Chapter 2
Cognitive Radio Networking Preliminaries

2.1 Cognitive Radio Technology

A cognitive radio is the key technology that allows a cognitive wireless terminal to dynamically access the available spectral opportunities. A cognitive radio was defined by Mitola in his seminal work as "a radio or system that senses, and is aware of, its operational environment and can dynamically and autonomously adjust its radio operating parameters accordingly" [1, 2]. This definition was generalized by the FCC to be "a radio or system that sense its electromagnetic environment and can dynamically and autonomously adjust its radio operating parameters to modify system operation, such as maximize throughput, mitigate interference, facilitate interoperability, access secondary markets" [3]. From these definitions, a cognitive radio has two key features that distinguish it from a traditional radio: the cognition capability and the reconfigurability. Figure 2.1 illustrates how these unique features of a cognitive radio conceptually interact with the radio environment. This illustration is referred to as the cognition cycle that is continually run by the cognitive radio to observe spectral opportunities, create plans to adapt itself, decide, and act to explore the best opportunities.

2.1.1 Cognition Capability of a Cognitive Radio

The cognition capability of a cognitive radio is defined as the ability of the cognitive radio transceiver to sense the surrounding radio environment, analyze the captured information and accordingly decide the best course of action(s) in terms of which spectrum band(s) to be used and the best transmission strategy to be adopted. Such a cognition capability allows a cognitive radio to continually observe the dynamically changing surrounding radio environment in order to interactively come up with the appropriate transmission plans to be used. The three main components of the cognitive radio cognition cycle can be briefly explained as follows.

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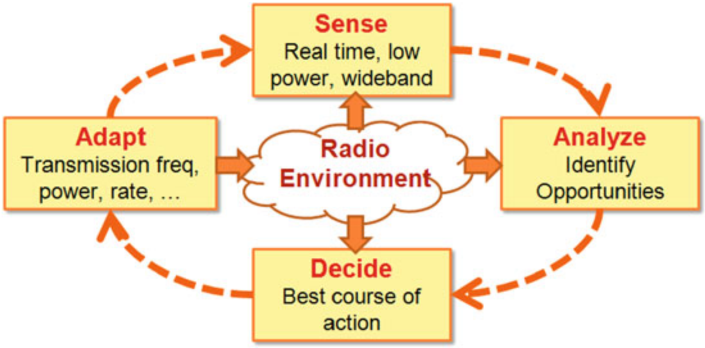


Fig. 2.1 Functional architecture of a cognitive radio

2.1.1.1 Spectrum Sensing

Spectrum sensing refers to the ability of a cognitive radio to measure the electromagnetic activities due to the ongoing radio transmissions over different spectrum bands and to capture the parameters related to such bands (e.g., cumulative power levels, user activities, etc.). Spectrum sensing is one of the most critical functions of a cognitive radio as it provides the awareness of the spectrum usage in the surrounding environment [4]. A cognitive radio must make real-time decisions about which bands to sense, when, and for how long. The sensed spectrum information must be sufficient enough for the cognitive radio to reach accurate conclusions regarding the radio environment. Furthermore, spectrum sensing must be fast in order to track the temporal variations of the radio environment. Such requirements of spectrum sensing puts stringent requirements on the hardware implementation of cognitive radios in terms of the sensing bandwidth, the processing power, the radio frequency (RF) circuitry, etc. Existing spectrum sensing techniques depend on detecting the activities of the primary transmitters. Such schemes are generally classified to matched filter detection, energy detection, feature detection, and interference temperature measurement.

2.1.1.2 Spectrum Analysis

Spectrum analysis is to infer the existence of spectral opportunities in the surrounding radio environment based on the sensed radio environment parameters. A spectral opportunity is conventionally defined as "a band of frequencies that are not being used by the primary user of that band at a particular time in a particular geographic area" [5]. However, such a definition is not general enough as it covers only three dimension of the spectrum space: frequency, time, and space. Other dimensions of a given spectrum can be exploited. For example, the coding dimension which utilizes spread spectrum coding techniques to create spectral opportunities over a given spectrum band currently utilized by its licensed users. Similarly, the angle dimension creates spectral opportunities through the use of beamforming to allow the cognitive radio users to simultaneously transmit over a currently utilized band. Furthermore, the recent advancements in radio transmission techniques, such as the use of Multiple-Input Multiple-Output (MIMO) at the physical layer, present new dimensions in the definition of a spectral opportunity. For instance, stream control and antenna selection [6] can be used to allow cognitive radio users to simultaneously transmit with the primary licensed users without degrading the performance of such legitimate users. Due to the existence of different dimensions of a spectrum, we use the following generalized definition a spectral opportunity in the remainder of the book: A spectral opportunity is "a theoretical hyperspace occupied by radio signals, which has dimensions of location, angle of arrival, frequency, time, and possible others" [4, 7, 8].

2.1.1.3 Spectrum Access Decisions

The last step of the cognition cycle of a cognitive radio is to decide the set of transmission actions to be taken based on the outcome of the spectrum sensing and analysis procedures. More specifically, a cognitive radio utilizes the information gathered regarding the spectrum bands identified as available spectral opportunities to define the radio transceiver parameters for the upcoming transmission(s) over such frequency bands. The set of transceiver parameters to be decided depends on the underlying transceiver architecture. Examples of the action set can include which spectrum is more favorable for an upcoming transmission, the time instant a transmission over a certain band should start, the maximum transmission power, the modulation rate, the spread spectrum hopping scheme, the angle of arrival for directional transmissions, and the number and identity of the antennas to be used in MIMO systems, etc. Based on the sensed spectrum information and the transceiver architecture, a cognitive radio defines the values of the parameters to be configured for an upcoming transmission.

2.1.2 Reconfigurability of a Cognitive Radio

The second key feature that distinguishes a cognitive radio from a traditional one, and completes the cognition cycle depicted in Fig. 2.1, is its ability to re-tune its transceiver parameters on the fly based on its assessment of the surrounding radio environment. While today's radios have considerable flexibility in terms of their ability to reconfigure some transmission parameters such as the transmission rate and power, they are typically designed to operate over certain frequency band(s) according to a certain communication protocol. A cognitive radio transceiver should be more flexible than just this in order to be able to exploit emerging spectral opportunities over a wider spectrum range. For instance, a cognitive radio must be able to configure the transmission bandwidth to adapt to spectral opportunities of different sizes. Furthermore, a cognitive radio cannot be constrained to a certain communication protocol. Instead, a cognitive radio must determine the appropriate communication protocol to be used over different spectral opportunities based its recognition of the radio environment.

In his seminal work, Mitola devised the software-defined radio as the ideal implementation environment of radios with seamless configuration capabilities (since parameter configuration is performed using software commands). Thus, cognitive radios were originally referred to as software radios with extended self-awareness capability [2]. However, software-defined radios cannot fulfill the data rate requirements of most of today's wireless services due to the software/hardware interface bottleneck [9, 10]. Thus motivated, a significant research effort has been—and is currently being—made towards realizing a fast multi-gigahertz cognitive radio transceiver hardware with the seamless configuration flexibility of software-defined radios at low cost.

2.1.2.1 Spectrum Mobility

The reconfigurability of a cognitive radio transceiver reflects the spectrum mobility function introduced by Mitola in his definition of the cognitive radio [1, 2]. Spectrum mobility refers to the process in which a cognitive radio terminal changes its frequency of operation. In order to maintain seamless wireless connectivity, a cognitive radio terminal should be able to switch to a new frequency band upon either the appearance of the primary licensed user(s) of the current band or the deterioration of the channel quality of the currently used channel. In other words, spectrum mobility is the cognitive radio functionality that actually allows the cognitive radio to dynamically explore the available spectral opportunities. Thus, spectrum mobility is associated with a handoff mechanism that guarantees the transition to the new frequency band without breaking (or significantly degrading the quality of) the communication between communicating cognitive radio terminals. While the cognition functions of the cognitive radio mainly affect the lower layers of the CRN, namely the physical and medium access layers, spectrum mobility and handoff also affect higher layers. Hence, spectrum mobility schemes should ensure smooth and fast frequency transition and protocol/paramter adjustment in order to minimize the latency that could harm the performance of higher layer protocols. Even though mobility-based handoff mechanisms have been investigated in the context of cellular networks and can be used to lay the foundation for spectrum mobility, CRN spectrum mobility poses several new challenges. However, spectrum mobility is beyond the scope of this book.

2.2 Cognitive Radio Network Architectures

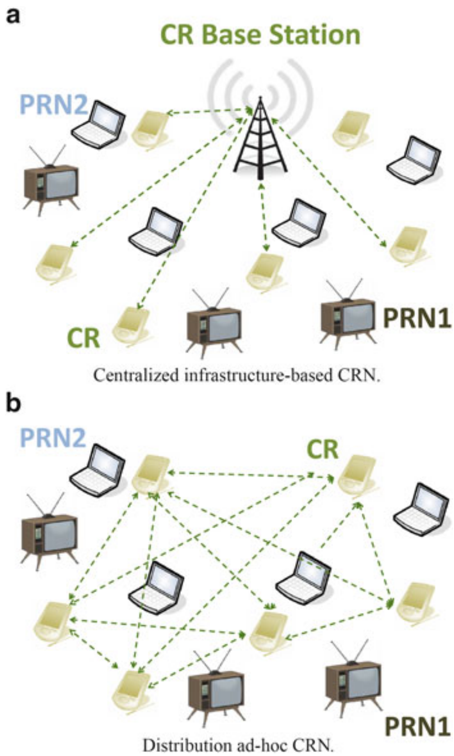
A typical CRN environment consists of a number of Primary Radio Networks (PRNs) that coexist within the same geographical area of a single CRN (also referred to as the secondary network). A primary network is an existing network that is licensed to operate in a certain spectrum band. Hence, a primary network is also referred to as a licensed network. Primary networks can either be based on a centralized infrastructure or distributed ad-hoc in nature. The users of a primary network can only access the spectrum licensed to this particular network. Primary users have priority with respect to spectrum access and operate as they are the sole users of their licensed spectrum. Hence, primary users do not provide any type of cooperation with the secondary network. PRNs are non-intrusive and the transmissions of the primary users should not be affected by the secondary users. Therefore, the primary networks define upper bounds on the CRN activities in their licensed bands, typically in terms of maximum power levels, to guarantee the promised performance level to their legitimate users.

On the other hand, the CRN is not licensed to operate in a predefined band. Spectrum access for the CRN is achieved in an opportunistic manner that allows the secondary users to opportunistically access the entire spectrum available to *all* of the geographically-collocated PRNs. Recall that the cognitive users can also exploit the unlicensed spectrum. This is referred to as spectrum heterogeneity of CRNs [11, 12]. When operating in a licensed band, the CRN transmissions must adhere to the constraints imposed by its primary owner. A CRN can either be centralized infrastructure-based network or a distributed ad-hoc network as shown in Fig. 2.2.

2.2.1 Centralized Cognitive Radio Networks

Centralized CRNs are infrastructure-based networks in which cognitive radio base stations control and coordinate the transmission activities of the secondary cognitive radio users as shown in Fig. 2.2a. The cognitive radio base stations control the secondary transmissions over both the licensed and unlicensed bands by collecting all the spectrum-related information from the cognitive radio users. Based on the collected information, the base stations take global spectrum access decisions for all nodes. An example centralized infrastructure-based CRN is the IEEE 802.22 network model. The IEEE 802.22 is the first world-wide standard for CRNs [13]. The IEEE 802.22 standard defines the specifications of a point-to-multipoint communication scheme over the unused television (TV) bands in which a base station manages cognitive radio users within 33 km radius using a centralized spectrum database. Other examples include the European Dynamic Radio for IP services in Vehicular Environment (DRiVE) [14] and Spectrum Efficient Uni- and Multi-cast Services Over Dynamic Radio Network in Vehicular Environments

Fig. 2.2 Cognitive Radio Network architectures



(OverDRiVE) [15] projects. These projects have a centralized entity that coordinates the dynamic utilization of the temporal and spatial spectral opportunities. Centralized infrastructure-based CRNs are beyond the scope of this book.

2.2.2 Distributed Cognitive Radio Networks

Alternatively, CRNs can also have the cognitive nodes communicating with each other via ad-hoc point-to-point connections over either the licensed or the unlicensed bands as shown in Fig. 2.2b. While alleviating the infrastructure cost, such infrastructureless CRNs have increased networking complexity. In the absence of a controlling centralized entity, cognitive radio nodes in a distributed CRN jointly coordinate their spectrum access decisions to share the available spectral opportunities. Thus, global mechanisms such as network-wide synchronization might be needed for spectrum access coordination. In addition, distributed cooperative detection and communication techniques are used to improve the overall network performance. Example distributed CRNs include, the peer-to-peer mode of DARPA's neXt Generation (XG) dynamic access network [16, 17], DARPA's Wireless Network after Next (WNaN) military testbed [18], the Nautilus distributed scalable and efficient coordination project for open spectrum ad-hoc network [19, 20], and the cognitive radio approach for usage of virtual unlicensed bands (CORVUS) [21]. This book targets Opportunistic Spectrum Access in distributed CRNs. Our goal is to alleviate the network-wide coordination overhead by omitting inter-flow communications in such a network model.

2.3 Guidelines of Cognitive Radio Networking

The coexistence of the primary networks within the CRN environment distinguishes CRNs from other traditional networks. The CRN transmissions should not disturb the transmissions within the primary networks. This constraint does not exist in legacy wireless networks. Therefore, Medium Access Control (MAC) protocols developed for such networks (more specifically, those developed for multi-channel and/or multi-radio networks) are not well suited to the unique characteristics of CRNs. The existence of the primary users makes the Opportunistic Spectrum Access problem fundamentally different from the medium access problem in multi-channel networks since the latter problem is simply a resource sharing problem for users within a given network. In order to realize an Opportunistic Spectrum Access network, the following design guidelines are mandated [11, 12].

- An Opportunistic Spectrum Access network should be transparent to the users of the primary networks. Hence, no coordination is required between the primary and the secondary users.
- An Opportunistic Spectrum Access network should provide guarantees to the performance of the primary licensed networks.
- Cognitive radio nodes should make efficient and accurate spectrum sensing and spectrum access decisions while exploring either the unutilized or the utilized bands. These decisions should account for the dynamics of the time-varying activities of the primary users.
- The CRN should define a coordination mechanism (either explicit or implicit) to maximize the spectrum utilization efficiency and allow cognitive radio users to fairly share the available spectral opportunities.

2.4 Cognitive Radio Network Applications

Cognitive Radio Networking and Opportunistic Spectrum Access can be used in different applications. In what follows, we briefly discuss those applications that can benefit from the research conducted in this book.

2.4.1 Cognitive Mesh Networks

Multi-hop wireless mesh networks have recently gained significant popularity as a cost-effective solution for last-mile Internet access. Traditional wireless mesh network are challenged by the scarcity of the wireless bandwidth needed to meet the high-speed requirements of existing wireless applications. Opportunistic Spectrum Access can be used to alleviate the bandwidth scarcity problem of mesh networks by allowing the mesh nodes to dynamically explore any available spectral opportunities. Such cognitive mesh networks are meant be used to provide broadband access to rural, tribal, and other under-resourced regions [22].

2.4.2 Public Safety Networks

Public safety networks are another type of networks that can exploit Cognitive Radio Networking. Public safety networks are used for communications among police officers and fire and paramedic personnel. Such networks are also challenged by the limited amount of allocated spectrum. Even with the recent extensions of the allocated public safety spectrum bands, the public safety personnel do not have the technology to dynamically operate across the different spectrum segments. Recall that public safety licensees have a wide variety of bands available (VHF-Low, VHF-Hi, 220 MHz, UHF below 800, UHF-800, etc.). The cognitive radio technology can offer public safety networks more bandwidth through Opportunistic Spectrum Access. Furthermore, a public safety CRN can provide a substantial communication improvement by allowing the interpretability across different public safety services while smartly adapting to the high peak-to-average nature of the traffic carried out by such networks [23].

2.4.3 Disaster Relief and Emergency Networks

Natural disasters such as hurricanes, earthquakes, wild fires, or other unpredictable phenomena usually cause the communications infrastructure to collapse. For example, some base stations of cellular networks can fall, the connectivity between sensor nodes and the sink node in static wireless sensor networks can be lost, existing Wireless Local Area Networks (WLANs) can be damaged, etc. This results in a set of partially or fully damaged coexistent networks that were previously deployed and then became disconnected. Meanwhile, there is an urgent need for a means of communications to help the rescue teams to facilitate organized help, rehabilitation efforts, and to locate the disaster survivors. CRNs can be used for such emergency networks (e.g., see [24] and references therein). The use of Opportunistic Spectrum Access in disaster relief networks can provide a significant amount of bandwidth that can handle the expected huge amount of voice, video, and other critical and time-sensitive traffic. It is worth mentioning that WLANs were used in the relief of the Haiti earthquake. However, the communication over such a network was unreliable and suffered significant delays [25].

2.4.4 Battlefield Military Networks

Unfortunately, the recent advances in wireless technologies made the job of communication jamming and/or hacking much easier. Consequently, achieving reliable and secure communications in modern battlefields has become a more challenging task. Recall that a battlefield communication network provides the only means of communications between soldiers, armed vehicles, and other units in the battlefield amongst themselves as well as with the headquarters. This implies that such networks do not only require significant amount of bandwidth, but also mandate secure and reliable communications to carry vital information. The cognitive radio is the key enabling technology for realizing such densely deployed networks which use distributed Opportunistic Spectrum Access strategies to fulfill the bandwidth and reliability needs. Note that, the dynamic nature of OSA makes the ability to track and jam a communication more difficult. Thus motivated, DARPA initiated the Wireless Network after Next (WNaN) program aiming at creating a flexible architecture for military communications [18]. The main goal of the WNaN program is to develop a low-cost handheld cognitive radio terminal that is capable of selecting its own frequencies and forming a dense network within a large battlefield area.

2.4.5 Leased Networks

All of the aforementioned CRN applications have the secondary users exploiting the resources of the primary networks without being beneficial to the primary networks in any way. However, a primary network can benefit from leasing a fraction of its licensed spectrum to secondary operators adopting cognitive radio technology to opportunistically access the spectrum. The entrance of the secondary operator to the market of the incumbent primary network can increase the revenue of the primary licensed operator [26].

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