Smart Grid

Networking, Data Management, and Business Models

EDITED BY
HUSSEIN T. MOUFTAH
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Preface

Electricity, a core service for many societal functions, reaches consumers via the electrical power grid. Since the mid-2000s, efforts in modernizing the electricity grid have led to a number of advances in the way power is generated, delivered, transmitted, stored, and consumed. New models of supply and demand brought in new business perspectives. Climate change and the drive toward low-carbon economies played a critical role in the advancement and adoption of electric vehicles. In the heart of this fast-phased evolution of energy and transportation sectors, information and communication technologies had the lion's share in transforming legacy systems into the so-called smart grid and smart cities. Power systems are becoming more manageable with a high volume of data flowing between grid operators and customers. The management of data that is large in volume, variety, and velocity has led to a whole new area of research in the past few years. Communication between loads and suppliers, high-resolution monitoring of substations, and energy trading communities are among the few of the advancements we have witnessed so far. In addition, coordinated electric vehicle charging and vehicle-to-grid power flow are emerging areas of research with high impact on future generations.

This book covers a broad range of emerging topics in communication infrastructures for the smart grid and electric vehicles, management of smart grid data, as well as business and pricing models for the power grid. This book aims to be a complementary reference for utility operators, telecom operators, communications engineers, power engineers, electric vehicle OEMs, electric vehicle service providers, university professors, researchers, and students who would like to grasp the advances in the smart grid and electric vehicle world. This book accommodates 16 book chapters authored by world-renowned experts, all presenting their views on smart grid communications and networks, data management, and business models. The chapters are organized in four sections.

Section I: Smart Grid Communications focuses on the latest advancements in smart grid communications, including cognitive radio-based solutions and software-defined networking approaches. This section consists of three chapters.

Chapter 1, authored by Dimitris Kogias, Gurkan Tuna, and Vehbi Cagri Gungor, discusses the potential use cases of cognitive radio in the smart grid along with research challenges that need to be addressed. Cognitive radio is a revolutionary technology that allows for opportunistic use of unused spectrum frequencies to increase communication capabilities and improve the overall system performance. Recently, the use of cognitive radio networking technology for the smart grid has been explored and promising results that can lead to remarkable advances have been observed.

Chapter 2, authored by Ozgur Ergul, Oktay Cetinkaya, and Ozgur Baris Akan, focuses on the recently proposed cognitive radio sensor network (CRSN) paradigm, which is a distributed network of sensors armed with cognitive radio capabilities that sense the environment and collaboratively communicate their measurements over available spectrum bands. The advantages and disadvantages of CRSNs are discussed thoroughly. This chapter concludes with interesting future directions that pinpoint the open issues in this very active area of research.

Chapter 3, authored by Kemal Akkaya, A. Selcuk Uluagac, Abdullah Aydeger, and Apurva Mohan, is the last chapter of Section I. Software-defined networking (SDN) is a recently emerging networking paradigm that can provide excellent opportunities for reducing network management cost by integrating a software-based control that is flexible with software upgrades, flow-control, security patching, and quality of service. This chapter presents state-of-the-art research in adapting SDN for the existing needs of smart grid applications.

Section II: Smart Grid Security and Management consists of three chapters that address the cyber security of the smart grid along with management issues that arise around smart cities.

Chapter 4, authored by Guobin Xu, Paul Moulema, Linqang Ge, Houbing Song, and Wei Yu, systematically explores the space of attacks in the energy management process, including modules being attacked, attack venue, attack strength, and system knowledge, and develops a defense taxonomy to secure energy management with three orthogonal dimensions: methodology, sources, and domains. This chapter is a fundamental text treating security issues in the smart grid comprehensively.

Chapter 5, authored by Abdul Razaq, Huaglory Tianfield, Bernardi Pranggono, and Hong Yue, points out the need for developing a smart grid simulator and draws a road map for future research. A smart grid simulator needs to assess and evaluate the smart grid's reliability and cyber security across all the interdependent aspects such as power subsystems, automation, and communication networks while simulating the interactions among those different components. This chapter projects light on the smart grid simulator, which is a long-desired product by operators and researchers.

Chapter 6, authored by Stephen W. Turner and Suleyman Uludag, discusses in detail the challenges of positioning and managing the smart grid within the context of smart cities. This chapter prepares the readers for the following sections of this book where electric vehicles are discussed. The smart grid and electric vehicles are two interconnected infrastructures that are at the core of smart cities. This chapter explains the intertwined relationships among these with a language even a nonexpert reader can benefit from.

Section III: Demand Response Management and Business Models focuses on consumer and market aspects of the power grid. The five chapters included in this section explore the best ways of managing user demand along with optimal pricing schemes.

Chapter 7 is authored by Li Ping Qian, Yuan Wu, Ying Jun (Angela) Zhang, and Jianwei Huang. The authors present a real-time pricing scheme that aims to reduce the peak-to-average load ratio, while maximizing each user's payoff and retailer's profit. The formulated two-stage optimization problem considers user interactions at the lower scale and retailer pricing at the upper scale. Significant performance improvements have been suggested by the obtained results.

Chapter 8, authored by Zhi Chen and Lei Wu, proposes a sound real-time demand response management mechanism that can be embedded into smart meters and automatically executed for determining the optimal operation of appliances in the next 5-minute time interval while considering future electricity price uncertainties.

This chapter makes valuable contributions to the modeling of price-based demand response and scenario-based stochastic and robust optimization approaches.

Chapter 9, by Antimo Barbato, Cristina Rottondi, and Giacomo Verticale, provides an excellent overview of distributed and centralized demand side management. The authors present optimization approaches from both ends of the distributed and centralized spectrum and compare their performance in detail.

Chapter 10, by Melike Erol-Kantarci and Hussein T. Mouftah, has initially appeared in *Pervasive Communications Handbook* published by CRC Press in 2011. This chapter fills the gap in the area of low-carbon economies and the green smart grid and how these can be realized through pervasive management of demand.

Chapter 11, authored by Thomas H. Ortmeyer, is a reference chapter for every power and communications engineer who wishes to delve into the fundamentals of electricity distribution. This chapter provides an overview of distribution system characteristics that can impact the capability of the system to provide reliable power for electric vehicle charging stations.

Section IV: Microgrids, Electric Vehicles, and Energy Trading accommodates five chapters on cutting-edge research on microgrids, electric vehicles, and energy trading in the smart grid.

Chapter 12 is authored by Vincent François-Lavet, Quentin Gemine, Damien Ernst, and Raphael Fonteneau. The authors investigate how to optimally operate a microgrid given that supply and demand are known *a priori*. The authors' optimization model has been validated with real-life examples from Belgium and Spain.

Chapter 13, by Xavier Fernando, sets the stage for the final chapters of this book by giving a comprehensive review of the history and future of electric vehicles. The challenges of electrical vehicle charging along with the opportunities arising from utilizing their batteries as storage for blackouts are discussed thoroughly.

Chapter 14, authored by Christos Tsoleridis, Periklis Chatzimisios, and Panayiotis Fouliras, discusses the business and communication challenges behind V2G, which is electricity flowing from electric vehicle batteries toward the power grid. The authors provide a satisfactory list of open issues at the end of their chapter, which is an invaluable source for researchers who are seeking to advance the area.

Chapter 15, authored by Dhaou Said, Soumaya Cherkaoui, and Lyes Khoukhi, presents an optimization framework for electric vehicle charging that targets to minimize peak load on the distribution system. The proposed solution makes use of dynamic pricing of the smart grid and the obtained results suggest significant performance improvement.

Chapter 16, by Bhaskar Prasad Rimal, Ahmed Belgana, and Martin Maier, is the last chapter of this book. Energy trading is one of the leading-edge research topics in smart grid domain. The game-theoretic approach adopted in this chapter provides a real-time energy trading mechanism between multiple sources and multiple customers in an open energy market. The results suggest that noncooperative game models are promising and can optimize power losses among interconnected microsources.

This book contains 16 chapters grouped in four sections to make reading easy and pleasant for the audience of this book. Each chapter is authored by widely recognized scholars in smart grid research. This book aims to be a handbook for researchers, academics, and practitioners, who desire to take active part in smart grid and smart cities research.

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Hussein T. Mouftah has earned DSc in EE from Laval University, Quebec City, Canada (1975), MSc in Computer Science from Alexandria University, Egypt (1972), and BSc in EE from Alexandria University, Egypt (1969). He is a distinguished university professor and Tier 1 Canada Research chair in wireless sensor networks at the School of Electrical Engineering and Computer Science of the University of Ottawa, Canada. He has been with the ECE (Electrical and Computer Engineering) Department at Queen's University (1979–2002), where he was prior to his departure as a full professor and the department associate head. He has six years of industrial experience mainly at Bell Northern Research of Ottawa (then known as Nortel Networks). He served as editor-in-chief of the *IEEE Communications Magazine* (1995–1997) and director of *IEEE ComSoc Magazines* (1998–1999), chair of the Awards Committee (2002–2003), director of Education (2006–2007), and member of the Board of Governors (1997–1999 and 2006–2007). He has been a distinguished speaker of the IEEE Communications Society (2000–2008). He is the author or coauthor of 10 books, 71 book chapters and more than 1400 technical papers, 14 patents, and 144 industrial reports. He is the joint holder of 19 Best Paper and/or Outstanding Paper Awards. He has received numerous prestigious awards, such as the 2014 Technical Achievement Award in wireless ad hoc and sensor networks of the IEEE ComSoc AHSN-TC, the EIC 2014 K. Y. Lo Medal, the 2007 Royal Society of Canada Thomas W. Eadie Medal, the 2007–2008 University of Ottawa Award for Excellence in Research, the 2008 ORION Leadership Award of Merit, the 2006 IEEE Canada McNaughton Gold Medal, the 2006 EIC Julian Smith Medal, the 2004 IEEE ComSoc Edwin Howard Armstrong Achievement Award, the 2004 George S. Glinski Award for Excellence in Research of the U of O Faculty of Engineering, the 1989 Engineering Medal for Research and Development of the Association of Professional Engineers of Ontario (PEO), and the Ontario Distinguished Researcher Award of the Ontario Innovation Trust (2002). Dr. Mouftah is a Fellow of the IEEE (1990), the Canadian Academy of Engineering (2003), the Engineering Institute of Canada (2005), and the Royal Society of Canada RSC Academy of Science (2008).

Melike Erol-Kantarci is an assistant professor at the Department of Electrical and Computer Engineering, Clarkson University, Potsdam, New York. She is the director of Networked Systems and Communications Research (NETCORE) Lab. Previously she was the coordinator of the Smart Grid Communications Lab and a postdoctoral fellow at the School of Electrical Engineering and Computer Science, University of Ottawa, Canada. She earned her PhD and MSc in computer engineering from Istanbul Technical University in 2009 and 2004, respectively. During her PhD studies, she was a Fulbright visiting researcher at the Computer Science Department of the University of California Los Angeles (UCLA). She earned her BSc from the Department of Control and Computer Engineering of the Istanbul Technical University in 2001. Dr. Erol-Kantarci received a Fulbright PhD Research Scholarship (2006) and the Siemens Excellence Award (2004), and she has won two Outstanding/Best Paper Awards. She is the coauthor of the article *Wireless Sensor Networks for Cost-Efficient Residential Energy Management in the Smart Grid* (*IEEE Transactions on Smart Grid*, vol. 2, no. 2, pp. 314–325, June 2011), which was listed in *IEEE ComSoc Best Readings on Smart Grid Communications*. Her main research interests are wireless sensor networks, smart grid, cyber-physical systems, electrification of transportation, underwater sensor networks, and wireless networks. She is a senior member of the IEEE and the former vice-chair for Women in Engineering (WIE) at the IEEE Ottawa Section. She is currently the vice-chair of Green Smart Grid Communications special interest group of IEEE Technical Committee on Green Communications and Computing.

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Section I

Smart Grid Communications

1 Cognitive Radio Networks for Smart Grid Communications

Potential Applications, Protocols, and Research Challenges

Dimitris Kogias, Gurkan Tuna, and Vehbi Cagri Gungor

CONTENTS

1.1 INTRODUCTION

A smart grid (SG) is the next generation of power grid, where transmission, distribution, power generation, utilization, and management are fully upgraded to improve efficiency, agility, environmental friendliness, economy, security, and reliability [1–4]. It offers two-way communication between the base stations and power generation sites [2–5], and optimizes the overall system performance by taking the advantage of wireless sensor networks (WSNs) [6–13], using smart sensor devices, and implementing renewable energy solutions. Since SG consists of many different applications with different communication and quality of service (QoS) requirements, it involves heterogeneous communication technologies based on a multitier communication infrastructure.

In recent years, the use of cognitive radio networking (CRN) technology for SG environments [14–19] has been heavily investigated, and major and remarkable developments with very promising results has been seen. Cognitive radio (CR) is a revolutionary technology that allows for opportunistic use of unused spectrum frequencies to increase communication capabilities and improve overall system performance. As shown in Figure 1.1, CR permits secondary users (SUs) to communicate using frequencies in license-free spectrum bands and in this way increases the throughput of the system and its communication efficiency. Since CR uses the spectrum that is not used by primary users (PUs), it improves the utilization of radio frequencies and makes room for new and additional commercial, emergency, and military communication services [16].

A communication infrastructure is an essential part of the success of SG deployments. In this respect, a scalable, reliable, and pervasive communication infrastructure plays a key role. In this chapter, the novel concept of integrating CRN technology into SG communication infrastructure is presented. The implementation of CRN in SG infrastructure includes CR gateways in each communication architecture tier of SG [16] that will handle the connection between the different tiers, and will also play the role of a base station for the network nodes, that is, different kind of nodes, depending on the communication tier, that are connected to it. This gateway will be responsible for introducing CR technology on the network by continuously sensing the spectrum band for license-free frequencies and assigning them to SU nodes inside the network, improving the network's throughput. On top of this, certain CR gateways can also be assigned the task to distribute the frequencies to specific gateways that reside on different communication tiers. Recent communications standards for CR include, among others, the IEEE 802.22 [16,18] standard, which is the first air interface for CR networks based on opportunistic utilization of the TV broadcast spectrum. It is optimal for use in areas with typical

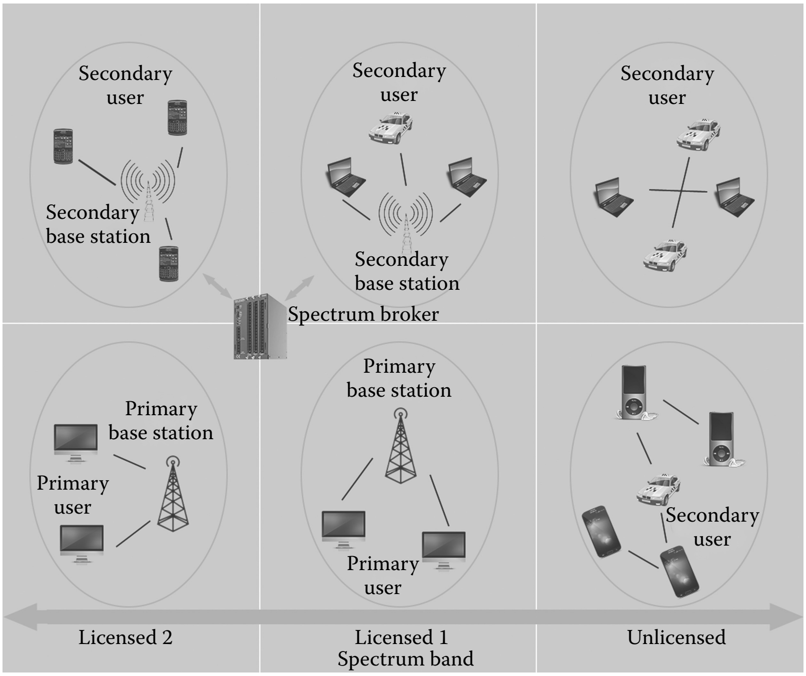

FIGURE 1.1 Opportunistic uses of frequencies.

cell radius of 30–100 km and, therefore, a very prominent candidate for use in an SG environment. Overall, CR technology can help us to fill the *regulatory gaps* in a particular interference environment and can give a better performance result because it is not only reliable, but it also reduces the sensing time in an infrastructure-based SG system.

The remainder of this chapter is organized as follows. Research issues and technical challenges on SG that can be addressed by CR technology are presented in Section 1.2. Section 1.3 deals with the multitier communication architecture of SG when CR technology is applied whereas Section 1.4 studies the system performance focusing on energy sources and introduces green cognitive mobile networks and their use in SG applications. Section 1.5 presents how CR technology improves SG communication and Section 1.6 studies the design objectives and challenges of various CR-based protocols that are used for SG communication, followed by a comparative table that summarizes the results. Finally, this chapter concludes with Section 1.6.

1.2 RESEARCH ISSUES AND CHALLENGES IN SGs AND SOLUTION FROM CR TECHNOLOGY

An SG is a new and improved system that manages electricity demand in a reliable, sustainable, and economic manner. An SG is built on a two-way communication infrastructure between the utility and its customers, and tuned to facilitate the integration of all involved [4]. The use of sensors, smart meters, self-healing technologies, and various tools for automatically monitoring and controlling two-way energy flow enables the utilities to meet quickly changing electric demand and dynamically incorporate energy from different sources, and consumers to control their energy usage. Basically, the objective of the transformation from the traditional grid to the SG is to achieve continuous balance between the operational, business, regulatory, and policy constraints.

Thanks to its innovative services and products, the SG brings several advantages to the utilities such as facilitating the connection and operation of a large number of generators. Therefore, it allows consumers to take part in the optimization of the operation of the grid system, reducing its environmental impact and delivering enhanced reliability and security to the existing grid infrastructure [4]. However, the creation of the SG requires many technological innovations and generates numerous research challenges. Since information and communication technologies are fundamental elements in the growth and performance of SGs and the SG system can be viewed as a large-scale network, consisting of a large number of interconnected components that produce a huge amount of data to be transmitted, managed, and analyzed by these technologies, a sophisticated information and communication infrastructure must be integrated to the existing grid infrastructure and the new distributed energy generation system for a successful SG transformation [4,5]. On the other hand, both field tests and real-world scenarios have shown that various issues such as connectivity problems, dynamic topology changes, interference, and fading are common in harsh SG environments. To this end, different existing and emerging solutions have been employed together for SG transformations. One of these solutions is the use of CR technology, the performance of which in SG will be thoroughly studied in this chapter.

1.2.1 Research Issues in SGs

Existing power grids are under strict pressure to provide a stable and sustainable supply of electricity to deliver the increasing demand resulting from the growing global population. In addition, they also need to reduce their carbon dioxide emissions by making effective use of renewable energy sources in their power chains. These complex challenges are driving the evolution of SG technologies, and as a consequence, the drivers for the future grids can be listed as capacity, efficiency, reliability, and sustainability.

- *Capacity*: It means meeting the growing demand of electrical energy.
- *Efficiency*: It means reducing losses in transmission, distribution, and consumption of electrical energy and increasing the efficiency of power generation.
- *Reliability*: It means providing high-quality energy whenever needed.
- *Sustainability*: It means ensuring the effective integration of renewable energy sources.

Information management and data flow are the key elements in the SG system and therefore make digital processing and communications critical to the operation of the grid. Various capabilities resulting from the highly integrated use of technology and integration of the new information flows into existing systems and utility processes are major issues in the design of SGs. They are either dependent on or result in a number of technical issues as follows:

- System evolution
- QoS
- Shared meaning of content
- Resource identification
- Time synchronization and sequencing
- Logging and auditing
- Transaction and state management
- System preservation
- Discovery and configuration

Most of the above-mentioned technical issues rely on effective two-way communication. However, most of the traditional communication technologies are not suitable for SG applications in terms of bandwidth, latency, reliability, and security requirements. Moreover, their investment, maintenance, and operational costs are high. Therefore, novel communication solutions particularly addressing the needs of the SG are required.

1.2.2 Challenges of SGs

An SG can be viewed as a highly complex system of systems integrating and interoperating across a broad spectrum of heterogeneous business and operations domains. Therefore, interoperability at all levels of the system, consisting of a large number of heterogeneous components, is critical to its success and a loosely coupled distributed system approach is a must. Owing to the broadness in its scope, a number of fundamental challenges must be addressed:

- *Lack of awareness*: Although there are available standards and best practices to facilitate SG deployments, a lack of awareness of those standards and regulatory guidelines is the main problem with adoption.
- *Standards*: There is an urgent need for interoperability standards that will allow utilities to buy equipment from any vendor knowing that they will work with each other and with existing equipment at every level.
- *Interoperability*: It addresses the open architecture of technologies and their software systems and enables integration, effective cooperation, and two-way communication among the many interconnected elements of the electric power grid system. In addition, it also simplifies the evolution of underlying technologies by isolating the application layers from the communication layers. Effectively defining and adopting standards to build a

unifying framework of interfaces, protocols, and other consensus standards is the only way to accomplish interoperability [9].

- *Technical challenges*: Since the SG network is composed of a large number of very distributed nodes that are tightly coupled and operating in real time, determining where intelligence needs to be added is highly complex. In addition, many SG components, services, and applications have different communication requirements in terms of bandwidth, latency, reliability, and security. This makes it difficult to design an appropriate communication infrastructure for the overall grid. Therefore, the choice for communication infrastructure is highly critical to provide efficient, reliable, and secure data delivery between the various SG components, services, and applications [1].

1.2.2.1 Technical Challenges

In this subsection, the main requirements of the SG are presented from the perspective of technology. These requirements will also be connected with the potential technical challenges that proposed communication technologies need to address satisfactorily.

- *Scalability*: When the SG grows significantly, its communication infrastructure must be able to grow easily and inexpensively to provide required scalability. Therefore, emerging low-cost communication technologies should be a part of the proposed solutions.
- *Long-standing*: Since everything in modern life requires electric power, power grids are designed and engineered to operate for a substantial amount of time such as 50 years. The communication infrastructures of those grids must work efficiently with minimum maintenance needs for long periods of time [9].
- *Security*: SG networks are sensitive targets for cyber terrorists due to their high complexity, interconnected networks, increased number of paths, and entry points. To resolve their vulnerabilities and increased exposure to cyber-attacks, security needs to be an essential design criterion.
- *Reliability and robustness*: By providing specific mechanisms, the whole communication infrastructure must be enabled to resist and recover from various conditions and challenges, such as bad weather conditions, equipment degradation, harsh radio propagation conditions, and electromagnetic interferences in order to ensure the correct operation of SGs.

1.2.3 CR for SGs

CR technology includes certain characteristics that can greatly contribute to the increased performance of an SG network. This subsection will introduce those characteristics, some of which will be thoroughly covered in the sections to follow.

1.2.3.1 CR Enhanced WSNs Applications Used in an SG

Since SGs require many applications to control the intelligent devices and sense the environment, WSNs are commonly used to achieve reliable, low-cost, remote monitoring, and control operations in various SG applications. Such applications include, among others, automatic meter reading, fault diagnostics, power automation, and demand response. However, different SG applications have different requirements in terms of bandwidth, delay, reliability, and QoS [20]. In addition, SGs pose significant challenges to electric utilities, mainly due to harsh radio propagation conditions, which affect the key design issue of an SG, making the support of reliable and real-time data delivery challenging. Some applications of an SG that can be affected by the use of CRN [21] are presented below:

- *Demand response and energy efficiency*: The minimization of energy consumption is crucial for both the WSN and the SG. Smart homes, with the use of sensors, are a step toward this direction and CRN can be used to enhance performance by allowing remote control of the devices and, therefore, achieve better energy efficiency.
- *Wide-area situational awareness*: CRNs, by enhancing SG's communication capabilities, as will be thoroughly discussed later on, can contribute to increased knowledge of the surrounding area. This knowledge can be used to address issues related to facility security and monitoring.
- *Energy storage*: Energy can be stored at different locations and then can be redistributed to the most wanted areas. By using CRN to address the various requirements and measure the amounts of energy, generated by renewable resources, that are offered to the system, a compensation of the users that have offered larger amounts of energy is easier to achieve and realized.
- *Electric transportation*: Power can be generated by remote power plants and then be distributed, using transmission lines, to the rest of the grid. CRN can be used for efficient monitoring of the transportation, especially on remote locations, enhancing WSN capabilities on an SG.
- *Network communication*: This can be largely affected and its performance can be seriously increased with the use of CRN. CRN introduced software defined radio (SDR) [22,23], which is the software implementation of known hardware components and which operates on many bands and accesses the spectrum as a secondary unlicensed user to increase the node's throughput. Many communication standards can be supported by the applied SDR platforms [24] that are used for CRN implementation on an SG.
- *Advanced metering infrastructure (AMI)*: AMI is an integrated system of smart meters, communications networks, and data management systems that enables two-way communication between utilities and customers. AMI provides utility companies with real-time data about power consumption and allows customers to make informed choices about energy usage based on the price at the time of use. The data generated by a smart meter can be securely delivered through the network with the use of CRN that will also contribute to prevent any theft at the customer premises by including cameras for surveillance at the AMI premises.
- *Cyber security*: The use of wireless technology for communication on parts of the SG architecture means that the delivered data are prone to attacks. CRN offers security attacks classification with respect to the attacker and solutions are discussed in References 24 and 25 for more efficient data security in CRN SG networks.

1.2.3.2 Communication Technologies for CR-Based SG Network

Electromagnetic interferences, line-of-sight issues, noise-cancellation phenomena, and frequency overlapping are the main reasons for harsh propagation conditions. On top of this, SG communication infrastructure is basically a *heterogeneous multi-tiered topology*; therefore, interoperability among its subnetworks is a major concern.

As it is well known, the spectrum in home area networks (HANs) is becoming exceedingly crowded due to the coexistence of various communication technologies, such as ZigBee, WiFi, and Bluetooth, and some domestic appliances such as microwave ovens. In addition, the competition and interference over the ISM (industrial, scientific, and medical) radio bands may endanger reliable communications in an SG. To this end, heterogeneous subnetworks can be converged through radio-configurability capability offered by CR networks to increase the performance of the communications on an SG. Furthermore, CR networks will also be able to offer intelligent power coordination schemes for interference mitigation or for delivery of the expected QoS requirements.

Basically, as shown in Figure 1.2, CR can be described as a set of concepts and technologies that enable radio equipment to have the autonomy and cognitive abilities to become aware of their environment as well as of their own operational abilities [26,27]. In this way, any device with this ability can collect information through its sensors and use past observations on its surrounding environment in order to improve its behavior [26,27]. CR networks can improve the overall network performance with their opportunistic spectrum access (OSA) capability and increase spectrum utilization efficiency in SG environments [28]. In this way, the communication capacity of SG networks can be improved to carry the tremendous amount of

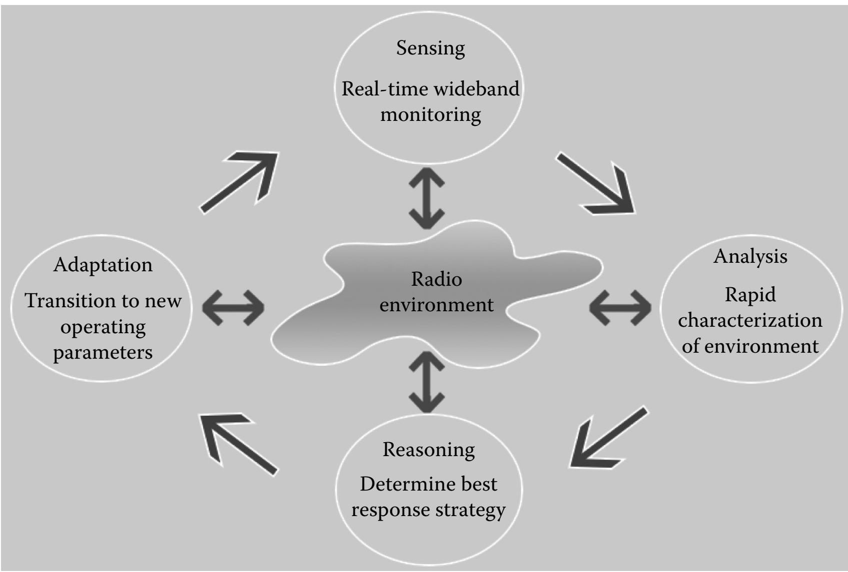

FIGURE 1.2 Principles of CR.

data produced by SG applications. In Section 1.3, more details regarding the way the communication architecture of an SG enhanced with CR technology capabilities are thoroughly presented and examined.

1.2.3.3 CRN's Channel Selection Strategies for Use in an SG

Channel selection strategy is very important for CRN's performance because its efficiency can play a very important role in the dissemination of information inside a CR-based SG network. This efficiency will also be crucial to any routing mechanism that is applied on the multitier SG communication system, affecting therefore the network's overall functionality and efficiency in communications.

One of the goals of channel selection strategy is to achieve maximization of throughput [29,30] and minimization of the delay, which is the minimization of the switching delay [31]. Finally, routing requirements affect the channel selection strategy. Common routing requirements include the selection of channels with low PU activity, high bandwidth, less interference, and maximum connectivity.

The nature of the channel's selection depends on its type:

- *Proactive*: Based on a prediction of the PU activity, the SUs will move to appropriate channels, which are characterized by longest idle time, thus reducing the number of channel switches and produced delays.
- *Reactive*: The SUs monitor the spectrum for any PU activity and spread the information regarding it to all other SUs in order to keep a track of the available holes in the spectrum.
- *Threshold-based*: In this case, PUs occupy the channel all the time and then a certain discussed threshold is set under which the SUs can utilize the channel, even though a PU transmission is in place since no idle time slots will ever be available. If the threshold value holds, then the interference is considered nonharmful.

Finally, the channel selection can be executed in a centralized fashion, where the spectrum administrator is responsible for channel allocation and switch. This solution does not scale well nor is preferred in multitier communication architectures, like SGs, where distributed channel selection based on local knowledge is better applied.

1.3 CR-BASED COMMUNICATION ARCHITECTURE FOR SG

Most SG deployments usually cover large geographic areas. Therefore, for a robust communication architecture that can efficiently cover the SG network, a multitier hierarchical solution is proposed [15,16,32,33]. This solution consists of three different segments: a HAN, a neighborhood area network (NAN), and a wide-area network (WAN) that span throughout the whole SG infrastructure as shown in Figure 1.3. HANs consist of various smart devices and sensors that provide for efficient energy management and demand response [34]. NANs are responsible for interconnecting multiple HANs to local access points or cognitive gateways, whereas WANs are responsible for the communication between NANs and the utility system.

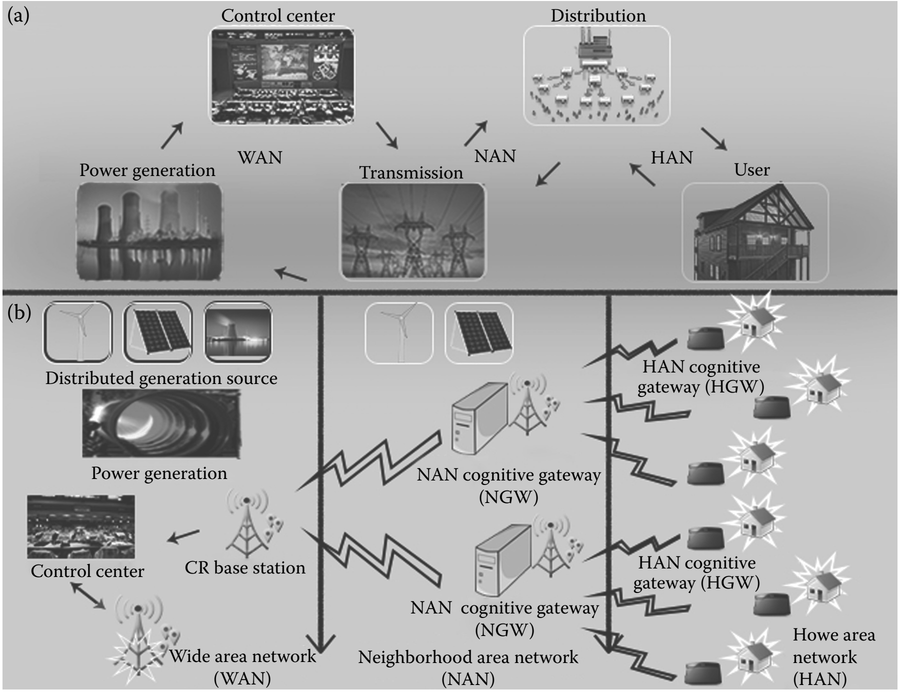

FIGURE 1.3 CR-based hierarchical communications architecture in SG. (a) Communications architecture in traditional SG, (b) CR-based hierarchical communications architecture in SG.

The use of CR technology in these segments encourages the utilization of the overall available licensed spectrum by allowing unlicensed devices to transmit in spectrum *holes* [28,35] and can lead to the increased network performance of an SG. Especially in HANs, CR's capability for dynamic spectrum access allows the opportunistic access of the licensed and license-free [16] bands by the sensors in order to coordinate the coexistence of various heterogeneous communication technologies and help to enhance the system's communication performance. On the other hand, in NANs and WANs, cognitive operation that utilizes the license bands is preferred. The rest of this section covers the cognitive operation in the three existing but different tiers of the CR communication infrastructure on an SG.

1.3.1 Cognitive Communication in HANs on an SG

A HAN is a dedicated network that allows the transfer of information between various electronic devices in the home, including home electrical appliances, smart meters, in-home displays, energy management devices, distributed energy resources, actuators, and sensors.

HANs establish a real-time two-way communication between the various smart devices placed in or near the user residence and the network's utility centers, with the help of a home area gateway (HGW), which will be responsible to forward the information to each direction. The disseminated information will, most commonly, include power data and information about the sensor's load, from the user side, and dynamic pricing details from the control's center side. The HGW will also be responsible for the autonomic operation of the network. This includes controlling the joining procedures, when a new device connects to the network, and the maintenance procedures, to ensure that a link remains alive and works well.

Inside the HAN, the smart devices will connect to the HGW using different communication technologies: wired connections, Wi-Fi connections, or ZigBee connections. ZigBee is a wireless standard that operates by the IEEE 802.15.4 radio specification and is designed for use especially by low-cost and low-energy-demand devices. Recently, an application layer standard was released that enhances ZigBee's performance on devices with the aforementioned characteristics. It is the role of the HGW to manage the communications inside a HAN, through all these heterogeneous technologies, while at the same time control the communications between the HAN and the connected NAN.

1.3.1.1 Dynamic Spectrum Sharing in a HAN

To integrate CR technology, the HGW should be enhanced with advanced cognition capabilities that will allow interaction with the environment and adaptation of transmission characteristics and parameters based on current environmental conditions. Cognitive HGW will scan the available frequency band for holes in the spectrum, which are frequencies that are not used by licensed (or primary) users, and will utilize them to enhance the communication process, subject to interference constraints.

Cognitive HGWs will connect to the HAN and to the external network, for example, NAN and Internet, and will provide for two-way real-time communication between the two sides, disseminating the smart meters data and/or the control information of the utility center to the other side. It will also control the communication inside the HAN, between the smart devices. In addition, cognitive HGWs will deal with the connection characteristics in the license-free band, based on the sensing measurements, and will aim for the optimal parameters that will allow for the higher transmission rate with the smallest interference. Finally, cognitive HGWs should efficiently share the available spectrum among the various smart devices in the HAN and control the seamless entrance of new devices in the network, by assigning channels and IP addresses to each new device.

In Figure 1.4, we can see the block diagram of a CRN node, consisting of the sensor part and a smart transceiver to detect any spectrum holes that will allow the node to be used as an SU. The transceiver can adapt to the demanded communication requirements such as frequency or transmission power.

1.3.2 Cognitive Communication in NANs

A NAN is the second tier in the multitier communication architecture for CR in an SG. The dimensions of a NAN differ from a few hundred meters to a few kilometers. It is developed between customer premises and substations with the deployment of intelligent nodes to collect and control data from the surrounding data points. The NANs gateways (NGWs) interconnect multiple HNGs together and forward their data, through a WAN, to the utility control center and vice versa.

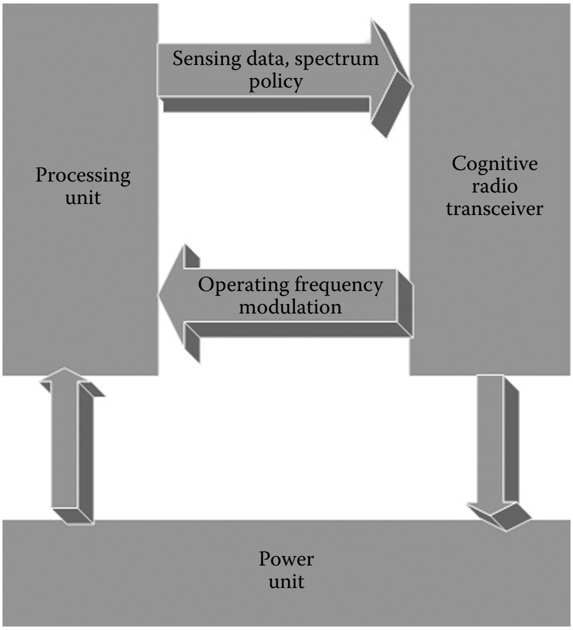

FIGURE 1.4 CRN node block diagram.

NANs are deployed over urban, suburban, and rural environments and are supported by advanced metering infrastructure deployments, which use various communication technologies according to the SG application served. Fiber optics, WiMAX, cellular, RF mesh technologies, and TV White Spaces (TVWS) can be used in a NAN, depending on the circumstances and their availability [18,36].

The HGWs are considered, from an NGW's perspective, as cognitive nodes that are data access points of the individual HANs, and to whom the NGWs have a single point connection. In addition, the NGWs distribute spectrum bands to each HGW, which, in turn, are able to share among the smart devices connected to them.

1.3.2.1 Dynamic Spectrum Sharing in a NAN

For the communication between HGWs and an NGW, a licensed frequency band should be bought or leased from a telecom operator, in order to be able to ensure diverse QoS requirements. But since the amount of generated traffic is very large, the use of a licensed band only will not suffice. For effective communication performance, opportunistic use of the license-free band is supported in cognitive NGWs, allowing the implementation of a hybrid dynamic spectrum access technique to take place. Therefore, cognitive technology can help to better utilize the available frequency spectrum to optimize the performance of networks.

1.3.3 Cognitive Communication in WANs

WANs are the last tier in the CR communication architecture in an SG. Basically, it is a high-bandwidth, two-way communication network that can handle long-distance data transmissions for automation and monitoring of SG applications. The best candidate technologies for WANs are considered to be WiMAX, cellular networks, and wired communications. Microwaves and fiber are, also, preferred for reliable and high-bandwidth communications [4].

A WAN consists of multiple NANs that exchange information with the utility center utilizing the licensed frequency band. For the WAN, NGWs are considered as cognitive nodes with the capability of using the licensed band. CR base stations are also scattered throughout the SG, for example, in an area as large as a city, and use spectrum brokers to share the available frequencies around the SG infrastructure. The effective distribution of the available frequency bands among the various NANs will allow for the coexistence and use of the same frequencies on different NANs without any interference among them.

1.4 GREEN COGNITIVE MOBILE NETWORKS FOR SG APPLICATIONS

In recent years, there has been an increased demand in telecommunication services, the need for ubiquitous connections, and the required throughput. To address all these, there are some issues that need to be studied: restrictions, such as scarce and expensive spectrum resources; theoretical limits, such as Shannon capacity; and ecological issues, such as increase in CO_2 emissions [26].

Although communication networks are intrinsically green, in recent years, the volume of transmitted data has increased significantly and network design rules to limit CO_2 emissions have been ignored. On the other hand, it has been shown that processes related to manufacture, use, and disposal of information and communication technology (ICT) equipment contribute to around 2% of global CO_2 emissions [37]. Since the telecommunication sector is responsible for 37% of the total ICT-related CO_2 emissions, a sustainable growth of telecommunication networks should be accomplished by efficient design and disposal techniques.

Green (or energy-efficient) communications enable network operators to reduce the cost of their services, according to the demand of use, and also best describe them as environmentally friendly. With this approach, network operators can set up networks that offer connections with QoS guarantees and, at the same time, use the lowest consumption of energy and available resources. By developing intelligent power coordination schemes and energy-efficient information coding and transmission techniques with a smaller CO_2 footprint, the adverse environmental effects of communication technologies can be reduced. CO_2 emissions of ICT equipment can be reduced significantly using a number of techniques such as computationally efficient algorithms, local decision-making, and optimization of the transmitted power [38]. In addition to the techniques aiming at reducing CO_2 emissions, efficient sharing of scarce spectrum resources, recycling of ICT equipment and electromagnetic waves, limiting electromagnetic pollution of wireless communications, and reducing human exposure to radiation are other major issues for sustainable ICT development [38]. Although not all these issues can be addressed using a single approach or methodology, CR could be an efficient tool for this objective.

Although CR was proposed first for the optimization of spectrum resources, it can address the requirements of green communications. CR terminals can determine the transmission channel quality in real time and adjust their transmission power. Using emerging techniques such as beamforming with smart antennas and reduction in the peak to average power ratio (PAPR) to increase the efficiency of the high-power amplifier level of the transmitted signal [38], the transmission power can be further optimized. In addition, using channel impulse response sensors, CR terminals can locally manage their radio links and put off some functions for energy saving. Beamforming also helps to reduce human exposure to radiation.

1.5 CR NETWORK-BASED SG APPLICATIONS

In SGs, the reliability of the two-way transferred information between control centers and smart meters is of crucial importance for the efficiency of the system's communications and its overall performance. In addition, the use of WSNs in SG deployments [2,7–12] has introduced modern wireless technologies for communications, creating a rather heterogeneous communication architecture in an SG. At the same time, it has significantly increased the number of applications that deal with common problems met in an SG environment. These applications not only address issues related to sensors' energy exhaustion, their mobility, and communications, but also deal with real-time decision-making based on the transferred information regarding the network's current condition [11–13]. This rapid increase in the number of applications was followed by a vast increase in the amount of generated, and therefore transmitted, data, creating a heavy load on the communication system that needed to be overcome and served in order to perform efficiently. Expectations about the size of the generated data in an SG environment, enhanced with WSN functionality, are considered to be around tens of thousands of terabytes, revealing a very significant challenge to collect, share, and store such a large amount of data [17].

To better address these challenges, the use of CR has been recently examined, as a novel communication infrastructure that can enhance SG performance by providing two coexisting systems, that is, one primary system for PU with access to legacy spectrum and one secondary unlicensed system for secondary CR users, in the same frequency band [14–16,18]. The secondary system can opportunistically search for access in the spectrum holes that are left unused by the primary one, increasing the functionality and overall performance of the system. These characteristics of CR networks make it extremely attractive for use in an SG environment because it offers a potential improvement on the spectrum utilization and the capacity of the communications. As a result, an improvement of the available throughput for the various applications and communications and, eventually, for the overall performance of the system can be achieved.

The application of CR technology in SGs can play an important role in the minimization of the interference that is produced by the parallel existence of several types of radio systems that are operating at similar frequencies in small HANs [15,16]. For this to be successful, the inherent capability of CR to adapt its capacity based on certain parameters will be used to provide for intelligent scheduling of the several transmissions, combined with effective coordination of the power consumption.

On top of this, WSNs have many applications concerning home energy management, for example, wireless automatic metering, building automation, etc., that can take advantage of the network's communication improvements.

CR can also be used in NANs where with the opportunistic spectrum utilization of unused frequencies it can achieve efficient communication, directly or via mesh networks, with each other with the help of a WAN gateway connected to a spectrum database. This WAN gateway will be responsible to decide the frequency to be used during the communication period. In Reference 17, taking advantage of the TVWS is suggested as a means of applying CR technology in NANs. The TVWS channels in rural areas are abundant and if the sensors and gateways are static, then with the use of a fixed transmission power and the given TV band propagation characteristics, it will be possible to reach all the nodes in one or two hops.

At the same time, CR can be used to face the challenge and improve the system's performance by assisting in the delivery of the augmented size of data, generated by the various smart sensors and multimedia devices spread diversely in the SGs [15,16]. This can be achieved by offering dynamic spectrum access and opportunistic use of the unused frequencies to enhance the demanded information dissemination in the SG and provide a flexible and reliable enhancement in the system's communications. In addition, the context awareness capability that is available in CR, along with the capabilities for hardware reconfigurability, can be used to enhance the interoperability of the communications through the various complementary technologies that create the heterogeneous communication network of an SG. To achieve this, intelligent devices are needed to be spread around the infrastructure to better manage the communications between different areas and distances.

Furthermore, in Reference 15, it has been studied that the majority of continuously increasing, generated data comes from multimedia applications such as real-time wireless camera surveillance, which is used to monitor the working conditions of several facilities and is able to prevent and detect faulty performance that can have a costly effect on the overall system. Another multimedia sensor application example is the monitoring of renewable resources, for example, solar or wind panels, in order to predict the amount of harvested energy that will define the system's performance, while also allowing for the customer's participation in the scheduling of the generated electricity. In addition, monitoring of the system's equipment can be benefitted from the new network characteristics, since it can be used in order to report malfunctions and increase the equipment's lifetime.

Finally, in Reference 14, the traffic over a CR system is prioritized in several tiers and a study to allocate, via the secondary or the primary system, enough channel resources to achieve the demanded quality of experience (QoE) is conducted. The motivation is to find a better way to integrate CR into the SG communication infrastructure, especially in order to better serve heavy multimedia transmission.

1.6 COMMUNICATION PROTOCOLS FOR CR-BASED SG APPLICATIONS

As discussed in the previous sections, CR uses dynamic spectrum allocation (DSA) to increase spectrum utilization and achieve better throughput performance by allowing access to the licensed band not only for primary system users, but also for secondary CR users who are able to use it when it is free, while at the same time having access to unlicensed bands [14–19]. The need is to create a robust and reliable communication infrastructure, in an SG solution, which will seamlessly integrate CR technologies and efficiently optimize the system's performance. The next subsection will try to highlight the main design objectives of the communication protocols for CR-based applications in SG environments.

1.6.1 Protocol Challenges and Design Objectives

The various communication protocol challenges and the needed design objectives for CR applications in SG are presented here.

- *Intermittent connectivity*: Between the two types of users, primary and secondary, that can be present in a CR network, priority is given to PUs for the use of the licensed band. Therefore, when a secondary CR user senses the arrival of a primary one, he should leave the channel free but this handoff shall take place seamlessly in order not to interfere with the overall network performance [26,28,35]. This change of channel for the secondary user means that the spectrum characteristics might differ and this could affect the throughput and introduce more delay in the communication.
- *Spectrum sensing*: Sensing is a fundamental function that is performed by CR network nodes. The nodes try to detect license user activity to organize their future actions. Unfortunately, many nodes are not capable of sensing the spectrum and transmitting data to the receiver at the same time [26]; therefore, the time needed for detection must be well designed since it will prevent data transmission and reception during this period. In addition, since the CR network in an SG environment is a rather heterogeneous network, the time for spectrum sensing, by many different and scattered devices, will vary and diversities and asymmetries will be introduced in the network's communications. The effect of these asymmetries will be reflected on the jitter and delay parameters along any communication paths in the network.
- *Opportunistic spectrum access*: For SUs, the use of the license band is allowed only when a free slot is presented [27]. Therefore, consecutive arrivals of PUs, on such different spectrum holes, can diminish the level of the system performance, since a secondary user will need to keep sensing the spectrum for a gap. In extreme scenarios, this can lead to obsolete data arrival since the synchronization and the time limits in a communication path might have been exceeded.
- *Spectrum mobility*: Spectrum handoff, the move from one channel to another in search for free slots or frequency gaps, can cause significant transmission delays [1,39]. On top of this, continuous change of the channel characteristics will affect the communication and will further burden the nodes with the task of recalculation of these characteristics in order for estimation of the

next-spectrum hop candidate to be found. As a result, spectrum mobility can affect the network capacity and will introduce varying jitter values.

- *Spectrum coordination*: Since the spectrum sensing intervals might differ for each node in a CR network, control messages should be disseminated in order to coordinate the handoff procedure and spectrum decision functionalities. In a communication path, between a sensor and a receiver, each node should be aware about the sensing cycles of its neighbors in order to schedule its transmissions and effectively communicate without introducing further delays. The heterogeneity of the CR network will also have to be addressed and an efficient scheduling of the sensing and transmitting cycles for each node in the path has to be determined [39].
- *Interoperability*: The CR network in SGs will use a variety of technologies in order to transmit and distribute the generated traffic and provide proper information to the control centers, aiming to enhance the performance of the network. CR is expected to be able to contribute heavily for optimal network functionality, despite the well-known heterogeneity in its communication infrastructure.
- *Quality of service*: The disseminated data in a CR network on an SG can be prioritized in terms of their requested bandwidth, reliability, and delay values, depending also on the device that generates them. For example, meter data should be highly prioritized where power price data might have a normal priority.

1.6.2 Various Protocols for CR-Based SG Communication

In this subsection, various protocols will be presented, covering most of the defined network layers and the way these protocols try to address the design objectives mentioned above.

1.6.2.1 Medium Access Control Protocols for CR Networks

Medium access control (MAC) protocols mainly focus on the problem of spectrum access, where multiple CR users share the channel and priority has to be determined in order for the network to operate efficiently.

There are two types of MAC protocols: the *random access* protocols and the *time slotted* protocols. Random access protocols do not require time synchronization and use a principle that closely relates to the carrier sense multiple access with collision avoidance (CSMA/CA) algorithm, where a PU senses the channel for neighboring transmissions and if one takes place, the user randomly backs off. On the other hand, time slotted protocols require network-wide time synchronization and divide time into certain slots that are used for control and data transmission.

Important design characteristics of MAC protocols are the common control channel (CCC) and its existence or not in the protocol implementation [40] and the number of transceivers that is required.

1.6.2.1.1 Random-Access MAC Protocols

For infrastructure-based CR networks, a CSMA-based random access protocol is proposed in Reference 41, which facilitates the coexistence of both primary and

CR users by keeping the interference level of the two communications under a predefined threshold. Both users maintain their coordination with the help of a CR base station. The PUs have priority since the time they spend on spectrum sensing is smaller than the one used by CR users.

For ad hoc topologies, a distributed channel assignment (DCA) protocol is presented in Reference 42. DCA uses multiple transceivers and a dedicated CCC mainly for control signaling. Each node maintains the list of occupied channels from its neighboring nodes, along with a list of the ones that are free. This list is updated and matched during the RTS-CTS (Ready-To-Send, Clear-To-Send) handshake that takes place between two nodes in the network. Moreover, this is where decisions regarding the channel to be used are made.

The single radio adaptive channel (SRAC) is proposed in Reference 43. SRAC uses a frequency division multiplexing scheme where CR users transmit on a larger spectrum band but accept packet acknowledgments on a smaller band. This smaller band is used for exchange of control messages during the handoff period. The main drawback of this solution is the very high number of signaling messages that are needed for efficient operation.

In References 44 and 45, CREAM-MAC (crenabled multichannel) and SCA-MAC (statistical channel allocation) protocols are introduced. These protocols assume the existence of a certain global CCC, agreed by all neighboring nodes. CREAM-MAC uses a four-way dialogue system consisting of RTS, CTS, channel-state-transmitter (CST), and channel-state-receiver (CSR) and allows for further communication details to be confirmed between the sender and the receiver. However, it introduces larger delays that are inappropriate for real-time applications. On the other hand, SCA–MAC uses a two-way dialogue system consisting of channel request to send and channel clear to send and is more suitable for delay-sensitive applications since it introduces smaller delay values while preserving energy consumption.

Opportunistic cognitive-MAC (OC-MAC) [46] and decentralized nonglobal MAC (DNG-MAC) [47] are examples of MAC protocols that do not require a global CCC. In OC-MAC, CR nodes compete with wireless nodes for data channel reservation. DNG-MAC uses time division multiplexing access (TDMA) to allocate the control channel to all CR nodes. The time slots are comprised from a listening period and a transceiving period. The main drawback of this approach is that data channel availability might differ from the time slot duration and hence the DNG-MAC protocol cannot efficiently handle frequent topology changes.

1.6.2.1.2 Time Slotted MAC Protocols

The infrastructure-based time slotted MAC protocols mainly rely on the IEEE 802.22 centralized MAC standard [48], where time is divided using time division multiplexing (TDM) in downstream and TDMA on demand upstream. The use of a superframe is introduced in each time slot to inform CR users about the available channels.

For CR ad hoc topologies, C-MAC (cognitive MAC) protocol is introduced in Reference 49. C-MAC uses synchronized time slots and defines rendezvous channels (RC) and backup channels (BC). RCs will be used for communication and coordination from CR users, while BCs will be determined locally and will be used as an alternative when a PU is detected.

Another recent research topic [48] is the use of channel hopping among the nodes in the CR network for control channel identification. The main idea is that each node follows its own channel hopping sequence and as soon as a sender and a receiver hop to a common channel, the exchange of control packets and negotiation of data communication is started.

1.6.2.2 Routing Protocols for CR Networks

The main challenge for routing in CR networks is the creation and maintenance of the communication path among the secondary (CR) users by deciding the relay nodes and the frequency channels of the links throughout the whole path. These decisions must be held while keeping in mind that changes in the spectrum band might be needed when a PU appears. Therefore, the proposed routing solutions should be closely coupled with spectrum management functionalities.

Depending on the available spectrum awareness, the routing solutions are divided in two main categories: full spectrum knowledge solutions, where spectrum availability between two nodes is known throughout the network (or by a central facility), and local spectrum knowledge, where the nodes locally exchange information about spectrum availability.

1. *Full spectrum knowledge*: The abstract representation of the whole topology as a graph that contains spectrum availability and network dynamicity is needed in order to apply route calculation algorithms to find a path to a destination.

   In Reference 42, a single half-duplex CR transceiver is used in order to create a layered graph whose layers feature the number of available channels. In this graph, there are three kinds of edges. *Access* edges connect a node with all its subnodes. On the other hand, *horizontal* edges connect two subnodes that can tune in the same channel, and therefore coexist in the same layer, and *vertical* edges connect subnodes of the same CR node that exist in different layers to represent the switch from one channel to another.

   In Reference 43, a centralized heuristic algorithm is proposed by expressing the horizontal edges with weights representing the traffic load and interference. The main drawback of the layered graph approach is the large number of signaling messages that need to be deployed for full spectrum knowledge.

   This scalability problem is addressed in Reference 44 by coloring the nodes with edges of a different color when a node can communicate in a particular channel.
2. *Local spectrum knowledge*: The protocols in this category are of distributed nature and use different metrics to assess the router quality. A class of such routing protocols assumes the availability of a CCC accessable by all the CR nodes in the network. CCC will host the route discovery cycle through a route–request–reply (RREQ–RREP) cycle. A routing protocol that closely resembles an ad hoc on-demand distance vector for CR is presented in Reference 50, where the relaying nodes keep track of the accumulated cost during RREQ dissemination in the CCC and find the path with

the minimum cost. The problem with using CCC for RREQ is the difficulty with predicting the availability of the data channels in the network.

Alternatively, a flood of RREQ can take place on all the available channels, allowing the destination to choose, based on its own criteria about the selected route. CAODV-BR, a cognitive adaptation of the AODV routing protocol, is presented in Reference 51, where backup routes are selected along the primary one and are used when one or more primary channels are occupied.

Apart from these two basic categories, the routing protocols are also further divided into other categories, most of them including probabilistic nature implementations. These categories are *minimum power routing*, *minimum delay-based routing*, *maximum throughput-based routing*, *geographic routing*, and *class-based routing*.

1.6.2.3 Transport Layer Protocols for CR Networks

Transport layer protocols have recently attracted research attention. A protocol in this layer should not only deal with concerns such as reliable end-to-end packet delivery, route failures due to node mobility, and link congestion, but also with concerns close to CR nature, such as intermittent spectrum sensing, large-scale bandwidth variation based on channel availability, and the channel switching process.

In Reference 52, a layer-preserving approach is presented. By using two different modules in cooperation, this approach aims to extend the existing TCP/IP protocol suite for CR networks. The *knowledge* module holds information about the application's needs along with the status of the global and local networks. At the same time, the *cognitive* module gathers knowledge about channel availability and generates the control signals for managing the layer operations by use of all the heuristics. This architecture can be used as a base to develop a family of protocols that are based on the requirements of individual applications.

A common problem for all the protocols in the transport layer is the unnecessary increase in the value of the retransmission timeout (RTO). This increase takes place when acknowledgments of received packets do not make their way back in time because the source has entered the sensing cycle, holding the transmissions and receipts of the packets during spectrum sensing. To address this problem, two solutions were proposed. The first solution, in Reference 53, proposes to not take into consideration the acknowledgment packets that were influenced by the spectrum sensing cycle of a node (intermediate or not) in their communication path. To achieve this, information from the knowledge module will be offered.

In Reference 52, another approach that proposed the marking of an acknowledgment packet should take place when its round trip time (RTT) is very different from the lately received one. Spectrum sensing should be denoted as the reason for this delay if the RTT of the packet is larger than the RTT of the last received ACK plus a number that is close to the spectrum duration period.

In Reference 53, a novel approach that tries to address the problems stated above is TP-CRAHN, where explicit feedback from the intermediate nodes and the destination is advised and studied. To achieve this, the classical TCP rate control algorithm running at the source is adapted to closely interact with the physical layer channel information, the link layer functions of spectrum sensing and buffer management, and a novel predictive mobility framework proposed in Reference 53.

1.6.3 Comparative Study of Various Protocols for CR-Based SG Communication

Table 1.1 summarizes the basic information regarding most of the protocols that were covered in the previous subsection.

TABLE 1.1
A Summary of the Discussed Protocols

Protocol	Layer	Type	Description
DCA [42]	MAC	Random-access	Employs multiple transceivers and a dedicated CCC for control signaling
SRAC [43]	MAC	Random-access	Employs a frequency division multiplexing scheme Drawback: large number of signaling packets
CREAM-MAC [44]	MAC	Random-access	Employs a four-way dialogue system Drawback: Not suitable for real-time applications
SCA-MAC [45]	MAC	Random-access	Uses a two-way dialogue system Suitable for delay-sensitive applications
C-MAC [49]	MAC	Time-slotted	Defines rendezvous channels and backup channels
Layered graph model [54]	Network/routing	Full spectrum knowledge	Creates a layered graph whose layers feature the number of available channels
Centralized heuristic algorithm [55]	Network/routing	Full spectrum knowledge	The horizontal edges have weights representing the traffic load and interference Drawback: large number of signaling packets
Ad hoc on-demand distance vector for CR [50]	Network/routing	Local spectrum knowledge	The relaying nodes keep track of the accumulated cost and use it to find the path with the minimum cost
CAODV-BR [51]	Network/routing	Local spectrum knowledge	Backup routes are selected and used when one or more primary channels are occupied
A layer-preserving approach [52]	Transport	–	Uses two different modules: the knowledge module holds information about the application's needs and the cognitive module is responsible for providing information about channel availability
TP-CRAHN [53]	Transport	–	Based on the feedback from the intermediate nodes and the destination

1.7 CONCLUSIONS

CR networks are a novel technology that is considered for use in a modern SG environment, to optimize the overall communication performance of the system. CR gateways continuously scan the spectrum to exploit the license-free band, in order to give the opportunity to SUs to transmit their data when no PU is transmitting. In addition, CR gateways can also deal effectively with the heterogeneity of the various communication technologies that are found on each communication tier on an SG's communication architecture, along with the enormous amount of data that is produced, especially in HANs, where the number of transmitting and receiving devices is increasingly high. The newest communication standards like IEEE's 802.22, designed specifically for CR networks, improve their performance and increase their role in an SG infrastructure.

Finally, the use of WSNs in an SG has been the main reason behind the continuously increased number of SG applications that exist. CR networks can help in optimizing the performance of those applications by providing different bandwidth, delay, reliability, and QoS requirements and, also, address the requirements of green communications. Therefore, the need to create a robust and reliable communication infrastructure, in an SG solution, which will seamlessly integrate CR technologies and efficiently optimize the system's performance, can be successfully met.

This chapter highlights a comprehensive review about SG characteristics and CR-based SG applications. In addition, architectures to support CRNs in SG applications, major challenges, and open issues have been discussed. This chapter attempts to exemplify the multidisciplinary nature of developing CR-based SG communication models, and to outline analogies and comparisons to applicable research communities. This chapter also attempts to illustrate that the traits of a CR, such as awareness and adaptation, are human traits that we as designers are attempting to impose on the SG environment.

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