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Cognitive Wireless Networks

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Chapter 1
Introduction

With the explosive surge of various applications and high data rate services, different wireless networks and communication technologies are proposed and developed in recent years. Considering the limited radio spectrum resources in various wireless networks, the scarcity of radio spectrum is becoming a bottleneck in face of the exponential surge of service demands. At the same time, spectrum measurement results depict that the average spectrum utilization over a period of time at different locations is quite low, leading to a waste of the valuable spectrum resources. Therefore, how to improve the efficiency of spectrum utilization is the first challenge to be solved for different wireless networks deployment. Besides, the heterogeneity and coexistence of different wireless networks will cause the low radio resource usage and mutual interference among heterogeneous networks due to the lack of cooperative control and information sharing among various networks in practice. Therefore, another big challenge is how to realize the seamless and efficient convergence of different heterogeneous networks to improve the end-to-end performance of users in wireless networks.

To solve these challenges, the heterogeneous wireless networks should be much more intelligent with adaptively reconfigurable parameters and working modes, in order to be aware of the changing wireless network environment. Therefore, the intelligent environment awareness and radio resource utilization technologies should be applied to obtain and analyze the network information learnt from the knowledge representing the dynamics and changing characteristics of radio environment, network traffic and various user demands. Thus, a cognitive wireless network (CWN) is proposed as a novel wireless network enabled by cognitive information awareness, analysis and management technologies, which can improve the efficiency of spectrum utilization and heterogeneous networks convergence.

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1.1 Challenges in Cognitive Wireless Networks

This section introduces three critical challenges faced by wireless communication in detail, which can promote the development of cognitive wireless networks.

1.1.1 Spectrum Scarcity and Spectrum Waste

As one of the most precious non-renewable resources, spectrum resources are licensed and managed by the government, which are facing a big challenge of spectrum scarcity for ubiquitous wireless applications. The feature of spectrum management policy is that a certain part of the spectrum is allocated to dedicated service, and meanwhile, other services are prohibited to utilize this part of spectrum. That is to say, the spectrum is assigned to license holders for a long term basis using a fixed spectrum assignment policy [5]. Figure 1.1 shows the situation of frequency allocation in the United States (U.S.). In Fig. 1.1, the spectrum from 3 KHz to 300 GHz has been allocated completely, which means that there is a small part of the spectrum which can be licensed to new wireless applications [2].

In the U.S., between 2004 and 2005, the Federal Communication Commission (FCC) and Shared Spectrum Company (SSC) had made a survey [3] about the spectrum utilization of 30 MHz∼3 GHz in Chicago and New York City. As shown in Fig. 1.2, the survey illustrated that in 2005 long-term spectrum utilization rate was only 5.2 % in Chicago and 13.1 % in New York. Some spectrum bands were

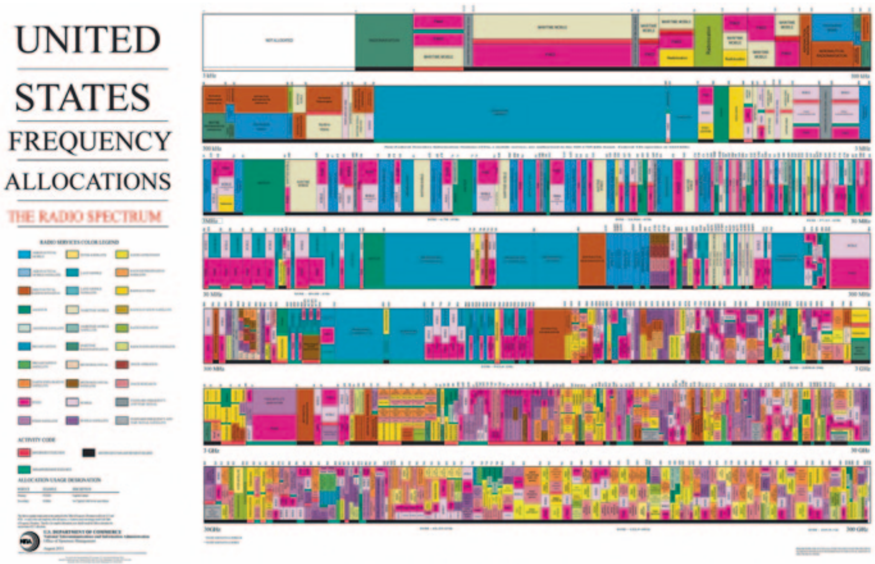

Fig. 1.1 Frequency allocations in the United States [6]

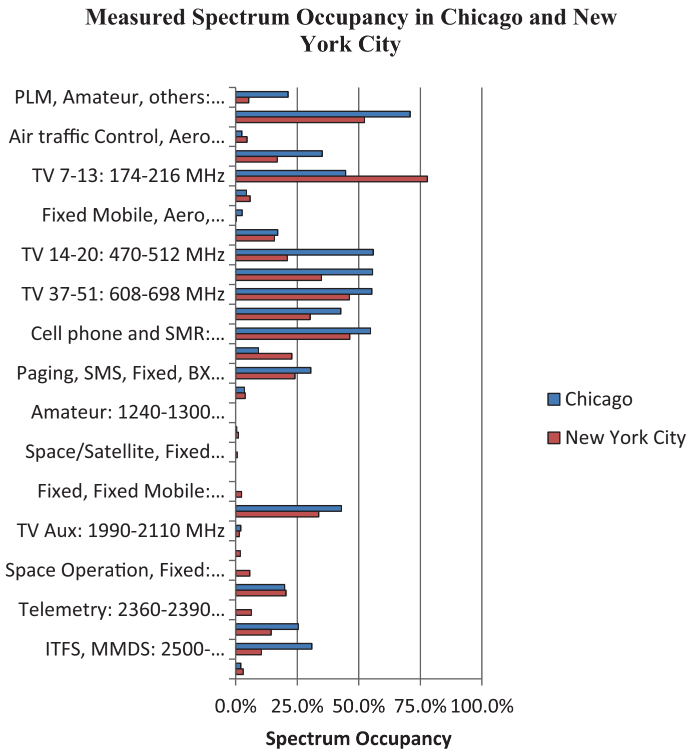

Fig. 1.2 Average spectrum occupancy by band—Chicago vs. New York [3]

overloaded while others were in the state of a low utilization, such as the spectrum band that assigned to radio astronomy.

In Europe, the radio spectrum utilization measurements have been carried out in three different locations, namely, in the suburb of the city of Brno, in the Czech Republic and in the suburb and the city of Paris in France, respectively [7]. The result of the measurement, shown in Fig. 1.3, analyzed the radio spectrum from 400 MHz to 3 GHz.

In China, the measurement results unveiled by [8] are shown in Fig. 1.4, which indicate a low spectrum utilization in Beijing over one month. The results in Beijing are similar to the results released by FCC.

The measurement results above show that some spectrum resources are heavily used by licensed systems in a specific location at a particular time. However, there are many spectrum bands which are only partly occupied or largely unoccupied. Besides, new services and applications need new spectrum resources which is an urgent problem and the bottleneck for the future wireless network. Therefore, how to improve the vacant spectrum utilization and solve the spectrum scarcity problem are key challenges to be addressed. Therefore, new technologies should be utilized in order to detect the vacant spectrum resources efficiently in different locations and

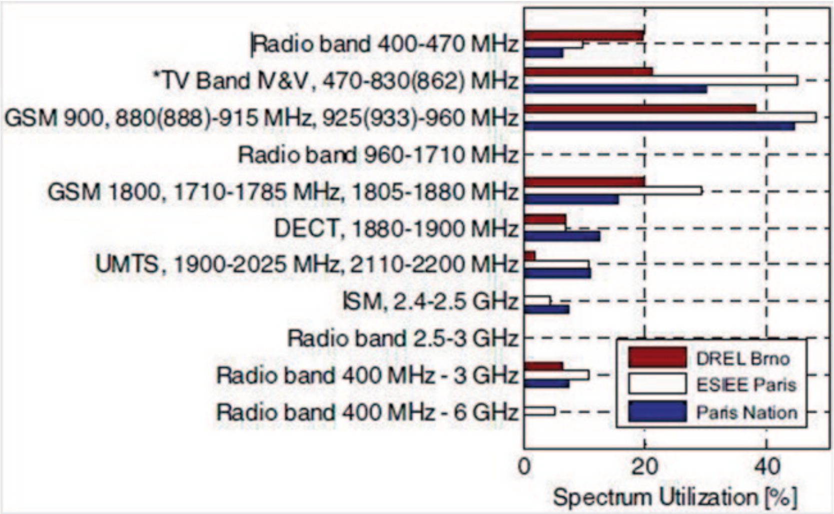

Fig. 1.3 Comparative summary on regional spectrum utilization [7]

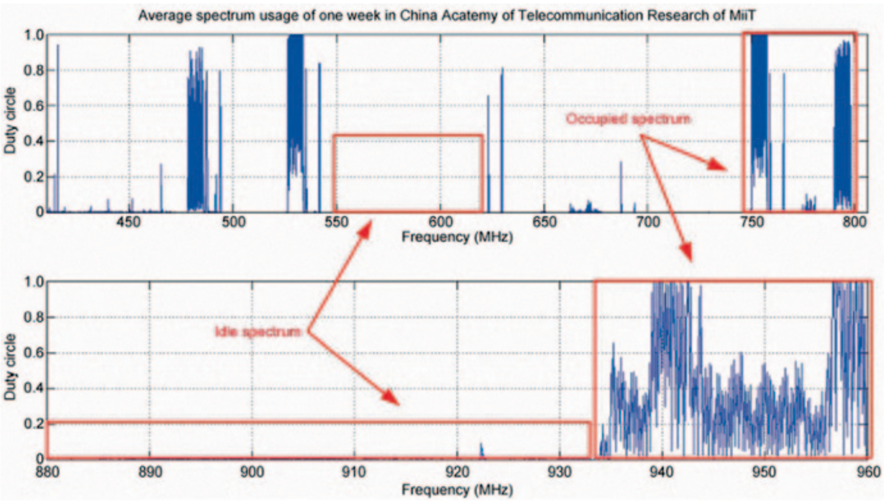

Fig. 1.4 Measurement on spectrum utilization in Beijing [8]

dynamically utilize radio resources. Cognitive wireless network is a candidate solution with intelligent spectrum sensing and dynamic resource management abilities, which can solve the vacant spectrum utilization and spectrum scarcity problems.

1.1.2 Heterogeneous Networks Isolation Problem

Historically, different operators are granted different licensed spectrums and operate different wireless networks with different standards, which leads to the co-existence of multiple radio access technologies (RATs) that may affect each other or sometimes induce excessive interference. In China, different RATs are utilized to provide various services with different quality of services to users, such as GSM, TD-SCDMA, WCDMA, CDMA 2000, WLAN, TD-LTE and so on. Since each network operator plans its own network's coverage independently, coverage holes and excessive coverage problems will exist and are hard to be solved among neighboring cells. Thus, the coverage and interference problems are even more serious in the densely-deployed small cell networks in hot spots and indoor scenarios. Due to this fact, different wireless networks using adjacent spectrum resources will interfere with each other, which seriously harm the overall spectrum usage efficiency of heterogeneous networks and the service experience of end users. Because different heterogeneous networks are lack of control information sharing algorithms and technologies, the cooperation and coordination among heterogeneous networks are difficult to realize and will result in the coverage and interference problems among different networks as big challenges unsolved.

To solve these problems, the cognitive wireless network is proposed to improve the coordination among different heterogeneous networks and promote the convergence of heterogeneous networks. As an efficient control information interworking technology, the cognition information flow technology is also designed to improve the interaction and information exchange among heterogeneous networks, which plays an important role to support the convergence of heterogeneous networks.

1.1.3 Uneven Information Density Distribution and Capacity Demand Surge

Service demands are distributed unevenly at different locations (such as the urban city, suburban area, hotspot, etc.) at different time (fluctuation from day to night), due to the population density distribution pattern and commuters from home to work. Base stations are also deployed with different densities in a large area. Furthermore, deployments of different heterogeneous networks are usually overlapped with each other in hot spot area. And wireless networks with different coverage types, such as macro, pico and femto cells, may be deployed hierarchically to fulfill the capacity demand.

Existing research works mostly focus on the interference mitigation and throughput enhancement techniques from a technical perspective. But how to theoretically define the information density from spatial and temporal perspectives has not been considered yet. Therefore, recent research works on cognitive information metrics, and temporal and geographic distribution entropy theories are proposed and described in this book in order to quantify the unevenly distributed information density in heterogeneous networks.

Furthermore, according to the forecast unveiled by Cisco, mobile data traffic is exploding and doubling each year with the popularization of intelligent terminal and data business growth. Therefore, the future wireless network is preparing for an astounding 1000 times increase of capacity in the next 10 years. How to improve the capacity is a critical issue for wireless researchers and engineers around the world. Obviously, the solution to this formidable challenge is a combination of increasing the efficiency of existing assets, employing more spectrum resources in the form of small cells, as well as adopting radically different ways of acquiring, deploying, operating and managing these resources. However, one of the key challenges is how to identify the unevenly distributed information density in the radio environment. Moreover, another challenge is how to quantify the information density effectively in an efficiently way. Therefore, enabled by cognitive information theory and metrics to solve the unevenly distributed information density, cognitive wireless network will be a good solution to this challenge.

1.2 Overview of Cognitive Wireless Networks

To improve the efficiency of spectrum utilization, cognitive radio (CR) was first proposed by Mitola in 1999 [4], which allows the secondary users (SUs) to opportunistically access the spectrum of the primary users (PUs) without causing any interference. As shown in Fig. 1.5, the spectrum can be dynamically and flexibly shared between PUs and SUs in an opportunistic manner by utilizing the spectrum holes in time and frequency domains, so that the spectrum utilization can be improved.

Recently, driven by the technology innovations and application requirements, wireless network technologies are developed rapidly with high data rate and wide system bandwidth. As different radio access technologies are deployed extensively in metropolises and rural areas, the heterogeneous network coexistence is a big challenge, which leads to interconnection of information, as shown in Fig. 1.6. Therefore, how to realize heterogeneous network convergence and how to improve spectrum utilization are critical issues in future wireless network.

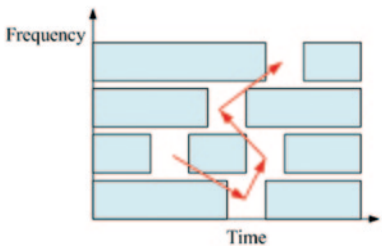

Fig. 1.5 Typical scenario for use of a CR [1]

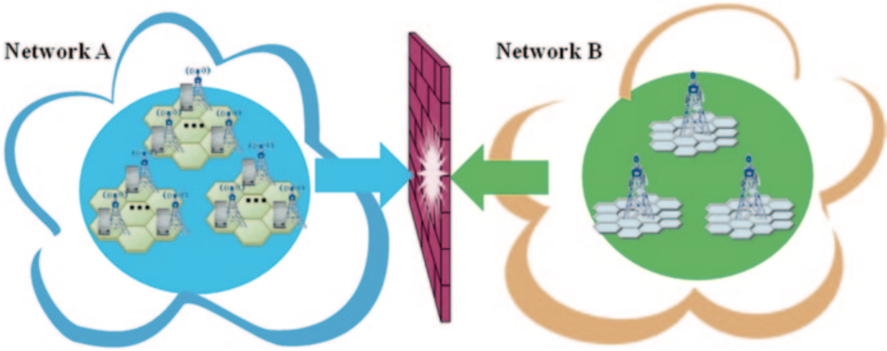

Fig. 1.6 Heterogeneous network

Considering the challenges of network heterogeneity and spectrum inefficient usage, the future wireless networks should have the intelligent network information awareness, flexible spectrum management and dynamic network reconfiguration abilities. This motivates the emergence of Cognitive Wireless Network (CWN). It is defined as a wireless network employing technology to obtain knowledge of its operational and geographical environment, established policies and its internal state; to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve end-to-end network objectives; and to learn from the results obtained.

Therefore, the purpose of this book is to provide a comprehensive introduction to the fundamental theories, disseminate cutting-edge research results, highlight research challenges and open issues, and describe the implementation scheme of the TD-LTE based CWN. The main parts of this book include the theoretical and functional architecture of CWN, cognitive abilities, autonomous decision making techniques and testbed implementation.

1.3 Outline of This Brief

In face of the dynamically changing wireless environment and exponential surge of various service demands, existing research works have not considered about the fundamental theories on how to represent and quantify the dynamic changing characteristics of multi-domains wireless networks with cognitive techniques. In order to enhance the intelligent environment awareness ability in heterogeneous networks, the cognitive information flow theory has been proposed first to identify the relationship between the uncertainty of the network environments and the mutual information awareness removed via the cognitive technology. Furthermore, existing wireless network architecture need to be revolutionarily changed to support the cooperation among different heterogeneous networks enabled by the cognitive information flow and resource flow technologies. Moreover, both the key

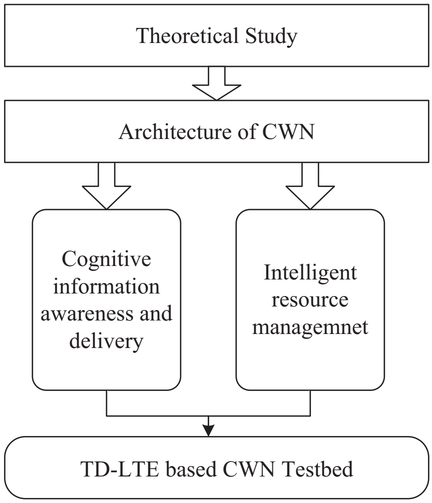

Fig. 1.7 Structure of the book

technologies of cognitive information awareness and intelligent resource management are designed to improve the efficiency of spectrum utilization and heterogeneous network convergence. This book consists of five main parts, which addresses a variety of fundamental theory problems and key technologies in CWN. The structure of this book is shown in Fig. 1.7, of which the overall skeleton is from theory to implementation.

Chapter 1 introduces the origin of CWN. Many studies show that while some spectrum bands are extensively used, and most of other bands are largely unoccupied. These potential spectrum holes result in the under-utilization of available bands. Hence, a novel technology to improve the spectrum utilization is proposed. Cognitive radio using dynamic spectrum access technology is considered as an efficient technology to solve this challenge. However, extending to the network perspective, the existing cognitive radio network lacks consideration of the heterogeneous network and the end-to-end performance. So, a novel architecture of CWN is proposed.

Chapter 2 introduces the cognitive information concept to characterize the information sequence in the radio environment awareness results, which applies several novel information theoretic concepts, namely, cognitive information, geographic entropy and temporal entropy to reveal the features of cognitive information.

Chapter 3 focuses on the architecture of CWN. First, some classical cognitive network architecture will be discussed, such as cognitive cycle of Mitola and basic cognitive cycle of Haykin, and then functional architecture proposed by IEEE 1900.4 work group will be illustrated. Second, the theoretical architecture and functional architecture are proposed, through analyzing the merits and drawbacks of previous architectures. Furthermore, in order to improve the network capacity of the proposed architecture, a heterogeneous network architecture based on the hierarchical deployment is proposed, which can effectively improve the resource utilization,