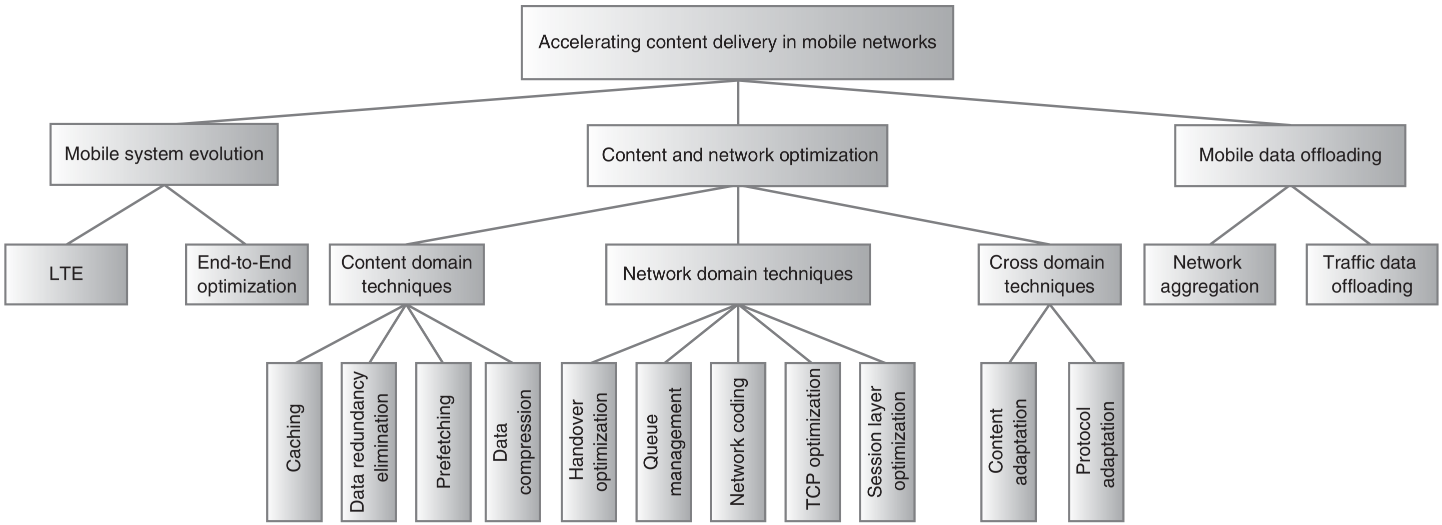


**Figure 1.6** Classification hierarchy of content delivery acceleration solutions in mobile networks. *Source:* Han 2013 [14]. Reproduced with permission of IEEE.

The content and network optimization techniques are further classified into three categories based on their application domains. The first category pertains to the content domain techniques including caching, data redundancy elimination, prefetching, and data compression. These techniques aim to reduce traffic volume over mobile networks, thus reducing network congestion and accelerating content delivery. The second category refers to the techniques applied in the network domain. These techniques include handover optimization, queue management techniques, network coding, TCP optimization, and session layer optimization. The network domain techniques optimize the operation of mobile networks and communication protocols, and thus enhance network performance. The third category includes cross domain techniques such as content adaptation and protocol adaptation. Content adaptation adjusts the original content according to the mobile network conditions and the characteristics of mobile devices. Content adaptation can efficiently reduce the data volume over mobile networks and accelerate content delivery. Protocol adaptation optimizes communication protocols according to application behaviors. It reduces network chattiness, and thus reduces content delivery delay.

A significant data traffic increase may congest the mobile network, and lead to long delays in content delivery and low energy efficiency. Offloading data traffic from congested mobile networks is a promising method to reduce network congestion. Mobile data offloading techniques include two perspectives. The first is to directly offload mobile data to high speed networks, for example, WiFi. The second is network aggregation, which allows subscribers to simultaneously utilize their multiple radio interfaces, for example, 3G, WiFi, and Bluetooth, to retrieve content. Mobile data offloading techniques reduce the pressure on mobile networks in terms of data volume, thus enhancing network performance in terms of content delivery.

The rest of this book is organized as follows. Chapter 2 gives an overview of multi-cell cooperation solutions for improving the energy efficiency of cellular networks. Chapter 3 covers the research challenges and existing solutions for green energy enabled mobile networks. Chapter 4 discusses state-of-the-art research on spectrum and energy harvesting networks. Chapter 5 presents a novel energy spectrum trading (EST) scheme to enable MBSs to offload their mobile traffic to Internet service providers' (ISPs') wireless access points by leveraging CR techniques. Chapter 6 investigates a framework for optimizing green energy utilization for mobile networks with hybrid energy supplies. Chapter 7 presents an energy efficient traffic load balancing scheme in mobile networks. Chapter 8 covers device-to-device proximity services-based energy efficient communications schemes. Finally, Chapter 9 presents solutions for optimizing content delivery in mobile networks.

# 2

# Multi-cell Cooperation Communications

It has been shown that, with the aid of multi-cell cooperation, the performance of a cellular network in terms of throughput and coverage can be enhanced significantly. However, the potential of multi-cell cooperation to improve the energy efficiency of cellular networks remains to be unlocked. In this chapter, we give an overview of multi-cell cooperation solutions for improving the energy efficiency of cellular networks. First, we introduce traffic intensity aware multi-cell cooperation, which adapts the network layout of cellular networks according to user traffic demands in order to reduce the number of active BSs. Then, we discuss energy aware multi-cell cooperation, which offloads traffic from on-grid BSs to off-grid BSs powered by renewable energy, and therefore reduces on-grid power consumption. In addition, we investigate how energy efficiency of cellular networks can be improved by exploiting CoMP transmissions. Finally, we discuss the characteristics of future cellular networks, and the challenges of achieving energy efficient multi-cell cooperation in future cellular networks.

## 2.1 Traffic Intensity Aware Multi-cell Cooperation

The traffic demand of cellular networks experiences fluctuations for two reasons. The first is the typical day-night behavior of users. Mobile users are usually more active in terms of cell phone usage during the day than during the night, and therefore traffic demand during the day is higher than at night. The second reason is the mobility of users. Users tend to move to their office districts during working hours and come back to their residential areas after work. This results in the need for a large capacity in both areas at peak usage hours but in reduced requirements during off-peak hours. However, cellular networks are usually dimensioned for peak hour traffic, and thus most BSs are working at low workload during off-peak hours. Owing to their high static power consumption,[1] BSs usually experience poor energy efficiency when they are operating at a low workload.

In addition, cellular networks are typically optimized for the purpose of providing coverage rather than for operating at full load. Therefore, even during peak hours, the utilization of BSs may be inefficient in terms of energy usage. Adapting the network layout of cellular networks according to traffic demands has been proposed to improve their

[1] The static power consumption of a BS refers to the power consumption of the BS when there are no active users in the coverage of the BS.

*Green Mobile Networks: A Networking Perspective*, First Edition. Nirwan Ansari and Tao Han.

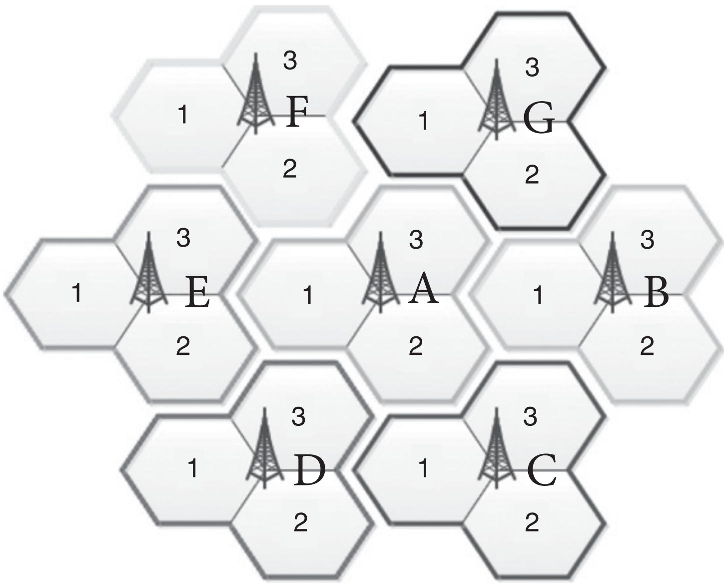


**Figure 2.1** Original Network Layout. *Source:* Han 2013 [5]. Reproduced with permission of IEEE.

energy efficiency. The network layout adaptation is achieved by switching BSs on/off dynamically. Figs. 2.1, 2.2, and 2.3 show several scenarios of network layout adaptations. Figure 2.1 shows the original network layout, in which each BS has three sectors. For cell A, if most of the traffic demands on it are coming from sector three, and the traffic demands in sectors one and two are lower than a predefined threshold, cell A

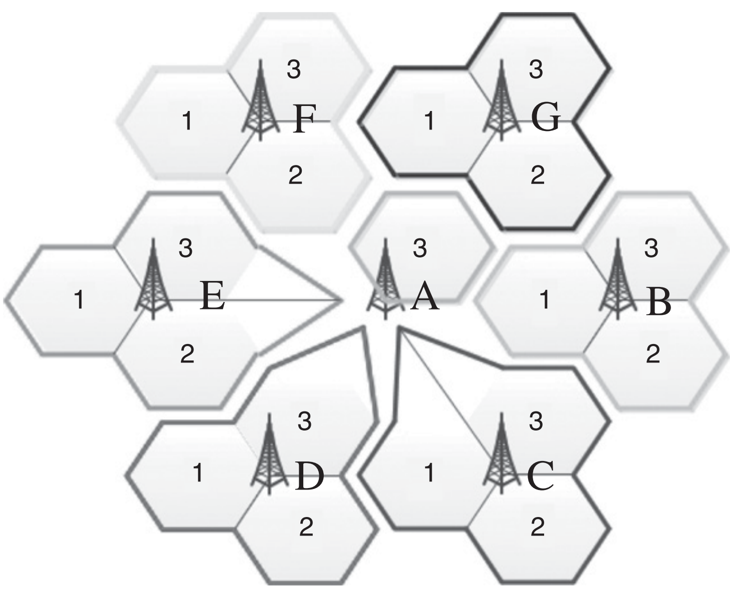


**Figure 2.2** BS partially switched off. *Source:* Han 2013 [5]. Reproduced with permission of IEEE.

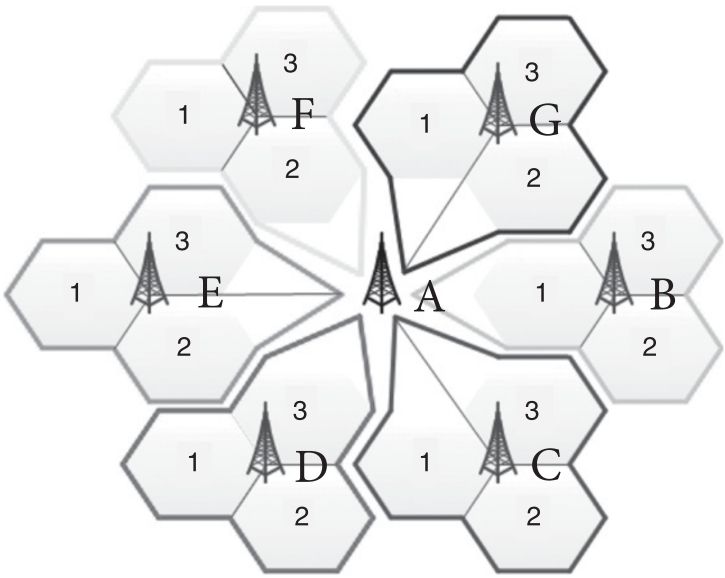


**Figure 2.3** BS entirely switched off. *Source:* Han 2013 [5]. Reproduced with permission of IEEE.

could switch off sectors one and two to save energy, and the users in the sectors that are switched off will be served by the neighboring cells. In this case, the network layout after the adaptation is shown in Figure 2.2. If traffic demands from sector three of cell A also decrease below the threshold, the entire green cell will be switched off, and the network layout is adapted to the one shown in Figure 2.3. Under this scenario, the radio coverage and service provisioning in cell A are taken care of by its active neighboring cells. When a BS is switched off, the energy consumed by its radio transceivers, processing circuits, and air conditioners can be saved. Therefore, adapting the network layout of cellular networks according to traffic demands can reduce energy consumption significantly.

While network layout adaptation can potentially reduce the energy consumption of cellular networks, it must meet two service requirements: (1) the minimum coverage requirement, and (2) the minimum quality of service (QoS) requirements for all mobile users. Therefore, in carrying out network layout adaptation, multi-cell cooperation is needed to guarantee service requirements. Otherwise, it will result in a high call blocking probability and a severe QoS degradation. For example, two adjacent BSs may both experience low traffic demands. However, only one BS can be switched off to save energy, and the other BS should be active to sustain the service provisioning in both coverage areas. In this case, if both BSs are switched off according to their own traffic demands, their subscribers will lose connections. Therefore, cooperation among BSs is essential to enable traffic intensity aware network layout adaptation.

### 2.1.1 Cooperation to Estimate Traffic Demands

Network layout adaptation is based on the estimated traffic demands at individual cells. Traffic demand estimation at individual cells requires the cooperation of neighboring cells. To avoid frequently switching BSs on/off, BSs are switched off only when their