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Green Radio Communication Networks

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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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 1: 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, multicell 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.