Green Radio Communication Networks

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The importance of reducing energy costs, reducing CO_2 emissions, and protecting the environment are leading to an increased focus on green, energy-efficient approaches to the design of next-generation wireless networks. Presenting state-of-the-art research on green radio communications and networking technology by leaders in the field, this book is invaluable for researchers and professionals working in wireless communication.

Summarizing existing and ongoing research, the book explores communication architectures and models, physical communications techniques, base station power-management techniques, wireless access techniques for green radio networks, and green radio test-bed, experimental results, and standardization activities. Throughout, theoretical results are blended with practical insights and coverage of deployment issues. It serves as a one-stop reference for key concepts and design techniques for energy-efficient communications and networking, and provides information essential for the design of future-generation cellular wireless systems.

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CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town,
Singapore, São Paulo, Delhi, Mexico City

Cambridge University Press
The Edinburgh Building, Cambridge CB2 8RU, UK

Published in the United States of America by Cambridge University Press, New York

www.cambridge.org
Information on this title: www.cambridge.org/9781107017542

First published 2012

Printed in the United Kingdom at the University Press, Cambridge

A catalogue record for this publication is available from the British Library

Library of Congress Cataloguing in Publication data
Hossain, Ekram, 1971–
Green radio communication networks / Ekram Hossain, Vijay K. Bhargava, Gerhard P. Fettweis.
p. cm.
Includes bibliographical references and index.
ISBN 978-1-107-01754-2 (hardback)
1. Wireless communication systems – Environmental aspects. 2. Wireless communication systems – Energy consumption. I. Bhargava, Vijay K., 1948– II. Fettweis, Gerhard P. III. Title.
TK5103.2.H675 2012
621.384028′6–dc23 2012009106

ISBN 978-1-107-01754-2 Hardback

For
our families

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Preface

A brief journey through "Green Radio Communication Networks"

Currently, the information and communications technology (ICT) industry sector accounts for about 2–6% of the energy consumption worldwide, and a significant portion of this is contributed by the wireless and mobile communications industry. With the proliferation of wireless data applications, wireless technology continues to increase worldwide at an unprecedented growth rate. This has resulted in an increased number of installed base stations and higher demand on power grids and device power usage, causing an increased carbon footprint worldwide. Current wireless industry therefore needs to embrace eco-friendly green communication technologies at different levels – from components, circuits, and devices to protocols, systems, and networks. Since the rate of improvement in power efficiency of hardware devices lags data traffic growth in both the radio access and core networks, network scaling will be increasingly tied to energy consumption in future wireless protocols, systems, and networks. Hence, it is crucial to develop green technologies for wireless systems and networks to improve energy efficiency and reduce CO_2 emissions. Again, from the perspective of network operators, energy is a significant portion of their OPEX (Operational Expenses). Therefore, green radio technologies will help to reduce the operating costs of wireless networks.

Green ICT has become a critical agenda item around the world. In this context, many organizations and standard bodies throughout the world including the European Commission (EC), US Environmental Protection Agency, US Department of Energy, ISO, IEC, ITU-T, ETSI, ATIS, and the IEEE are working towards the vision of green communication networks. In particular, the EC is developing a comprehensive code of conduct on the energy consumption of broadband equipment. The IEEE is developing energy-efficient protocols for Ethernet (i.e. IEEE P802.3az protocol). There are many ongoing projects on green communication networks. For example, EU FP7 projects EARTH (Energy-Aware Radio and Network Technologies) and C2POWER (Cognitive Radio and Cooperative Strategies for Power Saving) focus on developing energy-efficient mobile communications systems. The Mobile VCE Green Radio project aims at developing new green radio architectures and radio techniques to reduce the overall energy consumption. GreenTouch, which is a consortium of ICT industry, academia, and non-governmental research experts, has an ambitious goal of improving the energy efficiency of the ICT industry by three orders of magnitude by 2015 compared to that in 2010. Japan's Green-IT project aims to develop energy consumption metrics and energy efficiency standards for networking equipments. Some mobile network operators have already set targets to reduce their carbon emissions significantly within the next ten years.

This book provides a comprehensive treatment of the state of the art of existing and on-going research on energy efficient wireless/mobile communications and networking techniques with an emphasis on cellular wireless networks. It consists of articles covering different aspects of green cellular radio communications and networking issues that include the following: architecture issues and performance models for green radio networks including energy-harvesting wireless networks; physical communication techniques for green radio, including novel modulation and coding techniques and joint physical (PHY) and medium access control (MAC) optimized techniques; dynamic power-management/energy-conservation techniques for base stations in cellular wireless networks; relaying and user cooperation techniques and energy-cognizant wireless protocols (e.g. for scheduling, dynamic power management) for green radio communications; standardization initiatives, test-beds, prototypes, practical systems and case studies.

This book contains 17 chapters which are organized into 5 parts. A brief account of each chapter in each of these parts is given below.

Part I: Communication architectures and models for green radio networks

From the perspective of green wireless networks, it is necessary to develop a clear understanding of energy consumption in current networks and the network elements, base sites, and mobiles, and to determine the best backhaul strategy for a given architecture. Different trade-offs involved in the design of green cellular systems need to be understood considering practical system aspects. It is important to determine what is the optimum deployment scenario for a wide-area network given a clearly defined energy-efficiency metric. An emerging paradigm for green wireless networks is the concept of energy harvesting. Analysis and modeling of green wireless networks based on energy harvesting is therefore becoming increasingly important.

In *Chapter 1*, Chen, Zhang, and Xu focus on a fundamental framework for green radio research and propose four fundamental trade-offs to construct this framework. These trade-offs are: (i) spectrum efficiency–energy efficiency (SE–EE) trade-off, (ii) bandwidth–power (BW–PW) trade-off, (iii) delay–power (DL–PW) trade-off, and (iv) deployment efficiency–energy efficiency (DE–EE) trade-off. The authors illustrate these trade-offs for point-to-point communications predicted by the Shannons capacity formula, which gives a set of monotonically decreasing curves for each of the fundamental trade-offs. In practical systems, network deployment and operation cost as well as the non-linear efficiency of the power amplifier and the processing power and circuit power need to be considered. With considerations of these issues, the trade-off relations usually deviate from the simple monotonic curves derived from Shannon's formula, which bring a new design philosophy for green radio networks. The authors review the current state of the investigation on these trade-offs and also outline a number of open research issues.

In *Chapter 2*, Sharma, Mukherji, and Joseph focus on modeling and analysis of an energy-harvesting green wireless network. First, the authors consider a point-to-point channel in an energy-harvesting communication system. The harvested energy is stored in a battery (energy queue) and the data to be transmitted is stored in a data buffer. The necessary condition for the stability of the data queue is obtained and a throughput optimal transmission policy is proposed when the energy is spent only in transmission. Also, a delay-optimal transmission policy is proposed that minimizes the average delay. Next, a more realistic case is considered with channel fading when the energy is also spent in processing and other activities and there may be leakage in the battery storing the energy. Also, the transmission policies are modeled considering the sleep and wake-up mode of an energy-harvesting node. Subsequently, the Shannon capacity of a point-to-point additive white Gaussian channel (AWGN) is obtained for an energy-harvesting transmitter. Second, the authors develop the transmission policies for a multiple access scenario. Third, the authors model and analyze the problem of jointly optimizing power control, routing, and scheduling policies for a multi-hop network with energy-harvesting nodes.

In *Chapter 3*, Mehta and Murthy study the implications of energy harvesting on the design and optimization of the physical (PHY) and medium access control (MAC) layers. In particular, the authors focus on the transmission power control at the physical layer for a single-hop communication scenario, and the interactions among multiple energy-harvesting relay nodes in a two-hop communications scenario. The primary design focus of PHY and MAC layers is to judiciously utilize all the harvested energy and ensure that energy is available for consumption when required. Other design objectives are energy-conservation and spectral-efficiency maximization. The authors investigate the effects of several important factors such as the energy-harvesting profile, availability or unavailability of channel state information, and energy-storage capability on the design of both single-hop, and relay-based two-hop cooperative communications.

In *Chapter 4*, Kolios, Friderikos, and Papadaki describe the concept of mechanical relaying and outline its benefits in cellular wireless networks. In mechanical relaying (MR) mobile terminals are entitled to store and carry the information messages while in transit and forward the data to the base station only when at favorable locations within the cell coverage area. Due to this store-carry-and-forward operation, significant gains in energy consumption can be attained by utilizing the elasticity of a plethora of different Internet applications (such as adaptive progressive video download, file transfers, software/firmware updates over the air (OTA), and RSS feeds). While intrinsically a delay-tolerant networking scheme, mechanical relaying can in fact boost the cellular system performance at no expense to the perceived user experience. The authors outline the deployment challenges of mechanical relaying in current and emerging mobile networks, open-ended research problems, and future avenues of research in this area.

Part II: Physical communications techniques for green radio networks

Future green radio networks will need to support multimedia data services at two or three orders of magnitude lower transmission power than currently used. This will of course require energy-efficient transmission and modulation techniques. More importantly, a holistic and system-wide design of the system that exploits the cross-layer interactions will be required.

In *Chapter 5*, Abouei, Plataniotis, and Pasupathy study the energy efficiency of some popular modulation schemes for energy-constrained wireless networks in fading channels. The authors demonstrate that the non-coherent M-ary frequency-shift keying (NC-MFSK) provides superior energy-efficiency performance in short-range wireless networks when compared with other sinusoidal carrier-based modulations such as M-ary quadrature amplitude modulation (MQAM), differential offset quadrature phase-shift keying (OQPSK), and coherent MFSK. Also, the authors analyze the energy efficiency of Luby transform (LT)-coded MFSK modulation when compared to classical BCH and convolutional-coded modulation as well as uncoded modulation. The LT-coded MFSK scheme provides higher energy efficiency over other uncoded and coded schemes due to the flexibility to adjust its rate according to the channel condition. The authors conclude that LT-coded MFSK modulation is a candidate green modulation and coding scheme for energy-constrained wireless networks.

In *Chapter 6*, Amin, Bavarian, and Lampe focus on the cooperative communications techniques for energy efficiency in cellular wireless networks. The authors first introduce the instantaneous and average energy-efficiency metrics that consider both the transmission energy and the transceiver system (consisting of analog and digital circuits) energy along with the data rate of transmission. The average energy efficiency of a single-relay cooperative communication system is evaluated considering selective decode-and-forward, incremental decode-and-forward, amplify-and-forward, and incremental amplify-and-forward-based relaying strategies. The authors also demonstrate how the gain in energy saving in a single-relay network can be improved through optimizing the modulation constellation size and the power allocation at the source and the relay under an average error rate constraint. For a multi-relay system, the authors also investigate the effect of relay selection and also the number of hops (in a multi-hop cooperative network) on the energy-efficiency performance. To this end, the authors discuss the base station cooperation technique, namely, the coordinated multipoint (CoMP) technique to improve the system-wide energy efficiency in cellular wireless systems.

In *Chapter 7*, Abuzainab and Ephremides focus on the energy efficiency of different physical and network layer cooperative techniques for two wireless transmission models in fading channels. The first model considers that a relay is used to assist the source node to deliver its data to the destination node. The second model considers multicast transmissions from the source node to two destination nodes and in this case user cooperation is utilized. That is, the destination node that first receives the data successfully can assist the source in transmitting the data to the other destination. Alamouti coding is used in the physical layer, while random network coding is used in the network layer. For both the transmission models, the energy cost is defined as the expected energy spent per successfully delivered packet. Simulation results show that with proper selection of the coding parameter, random network coding-based cooperative transmission technique achieves better performance than automatic-repeat request (ARQ)-based cooperative technique even when it is enhanced with Alamouti coding. Also, further improvements in the performance are achieved when random network coding is used combined with Alamouti coding. The results also show that the performance of user cooperation depends on the channel quality between the different nodes in the network.

Part III: Base station power-management techniques for green radio networks

For green radio communication networks, it is essential to develop techniques to achieve significant improvements in the overall efficiency for base stations, which is measured as radio frequency (RF) power out to total input power, and techniques that will reduce the required RF output power required from the base station while still maintaining the required quality-of-service (QoS). When a base station's energy supply is derived from renewable energy sources in a smart power grid, it is important to determine how this would be best used for communications. It will be necessary to develop sleep mechanisms that deliver substantial reductions in power consumption for base stations with no loads and techniques that allow power consumption to scale with load. Also, multi-cell processing techniques based on the cooperation among base stations can reduce the energy consumption at the base stations.

In *Chapter 8*, Holland et al. investigate the concepts of opportunistic spectrum and load management across multiple frequency bands (owned by an operator or a group of operators) to reduce the power consumption of base stations while satisfying the QoS requirements in the network. In particular, the authors focus on concepts such as powering down radio network equipments (i.e. base stations) using particular frequency bands by reallocating traffic loads to other bands at times of low load, and opportunistic spectrum usage to exploit the propagation characteristics of spectrum bands and reduce necessary transmission power. Using simulations of GSM, HSDPA, and LTE networks, the authors demonstrate the power savings achievable through these concepts. However, there is a tradeoff between the power saving and network capacity improvement.

In *Chapter 9*, Lu, Niyato, and Wang consider the problem of power management for base stations with renewable power sources in a smart grid environment. With the demand-response (DR) and demand-side management (DSM) features in smart grids, base stations powered by the smart grids can reduce the cost of power consumption by using an adaptive power-management method. The authors provide an overview of the existing approaches of power management for wireless base stations, which include base station power control through beamforming, base station assignment based on the dynamic connectivity patterns between mobile units and base stations, smart mode switching, and cooperative relaying. The authors propose an adaptive power-management method, which dynamically controls the power consumption from the electrical grid and from renewable power sources given the varied price and the amount of renewable power generation. A stochastic optimization problem is formulated and solved to obtain the best decision on power consumption in an uncertain environment, so that the power cost for the base stations can be minimized while satisfying the traffic demand in the network.

In *Chapter 10*, Chen et al. propose an energy-saving technique for the base stations in 3rd Generation Partnership Project (3GPP) Long-Term Evolution (LTE) systems where femtocells are overlaid with macrocells. The authors also provide an overview of the different energy-saving techniques, divided into time, space, and frequency domains, for the LTE base stations. The main idea here is to off-load the downlink traffic of macrocells to femtocells. Simulation results for a scenario with one base station (i.e. eNodeB) and multiple femtocells (i.e. HeNodeBs) show that, with the proposed method, the total RF power in the system can be reduced when the number of HeNodeBs is relatively small.

In *Chapter 11*, Nakhai et al. develop cluster-based multicell processing strategies to improve energy efficiency in cellular wireless communications. In two of the proposed strategies, user signals are globally shared by the coordinating base stations, using both instantaneous and second-order statistics of channel state information. The third one is an iterative solution using statistical channel state information. These three schemes are referred to as the multicell beamforming (MBF) strategies where the base stations share users' data via backhaul links and possess full global channel state information. The objective of the MBF strategies is to find a set of beamforming vectors for a number of simultaneously active users such that the overall transmit power in a virtual cell (i.e. a cluster of three base stations) is minimized, while a prescribed signal-to-interference-plus-noise ratio (SINR) target is maintained for each user. The last one is a coordinated beamforming (CBF) strategy based on a standard semidefinite programming formulation, where user signals are not shared among the coordinating base stations. In this case, the user terminals are served by their local base stations only and a number of base stations coordinate at the beamforming level to minimize their mutual intercell interferences. With CBF, the backhaul overhead is lighter when compared to MBF. The performance evaluation results show that MBF is more power efficient than CBF even when the backhaul signaling is considered.

Part IV: Wireless access techniques for green radio networks

In addition to using the power-saving protocols at the base stations, energy-efficient radio resource (e.g. transmission power, time-slot, frequency band) management and channel access techniques will need to be used to reduce the power consumption in green wireless networks. In this context, cross-layer design and optimization of wireless access techniques would be crucial to improve the energy efficiency at the system level.

In *Chapter 12*, Karmokar, Anpalagan, and Hossain present a cross-layer (physical and MAC) optimization technique for energy-efficient packet scheduling in wireless networks while maintaining the QoS metrics, such as bit error rate, packet delay, and loss rate within the required limit. The cross-layer technique considers the channel gains as well as the buffer occupancy and the traffic characteristics. The authors first consider the case when the channel is fully observable, and then they discuss the cases when it is either partially observable or delayed, as often occurs in real networks. Results are presented to show the advantage of cross-layer optimization to conserve energy in wireless data communication networks.

In *Chapter 13*, Wei, Song, and Yu focus on the energy-saving performance of cellular wireless networks with cooperative relaying among the users. The objective is to minimize energy consumption while satisfying certain QoS performance criteria for the users. The authors present an energy-efficient distributed relaying method based on the selection of a single relay. The relay selection problem is modeled as a stochastic restless multi-armed bandit problem and the solution is obtained by linear programming relaxation and primal-dual index heuristic algorithm. The problem formulation considers finite-state Markov channels, adaptive modulation and coding, and residual energy at the wireless nodes. The method can be implemented based on an RTS/CTS-based handshaking mechanism. Performance of the proposed method is compared with a memoryless relay selection method and a random relay selection method in terms of system reward, which is calculated as a function of the bit error rate of source-to-relay link, spectral efficiency of relay-to-destination link, energy consumption of delivering the data packets from source to destination, as well as residual energy.

In *Chapter 14*, Phuyal, Jha, and Bhargava focus on the energy-efficient resource allocation strategies in a cellular system using a relay-based dual-hop transmission approach. The benefits and implementation challenges of this approach are discussed. For downlink transmission under this approach, the authors propose a green power allocation (GPA) scheme between the base station and the relay station (where the total transmit power is constrained), which minimizes the required transmit power per unit achievable throughput (i.e. [J/bit]) and at the same time it guarantees a minimum end-to-end data rate required by a user. Performance of this scheme is compared with three other power allocation schemes, namely, throughput maximization power allocation (TMPA) scheme, uniform power allocation (UPA) scheme, and GPA with no QoS provisioning (GPANQ) scheme. It is observed that the minimization of J/bit generally degrades the achievable capacity of the network. To this end, the authors extend the optimization model for GPA to a multi-objective optimization model where the objective function accounts for both power consumption and network capacity.

In *Chapter 15*, Long, Li, and Chong investigate four different time slot allocation schemes for energy-efficient communication in cellular single-hop and two-hop TDD-CDMA systems. These are fixed time slot allocation (FTSA) and dynamic time slot allocation (DTSA) schemes for single-hop systems, and multi-link fixed time slot allocation (ML-FTSA) and multi-link dynamic time slot allocation (ML-DTSA) for two-hop relay-based cellular systems. The authors consider four cases of relay station architectures: one fixed and three random relay station structures. With fixed relay station (FRS) structures, the locations of the RSs are determined in advance based on a certain algorithm, while with random relay station structures (RRS) the RSs can be randomly placed around the BS. The total energy consumption is considered to be the summation of transmission energy and hardware energy. Simulation results show that with two-hop transmission in the optimal FRS structure, the blocking and dropping probabilities as well as the total energy consumption can be decreased significantly.

Part V: Green radio test-bed, experimental results, and standardization activities

The research on green communication technologies has started to take shape within and between industry and academia. Internationally there are many ongoing green projects that aim to reduce the carbon footprint through energy savings.

In *Chapter 16*, Auer et al. focus on the assessment of the overall energy efficiency of a 3GPP LTE network over an average European country based on the EARTH E^3F framework. For this assessment the authors consider realistic power consumption at the base stations and traffic models in 3GPP networks. Two energy-consumption metrics are considered: power per unit area, measured in [W/m^2], and energy per bit, measured in [J/bit]. Based on the simulation results, the authors conclude that there is a huge potential for energy savings at the base stations when the network is not fully loaded.

In *Chapter 17*, Conte, Helmers, and Sehier describe the energy efficiency-related activities conducted in important standardization bodies and fora, as well as by the relevant industrial and academic joint projects and consortiums. In particular, the authors focus on the activities conducted by ETSI (European Telecommunication Standard Institute) and its partners, 3GPP (Third Generation Partnership Project), IETF (Internet Engineering Task Force), and the China Communication Standard Association (CCSA). In order to assist and influence these standardization fora, several other groups/projects/consortiums have been created, including the NGMN (Next Generation Mobile Networks) alliance, the GreenTouch consortium, and the EARTH (Energy-Aware Radio and neTwork tecHnologies) project within the European Commission (EC) 7th Framework Programme for Research and Technological Development (FP7). The EARTH project proposes technical solutions to improve the power efficiency of wireless mobile networks at component level, link level, and network level. It proposes a tool called the energy-efficiency evaluation framework (E^3F) to analyze the energy efficiency of network solutions. GreenTouch is a non-profit research consortium founded by experts from industry, academia, government, and research institutions around the world which aims to define new, clean-slate technologies that will be at the heart of sustainable communication networks.

Part I

Communication architectures and models for green radio networks

1 Fundamental trade-offs on the design of green radio networks

Yan Chen, Shunqing Zhang, and Shugong Xu

1.1 Introduction

There is currently a global concern about the rise in the emission of pollutants and energy consumption. The carbon dioxide (CO_2) footprint of the information and communications technologies (ICT) industry, as pointed out by [1], is 25% of the 2007 carbon footprint for cars worldwide, which is similar to that of the whole aviation industry. Within the ICT industry, the mobile network is recognized as being among the biggest energy users. The exponentially growing data traffic in mobile networks has made the issue an even grander challenge in the future. In a data forecast report provided by Cisco [2], it has been pointed out that the global mobile data traffic will increase 26-fold between 2010 and 2015. In particular, unexpectedly strong growth in 2010 has been observed mainly due to the accelerated adoption of smartphones. For instance, China Unicom's 3G traffic increased 62% in a single quarter from Q1 to Q2 of 2010, while AT&T reported a 30-fold traffic growth from Q3 2009 to Q3 2010. The unprecedented expansion of wireless networks will result in a tremendous increase in energy consumption, which will further leave a significant environmental footprint. Therefore, it is now a practical issue and demanding challenge for mobile operators to maintain sustainable capacity growth and, at the same time, to limit the electricity bill. For instance, Vodafone Group has announced the goal of reducing its CO_2 emissions by 50% against its 2007 baseline of 1.23 million tonnes, by the year of 2020 [3]. Figure 1.1 gives examples of the green demand from mobile operators worldwide.

As has been pointed out in [4], the radio access part of the wireless network accounts for up to more than 70% of the total energy bill for a number of mobile operators. Therefore, developing energy-efficient wireless architectures and technologies is crucial to meet this challenge. Research actions have been taken worldwide. It is now an important trend for the wireless designers to take energy consumption and energy efficiency into their design frameworks. Vodafone, for example, has predicted that energy-efficiency improvement will be one of the most important areas that demand innovation for wireless standards beyond LTE [5].

Green radio research is a large and comprehensive area that covers all layers in the design of efficient wireless access networks. There have been efforts devoted to traditional energy-saving ways, such as designing ultra-efficient power amplifiers, reducing feeder losses, and introducing passive cooling. However, these efforts are isolated and thus cannot make a global vision of what we can achieve in five or ten years for energy

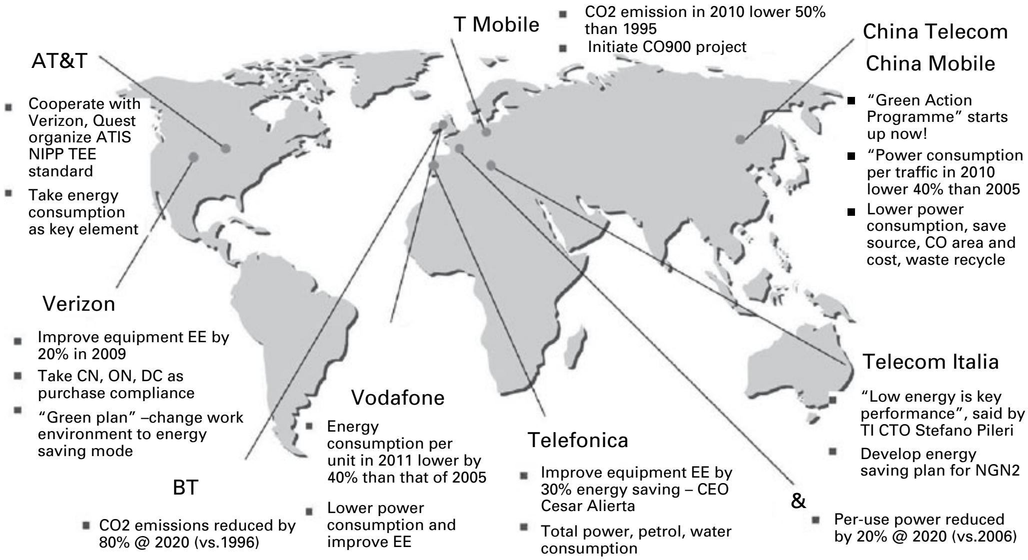

Figure 1.1 Global operators' demand on green communications.

saving as a whole. Innovative solutions based on top-down architecture and joint design across all system levels and protocol stacks are needed, which cannot be achieved via isolated efforts.

Green research projects with holistic approaches and joint efforts from the industry and the academia have sprung up all over the world during recent years. For instance, the EARTH (Energy Aware Radio and neTwork tecHnologies) project [6]–[7] under the European Framework Program 7, started to develop green technologies at the beginning of 2010. In the UK, *GreenRadio* [8] is one of the Core 5 Programs in Mobile VCE that has been set up since 2009. Most recently, the *GreenTouch* Consortium sets its 5-year research goal to deliver the architecture, specification, and roadmap needed to reduce the end-to-end energy-consumption per bit by a factor of 1000 from the current level by the year 2020. In addition, there are also active discussions in standardization organizations, such as ETSI, ATIS, and 3GPP, on energy-efficiency metrics and measurement, as well as studies for base station level or network level savings.

Instead of a survey that reaches every aspect of the matter, or a report elaborating one specific green research point, this chapter focuses on the fundamental framework for green radio research and strings together the currently scattered research points using a logical "rope." In this chapter we propose four fundamental trade-offs to construct such a framework. These were first introduced in [9]. As depicted in Figure 1.2, they are

- *Spectrum efficiency–energy efficiency (SE–EE) trade-off*: given the bandwidth available, to balance the achievable rate and the energy cost;
- *Bandwidth–power (BW–PW) trade-off*: given the target transmission rate, to balance the bandwidth utilized and the power needed;

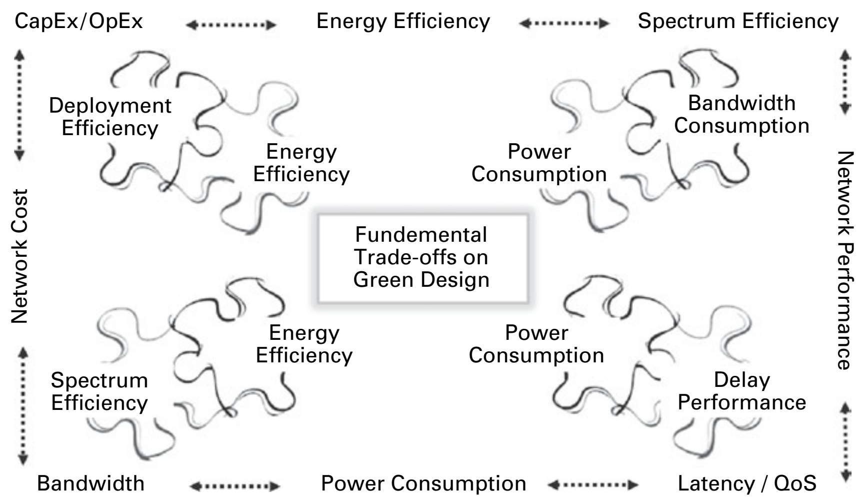

Figure 1.2 Four fundamental trade-offs form the core of green research.

- *Delay–power (DL–PW) trade-off*: to balance the average end-to-end service delay and the average power consumed in the transmission;
- *Deployment efficiency–energy efficiency (DE–EE) trade-off*: given the network traffic requirement, to balance the deployment cost, throughput, and energy consumption, in the network as a whole.

By means of the four trade-offs, key network performance/cost indicators are all strung together. In the rest of the chapter, we will elaborate in detail the definitions, justifications, practical concerns, as well as research directions for each of the trade-off studies. In particular, we shall show that in practical systems, the trade-off relations usually deviate from the simple monotonic curves derived from Shannon's formula, which brings a new design philosophy.

1.2 Insight from Shannon's capacity formula

Shannon's capacity formula [10] establishes a bridge between the maximum achievable transmission rate R and the received power $P^{(r)}$ for the point-to-point additive white Gaussian noise (AWGN) channel, i.e.

$$R = W \log_2 \left(1 + \frac{P^{(r)}}{W N_0} \right), \tag{1.1}$$

where N_0 is the noise power density at the receiver and W is the system bandwidth. Though Shannon's ground-breaking formula has been known for more than half a century, people mainly look at it from the channel capacity point of view. However, as we will show later in this section, the formula actually gives us a fundamental insight into the energy-related trade-offs in the wireless point-to-point link transmission. In this section, we shall formally introduce the definitions of the trade-offs and sketch their behavior predicted by Shannon's capacity formula.

The following are the equivalent transformations of the above formula, which will be used in the characterization of the different trade-offs.

$$\frac{R}{W} = \log_2\left(1 + \frac{R}{W}\frac{E_b^{(r)}}{N_0}\right). \tag{1.2}$$

$$\frac{1}{T_b} = W\log_2\left(1 + \frac{1}{T_b}\frac{E_b^{(r)}}{WN_0}\right). \tag{1.3}$$

In the equations above, $E_b^{(r)}$ stands for the average energy per bit and T_b denotes the average transmission time per bit. They are introduced through the relations $E_b^{(r)} = P^{(r)}/R$ and $T_b = 1/R$. Further, considering a constant attenuation on the transmitted signal, denoted as a simple function of the transmit power $P^{(t)}$, namely $f(P^{(t)}) = \kappa_0 P^{(t)}/d^{\alpha}$, where κ_0 and α are the attenuation coefficient and exponent, respectively, we have

$$\frac{R}{W} = \log_2\left(1 + \frac{R}{W}\frac{E_b^{(t)}}{N_0}\frac{\kappa_0}{d^{\alpha}}\right). \tag{1.4}$$

1.2.1 SE–EE trade-off

Spectrum efficiency (SE), defined as the system throughput for unit bandwidth, i.e. bits/sec/Hz, is a widely accepted criterion for wireless network optimization. The peak value of SE is always among the key performance indicators of standardization evolution such as 3GPP. For instance, the target downlink SE of 3GPP increases from 0.05 bps/Hz to 5 bps/Hz as the system evolves from GSM to LTE. On the contrary, energy efficiency (EE), defined as the data rate achievable per unit of transmitted power, i.e. bits/sec/Watt, namely bits/Joule, was previously ignored by most of the research efforts and has not been considered by 3GPP as an important performance indicator until very recently.

Shannon's groundbreaking work on reliable communication over noisy channels showed that there is a fundamental trade-off between SE and received/transmitted EE. Informally speaking, a lower transmission rate leads to a lower transmitted power, for the same system bandwidth. Given the definitions above, SE can be expressed as $\eta_{SE} = R/W$ and the received EE as $\eta_{EE}^{(r)} = 1/E_b^{(r)}$. From (1.2), the SE–EE trade-off can be characterized by

$$\eta_{EE}^{(r)} = \frac{\eta_{SE}}{(2^{\eta_{SE}} - 1)N_0}, \tag{1.5}$$

which is depicted on the left-hand side (LHS) of Figure 1.3, where $N_0 = -174$ dBm. Seen from both the mathematical relation and the figure, η_{EE} converges to a constant, $1/(N_0 \ln 2)$, when η_{SE} approaches zero. On the contrary, η_{EE} approaches zero when η_{SE} tends to infinity. Similarly, considering the relation in (1.4), the transmit EE-SE trade-off

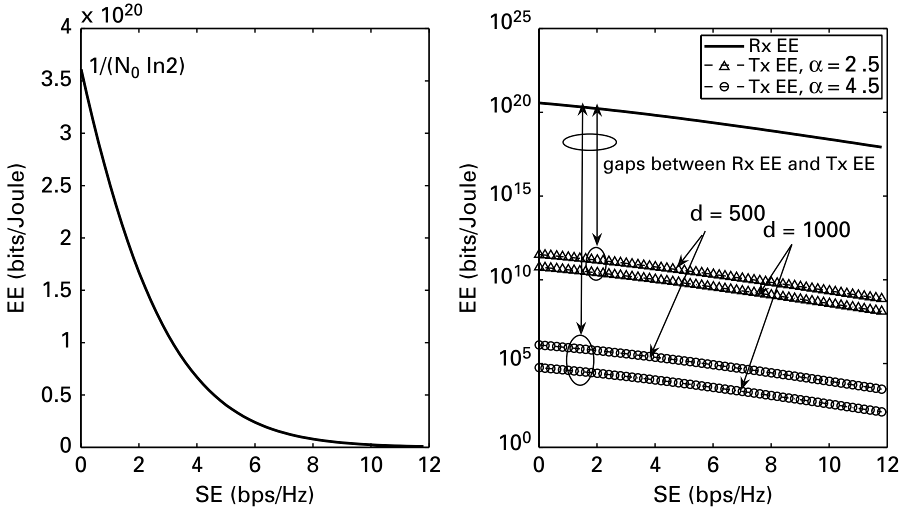

Figure 1.3 Illustration of the SE–EE trade-off. On the LHS, the figure shows the trade-off relation between SE and received EE from Shannon formula, while on the RHS, the figure depicts the transmit EE as function of the path-loss exponent α at different distance d.

can be expressed as

$$\eta_{EE}^{t} = \frac{\eta_{SE}}{(2^{\eta_{SE}} - 1)N_0} \cdot \frac{\kappa_0}{d^{\alpha}}, \tag{1.6}$$

as shown on the right-hand side (RHS) of Figure 1.3. The gaps between the received EE and the transmit EE depend heavily on the transmission channel degradation, i.e. the path-loss exponent α and the transmission distance d.

1.2.2 BW–PW trade-off

Bandwidth (BW) and power (PW) are both fundamental but limited resources in wireless communications. From the Shannon's capacity formula in (1.1) and (1.4), the relation between the transmit power, P^t, and the transmission bandwidth, W, for a given transmission rate, R, can be expressed as

$$P^t = W N_0 (2^{\frac{R}{W}} - 1) \cdot \frac{\kappa_0}{d^{\alpha}}. \tag{1.7}$$

The expression above exhibits a monotonic relation between PW and BW, as sketched in the LHS of Figure 1.4. The fundamental BW–PW trade-off shows that, to transmit at a given data rate, the expansion of the transmission bandwidth is preferred in order to reduce transmit power and thus achieve better energy efficiency. From (1.7), in the extreme case, the minimum power consumption is as small as $N_0 R \ln 2$ if there is no bandwidth limit.

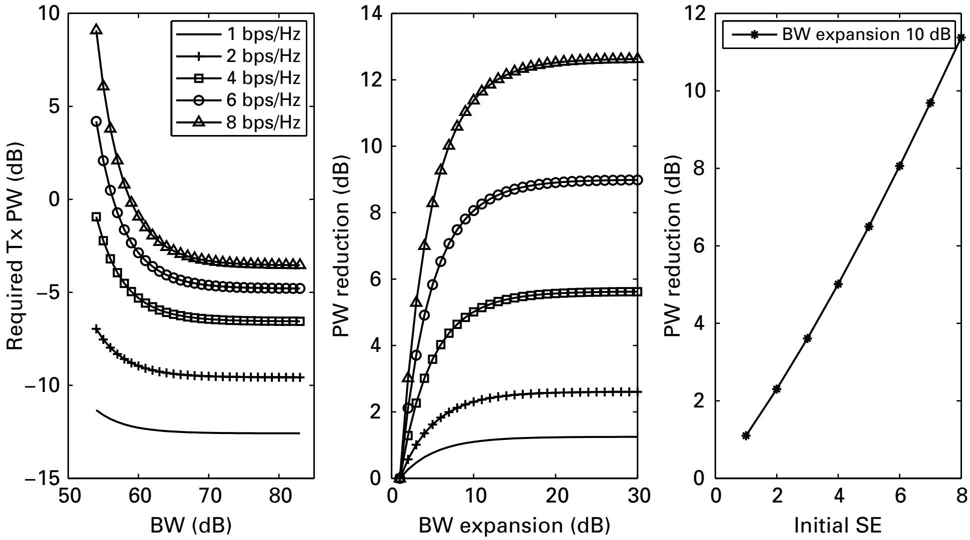

Figure 1.4 Illustration of the BW–PW trade-off derived from Shannon formula. The difference between the set of curves is the initial SE values before any BW expansion. The left figure gives the absolute value of the required transmit power while the middle one shows the PW reduction gain. The right figure depicts the PW reduction gain at 10 dB BW expansion at different initial SE values. $\kappa_0/d^\alpha = -140$ dB.

Figure 1.4 depicts the BW–PW trade-off from three different angles. Firstly, the left-most figure shows the relation between the required transmit power and the system bandwidth, the trend of which behaves exactly as equation (1.7) predicts. The middle figure shows the PW reduction as function of the BW expansion. From (1.4), the reduction in the transmit power is the same as that in the received power. It can be observed from the figure that increasing the BW by ten (10 dB) brings considerable gain in PW reduction, no matter what the initial SE of the system is. Larger than 10 dB BW expansion, however, only adds marginal gain. Moreover, the higher the initial SE, the larger the PW reduction gain. It can be found from the right-most figure that expanding the BW 10 times brings less than 3 dB PW reduction gain to a system with the initial SE at 2 bps/Hz, but offers a larger than 10 dB gain to the system with the initial SE larger than 8 bps/Hz.

1.2.3 DL–PW trade-off

The metrics such as EE, SE, and BW, as described in the two trade-offs above, are important system performance criteria but cannot be directly observed by end users. Delay (DL) is different to these metrics and is usually taken as a measure of quality of service (QoS) and user experience. According to the scope of the definition, there are different types of delay. Two major ones are the physical (PHY) delay, defined as the time spent during the physical layer transmission, and the medium-access-control (MAC) delay, defined as the sum of both waiting time in the MAC layer data queue and transmission time in the PHY layer.

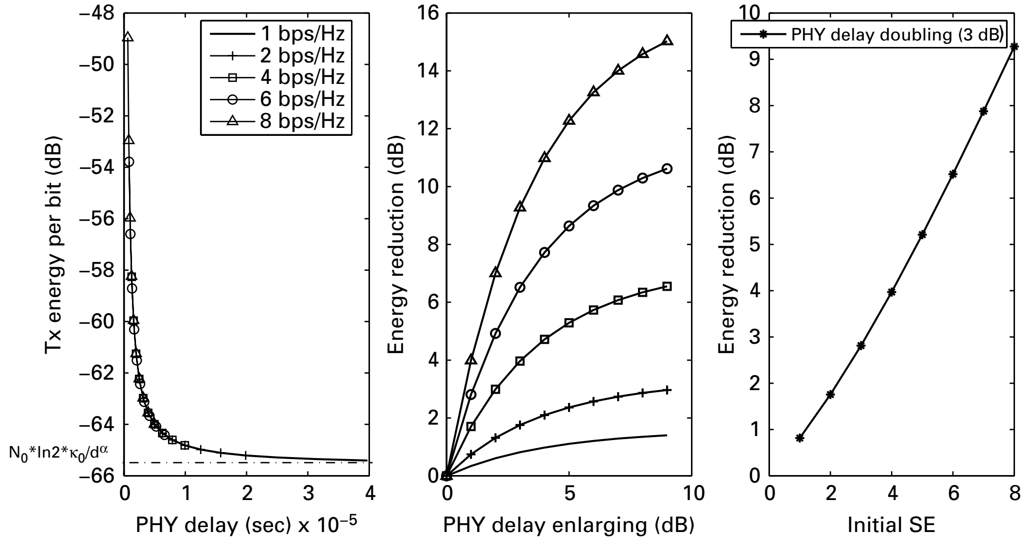

Figure 1.5 Illustration of the PHY DL–PW trade-off derived from Shannon's formula. The middle figure shows the gain of energy reduction as a function of the PHY delay increasing. The right figure shows the energy reduction gain provided by doubling the PHY delay at different initial SE values. $\kappa_0/d^{\alpha} = -140$ dB and $W = 200$ kHz.

Let us start with the simpler one, the PHY delay, for which the Shannon's capacity formula reveals most of the characteristics. For point-to-point transmission over AWGN channels, formulas (1.3) and (1.4) tell us the average energy per bit required to transmit a data bit in time T_b can be calculated as

$$E_b^t = N_0 T_b W \left(2^{\frac{1}{T_b W}} - 1 \right) \cdot \frac{\kappa_0}{d^{\alpha}}. \tag{1.8}$$

The above expression shows a monotonically decreasing relation between received energy per bit and PHY delay, as sketched on the left of Figure 1.5. The middle figure of Figure 1.5 shows that the higher the initial SE, the more energy reduction gain can be obtained from enlarging the PHY delay. For instance, doubling the PHY delay reduces the average transmit energy per bit by less than 2 dB for the initial SE of 2 bps/Hz but more than 6 dB for that of 6 bps/Hz. This is true for single symbol transmission or continuous symbol transmission (full buffer). However, the relation may change when we consider bursty data blocks, as will be shown later in Section 1.3.

The MAC delay, on the other hand, is closely related to the upper layer traffic arrivals and statistics. By Little's law [11], the average delay has a direct relation with the average queue length in the data queue. As a result, the design of transmission schemes shall cope with both channel uncertainties, traffic variations, and queue dynamics, which makes the characterization of DL–PW trade-off more complicated. Shannon theory alone is not enough to characterize the DL–PW in these scenarios. Other theoretical analysis tools are needed, such as queueing theory [11] and control theory [12]. Moreover, as technologies evolve, the types of future wireless services become diverse enough to have heterogeneous delay requirements. Therefore, in order to build a green radio, it is important to know when and how to trade tolerable delay for low power.

1.2.4 DE–EE trade-off

Deployment efficiency (DE), a measure of network throughput per unit of deployment cost, namely bits/$ or Mbits/$, is an important network performance indicator for mobile operators. The deployment cost consists of both capital expenditure (CapEx) and operational expenditure (OpEx). For radio access networks, the CapEx mainly includes infrastructure costs, such as base station equipment, backhaul transmission equipment, site installation, etc., while the key drivers for the OpEx are electricity bill, site and backhaul lease, and operation and maintenance costs. The scope of the EE definition in the previous trade-offs can either be for a single base station or for a network; the EE concept involved in the DE–EE trade-off is a metric for the whole network, namely a measure of network throughput per unit of network energy consumption, i.e. bits/Joule.

The two different metrics often lead to opposite design criteria for network planning. For example, to save the expenditure on site rental, base station equipment, and maintenance, network planning engineers tend to "stretch" the cell coverage as much as possible. However, the path loss between the base station and mobile users will degrade by 12 dB whenever the cell radius doubles if the path-loss exponent is four, which induces a 12 dB increase in the transmit power to guarantee the same signal strength for those users at the cell edges. Some simple calculations give the result that to provide cellular coverage for a given area, increasing the number of base stations will save the total network transmit power by the same factor.

Table 1.1 helps to understand the inner logic. Assume the reference cell radius is d_0, β and γ are two coefficients associated with the cell size shrinking scenario where $0 \leq \beta, \gamma \leq 1$, inter-cell interference is not considered, and the transmit power for all users is kept the same, derived from the SE requirement η_{SE} of the cell-edge user. Figure 1.6 further depicts the DE and EE performance at different β. The DE and EE values in the figure are normalized by that of the reference scenario. An implicit assumption is that the total traffic served by different scenarios on the given area A is the same. The left-most figure shows that the improvement in EE via cell size shrinking depends heavily on the wireless channel environment, e.g. the path-loss exponent α. The larger the α is (faster degradation of the transmitted energy), the more benefit small cells could bring. As shown in the middle figure, the value of γ impacts the DE performance. Here, $1-\gamma$ can be interpreted as the average cost reduction ratio per base station. Note that the increase in the number of cells adds extra cost in the backhaul and site maintenance. The constant offset in γ is added to account for that. Finally, the right-most figure shows how the network EE trades off DE. Note that when transmitting in free space ($\alpha = 2$), the trade-off relation no longer holds.

1.2.5 Summary

In the previous four subsections, we have elaborated the definitions of the four fundamental trade-offs as well as their behavior predicted by the Shannon's capacity formula.

Table 1.1. Simple calculations with the cell size shrinking ratio β. The constants k_1 and k_2 are $k_1 = A/\pi$, $k_2 = (2^{\eta_{SE}} - 1)/(\kappa_0 \eta_{SE})$, where A is the total area considered and η_{SE} is the target SE for cell-edge users. γ is the ratio of cost per base station against the initial value c_0.

Scenarios	Cell radius D	No. of cells N	Total cost C	Total E_b^t/N_0
Reference	d_0	$\frac{k_1}{{d_0}^2}$	$N \cdot c_0 = \frac{k_1 c_0}{{d_0}^2}$	$k_2 {d_0}^\alpha$
Shrinking ratio β	$d_0 \cdot \beta$	$\frac{k_1}{{d_0}^2} \cdot \frac{1}{\beta^2}$	$N \cdot \gamma c_0 = \frac{k_1 c_0}{{d_0}^2} \cdot \frac{\gamma}{\beta^2}$	$k_2 {d_0}^\alpha \cdot \beta^{\alpha-2}$

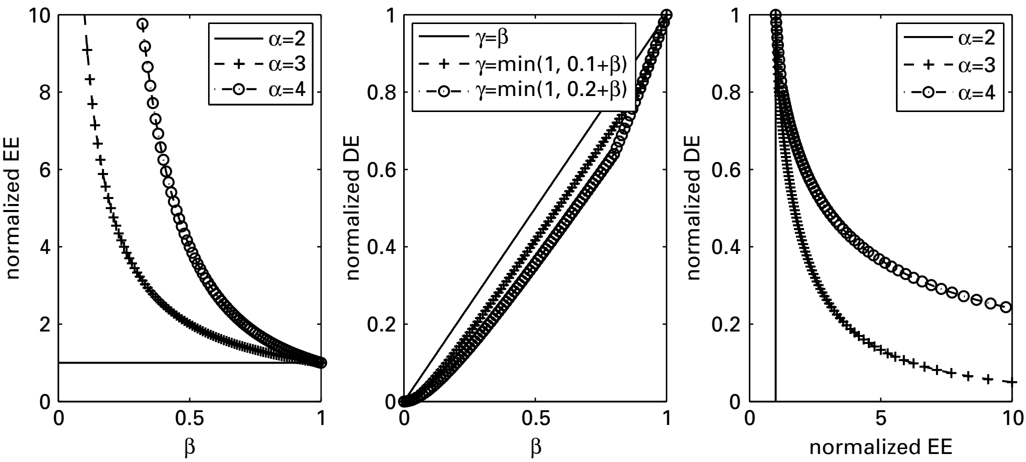

Figure 1.6 Illustration of the DE–EE trade-off derived from Shannon's formula. The left one shows the EE trend at different path-loss exponent α, while the middle one shows the DE behavior under different assumptions of γ, and the right one shows the trade-off relation between the two. The DE and EE values are normalized by that of the reference scenario. γ in the right-most figure is chosen as $\min\{1, 0.1 + \beta\}$.

In this subsection, we would like to summarize what we have learnt so far. Figure 1.7 gives the sketch of the trend curve for each of the trade-offs, which are monotonically decreasing as predicted by Shannon's formula.

Along each curve, we can identify the operation region with high power and that with low power, respectively, as shown by the shaded ellipses in the figures. The two large arrows in each sub-figure suggest two potential directions to improve EE or to reduce power. Having identified the operating regions with different power requirement, one possible direction for energy-oriented system optimization is to shift the operating point of the system along the trade-off curve, from the high-power region to the low-power region. This can, in general, be achieved by optimizing the key system parameters and adapting them to the dynamics of the system traffic requirement. For instance, when there is extra bandwidth available, aggregating them and then transmitting on the wider band also results in lower transmit power requirement (shifting the operating point along the curve from right to left as in Figure 1.7 (b)). Similarly, for a delay tolerant service,

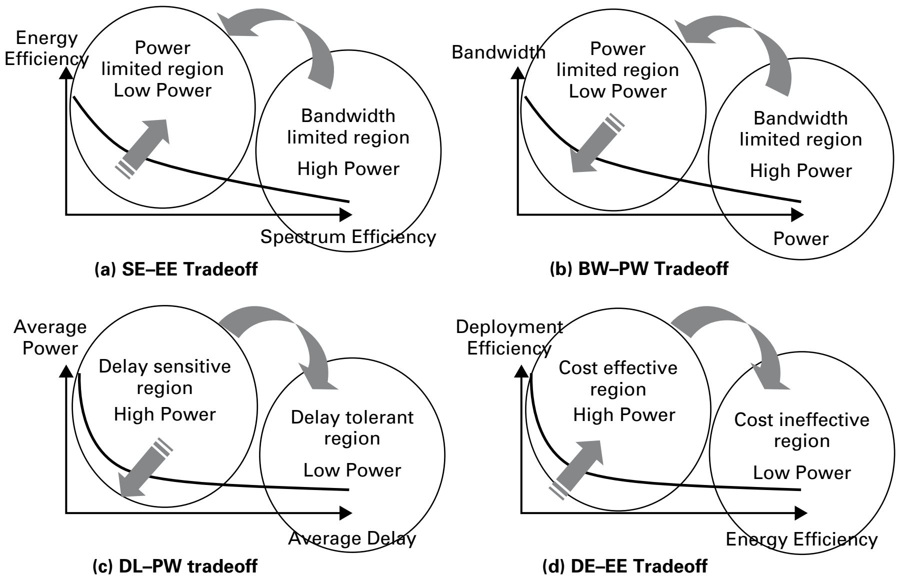

Figure 1.7 Summary of the sketch of the four fundamental trade-offs derived from Shannon's formula. Along the curves, high-power regions and low-power regions are identified and marked using shaded ellipses. The bold arrows suggest the potential direction of energy performance improvement.

lowering the modulation level to transmit more slowly can help to reduce the transmit power needed (shifting the operating point along the curve from left to right, as in Figure 1.7 (c), for PHY delay).

On the other hand, it is possible to improve the two ends of the trade-off simultaneously, i.e. pushing the trade-off curve outwards as for the SE–EE and DE–EE relations and pushing the curve inwards for the other two trade-offs. Multiple-input-multiple-output (MIMO) techniques, which can provide higher SE without increasing power for transmission, are potential candidates in this case. However, as we will see from the next section, it is not always good to have MIMO for energy-oriented design, because the power expenditure in other parts of the system (e.g. the electronic circuits) to support MIMO may degrade the gain obtained for the transmit power only.

1.3 Impact of practical constraints

In the results derived from Shannon's capacity formula, only the transmit power (radiated energy) is considered. In this case, we obtain a set of monotonically decreasing curves for each of the fundamental trade-offs. In fact, however, for any base station available today, the power radiated to the environment for signal transmission is only a portion of its total power consumption [13]. The ratio of the base station's total power consumption over its radiated power is called *base station efficiency*, which is far from the ideal value of 1. For

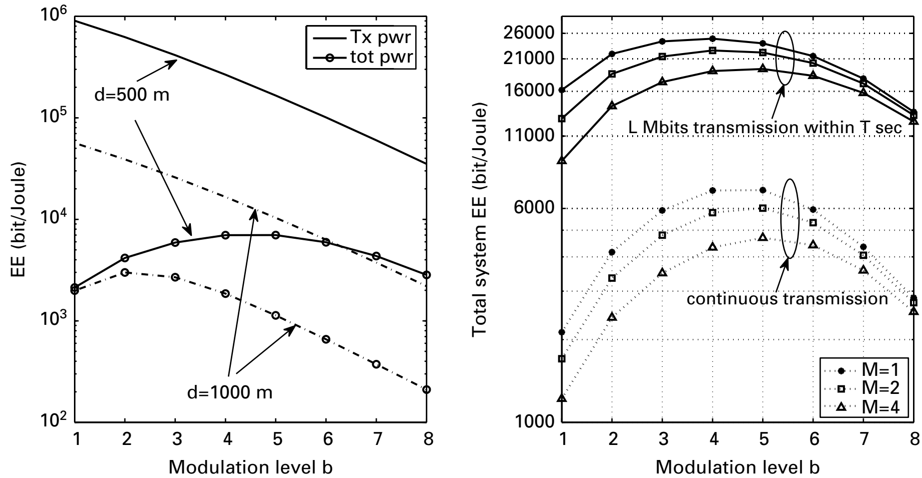

Figure 1.8 The SE–EE curves under practical constraints. The LHS figure show the EE at difference transmission distance with either transmit power or total power considered. The RHS figure compares the system EE ($d = 500$ m) with total power considered in both the full buffer case (continuous transmission) and the bursty traffic case (L bits before T sec.), given different numbers of beam-forming antennas M.

instance, if the base station efficiency is 10%, then to transmit 100 Watt for delivering information, about 900 Watt extra power is needed to keep the system working properly. As technologies evolve, the power efficiency has been improved greatly but is still far from the ideal (close to 1). Therefore, for an energy-efficient design of wireless networks, it is important to consider not only the radiated power, but also the overall system input power. Moreover, for the DE–EE trade-off from the whole network's aspect, it is also essential to have a correct model of the network deployment and operation cost.

In the following, we just give some examples of how the trade-off curves derived in Section 1.2 are impacted by the practical constraints elaborated above. We shall see that when the non-linear efficiency of the PA and the processing power and circuit power are considered, the trade-off relation usually deviates from the simple, monotonically decreasing curve.

As a comparison to Figure 1.3, we show in the LHS of Figure 1.8 the relation between the transmit EE and the modulation level of the uncoded M-QAM signals, which can be seen as the SE of the uncoded transmission. Similar issues were also investigated in [15, 16]. We further study the impact of multiple antennas and bursty transmission with sleep mode in the RHS of Figure 1.8. Transmit beamforming is assumed at the transmitter, which has been proved to reduce the transmit power by M times if the antenna array is equipped with M antennas [17]. However, when considering the total system power, we have the inverse observation, namely the beamforming gain may become negative and get worse with more antennas. This is because the transmit energy reduction becomes smaller than the circuit power increase brought by the increase of extra beamforming antennas. Also, it is easy to see that sleep mode helps to boost the energy efficiency of

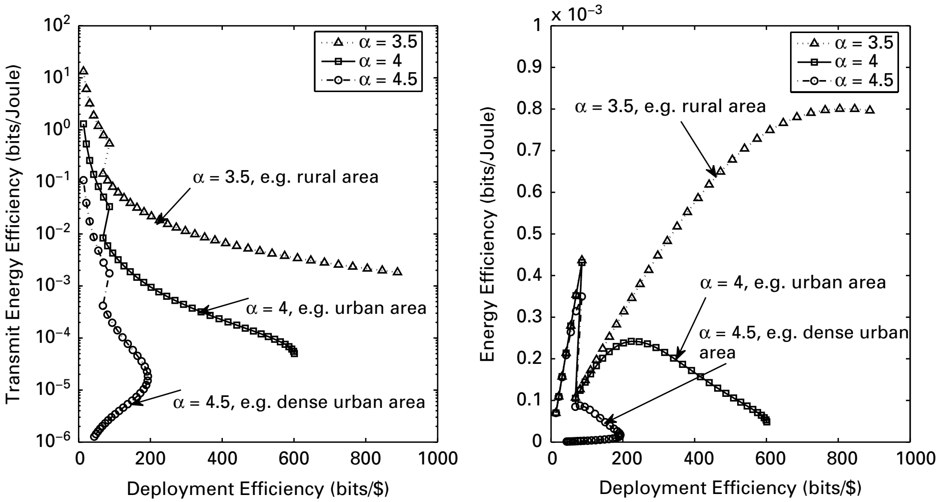

Figure 1.9 The DE–EE curves under practical concerns. The LHS figure considers only the transmit power of the network, while the RHS figure take the total input power into consideration. α is the path-loss exponent, whose value implies the service areas.

the system, since it directly reduces the circuit power and part of the processing powers in the system.

Another example is shown in Figure 1.9 for the DE–EE trade-off, based on the preliminary study in [18]. From the right-most plot, there might not always be a trade-off between DE and EE and the shape of a DE–EE curve depends on the specific deployment scenarios. For the suburb scenario, where the path-loss exponent is small (about 3.5), the network EE even increases with its DE. For the dense urban scenario, where the path-loss exponent is large (about 4.5), two different EE values may result in the same DE value, corresponding to very small and very large cell radii, respectively. The former is because of the huge increase in CapEx by increasing the number of sites; the latter is due to the sharply increased electricity bill in OpEx.

1.4 Latest research and future directions

1.4.1 SE–EE trade-off

The previous illustrations show that the SE–EE trade-off curves are highly relevant to the static circuit power consumptions. However, this is not the only factor that causes the different behavior of the SE–EE trade-off curves. Current literature also shows that the transmission technologies and the network architectures will affect the trade-off curve as well. In the current literature, the SE–EE trade-off relations has been extensively studied in the OFDMA and MIMO systems.

- *OFDMA systems*: The concept of EE in OFDM systems first appeared in [15] with the consideration of the circuit power consumption. In contrast to the traditional