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Cognitive Radios: An Insight

Swati Chawla[1], Divya Sharma[2]

[1,2]ITM University, Sector, 23A, Gurgaon, India

Abstract: **Cognitive radio is an exciting emerging technology that has the potential of dealing with the stringent requirement and scarcity of the radio spectrum. Such revolutionary and transforming technology represents a paradigm shift in the design of wireless systems, as it will allow the agile and efficient utilization of the radio spectrum by offering distributed terminals or radio cells the ability of radio sensing, self-adaptation, and dynamic spectrum sharing. Cooperative communications and networking is another new communication technology paradigm that allows distributed terminals in a wireless network to collaborate through some distributed transmission or signal processing so as to realize a new form of space diversity to combat the detrimental effects of fading channels. In this paper, we consider the application of these technologies to spectrum sensing and spectrum sharing. One of the most important challenges for cognitive radio systems is to identify the presence of primary (licensed) users over a wide range of spectrum at a particular time and specific geographic location. We consider the use of cooperative spectrum sensing in cognitive radio systems to enhance the reliability of detecting primary users. We shall describe spectrum sensing for cognitive radios and propose robust cooperative spectrum sensing techniques for a practical framework employing cognitive radios. We also investigate cooperative communications for spectrum sharing in a cognitive wireless relay network. To exploit the maximum spectrum opportunities, we present a cognitive space-time-frequency coding technique that can opportunistically adjust its coding structure by adapting itself to the dynamic spectrum environment.**

Keywords: **Cognitive radio, cooperative communications, spectrum sensing, spectrum sharing, radio spectrum utilization, frequency allocation, distributed terminal, space time codes, diversity reception, signal processing.**

1. INTRODUCTION

1.1. Background

THE electromagnetic *radio spectrum* is a natural resource, the use of which by transmitters and receivers is licensed by governments. In November 2002, the Federal Communications Commission (FCC) published a report prepared by the Spectrum-Policy Task Force, aimed at improving the way inwhich this precious resource is managed in the United States [1]. The task force was made up of a team of high-level, multidisciplinary professional FCC staff—economists, engineers, and attorneys—from across the commission's bureaus and offices. Among the task force major findings and recommendations, the second finding on page 3 of the report is rather revealing in the context of spectrum utilization:

"In many bands, spectrum access is a more significant problem than physical scarcity of spectrum, in large part due to legacy command-and-control regulation that limits the ability of potential spectrum users to obtain such access." Indeed, if we were to scan portions of the radio spectrum including the revenue-rich urban areas, wewould find that:

1) some frequency bands in the spectrum are largely unoccupied most of the time;

2) some other frequency bands are only partially occupied;

3) the remaining frequency bands are heavily used.

The underutilization of the electromagnetic spectrum leads us to think in terms of *spectrum holes*, for which we offer the following definition [2]:

A spectrum hole is a band of frequencies assigned to a primary user, but, at a particular time and specific geographic location, the band is not being utilized by that user.

Spectrum utilization can be improved significantly by making it possible for a secondary user (who is not being serviced) to access a spectrum hole unoccupied by the primary user at the right location and the time in question. *Cognitive radio* [5], [6], inclusive of software-defined radio, has been proposed as the means to promote the efficient use of the spectrum by exploiting the existence of spectrum holes.

But, first and foremost, what do we mean by cognitive radio? Before responding to this question, it is in order that we address the meaning of the related term "cognition." According to the Encyclopedia of Computer Science [7], we have a three-point computational view of cognition.

1) *Mental states and processes* intervene between input stimuli and output responses.

2) The mental states and processes are described by *algorithms*.
3) The mental states and processes lend themselves to *scientific investigations*.

Moreover, we may infer from Pfeifer and Scheier that the interdisciplinary study of cognition is concerned with exploring general principles of *intelligence* through a synthetic methodology termed*learning by understanding*. Putting these ideas together and bearing in mind that cognitive radio is aimed at improved utilization of the radio spectrum, we offer the following definition for cognitive radio.

Cognitive radio is an intelligent wireless communication system that is aware of its surrounding environment (i.e., outsideworld), and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters (e.g., transmit-power, carrier-frequency, and modulation strategy) in real-time, with two primary objectives in mind:

- highly reliable communications whenever and wherever needed;
- efficient utilization of the radio spectrum.

Six key words stand out in this definition: awareness, intelligence, learning, adaptivity, reliability, and efficiency.

Implementation of this far-reaching combination of capabilities is indeed feasible today, thanks to the spectacular advances in digital signal processing, networking, machine learning, computer software, and computer hardware.

In addition to the cognitive capabilities just mentioned, a cognitive radio is also endowed with *reconfigurability*.2 This latter capability is provided by a platform known as *software-definedradio*, upon which a cognitive radio is built. Software-defined radio (SDR) is a practical reality today, thanks to the convergence of two key technologies: digital radio, and computer software

1.2. Cognitive Tasks: An Overview

For reconfigurability, a cognitive radio looks naturally to software-defined radio to perform this task. For other tasks of a cognitive kind, the cognitive radio looks to signal-processing and machine-learning procedures for their implementation. The cognitive process starts with the passive *sensing of RF stimuli* and culminates with *action*.

In this paper, we focus on three *on-line* cognitive tasks3:

1) Radio-scene analysis, which encompasses the following:
- estimation of interference temperature of the radioenvironment;
- detection of spectrum holes.

2) Channel identification, which encompasses the following:
- estimation of channel-state information (CSI);
- prediction of channel capacity for use by the transmitter

3) Transmit-power control and dynamic spectrum management.

Tasks 1) and 2) are carried out in the receiver, and task 3) iscarried out in the transmitter. Through interaction with the RF environment, these three tasks form a cognitive cycle, 4 which is pictured in its most basic form in Fig. 1.

From this brief discussion, it is apparent that the cognitive module in the transmitter must work in a harmonious manner with the cognitive modules in the receiver. In order to maintain this harmony between the cognitive radio's transmitter and receiver at all times, we need a *feedback channel* connecting the receiver to the transmitter. Through the feedback channel, the receiver is enabled to convey information on the performance of the forward link to the transmitter. The cognitive radio is, therefore, by necessity, an example of a *feedback communicationsystem*.

One other comment is in order. A broadly defined cognitive radio technology accommodates a *scale of differing degrees ofcognition*. At one end of the scale, the user may simply pick a spectrum hole and build its cognitive cycle around that hole. At the other end of the scale, the user may employ multiple implementation technologies to build its cognitive cycle around a wideband spectrum hole or set of narrowband spectrum holes to provide the best expected performance in terms of spectrum management and transmit-power control, and do so in the most highly secure manner possible.

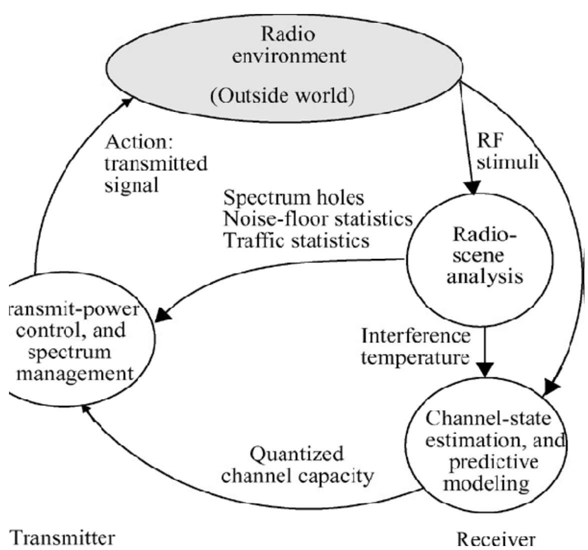

Fig. 1. Basic cognitive cycle. (The figure focuses on three fundamental cognitive tasks.)

1.3. Historical Notes

Unlike conventional radio, the history of which goes back to the pioneering work of Guglielmo Marconi in December 1901, the development of cognitive radio is still at a conceptual stage. Nevertheless, as we look to the future, we see that cognitive radio has the potential for making a significant difference to the way in which the radio spectrum can be accessed with improved utilization of the spectrum as a primary objective. Indeed, givenits potential, cognitive radio can be justifiably described as a “disruptive, but unobtrusive technology.”

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1 According to Fette [8], the awareness capability of cognitive radio embodies awareness with respect to the transmitted waveform, RF spectrum, communication network, geography, locally available services, user needs, language, situation, and security policy.

2 Reconfigurability provides the basis for the following features [9].

- Adaptation of the radio interface so as to accommodate variations in the development of new interface standards.
- Incorporation of new applications and services as they emerge.
- Incorporation of updates in software technology.
- Exploitation of flexible heterogeneous services provided by radio networks.

3. Cognition also includes language and communication. The cognitive radio’s language is a set of signs and symbols that permits different internal constituents of the radio to communicate with each other. The cognitive task of language understanding is discussed in Mitola’s Ph.D. dissertation [6].

4. The idea of a cognitive cycle for cognitive radio was first described by Mitolain [5]; the picture depicted in that reference is more detailed than that of Fig. 1.The cognitive cycle of Fig. 1 pertains to a one-way communication path, with the transmitter and receiver located in two different places. In a two-way communicationscenario, we have a transceiver (i.e., combination of transmitter and receiver) at each end of the communication path; all the cognitive functions embodied in the cognitive cycle of Fig. 1 are built into each of the two transceivers.

2. COGNITIVE RADIO TECHNOLOGY

The key enabling technologies of CR networks are the cognitive radio techniques that provide the capability to share the spectrum in an opportunistic manner. Formally, a CR is defined as a radio that can *change its transmitter parametersbased on interaction with its environment* [1].

From this definition, two main characteristics of cognitive radio can be defined [3]:

- *Cognitive capability*: Through real-time interaction with the radio environment, the portions of the spectrum that are unused at a specific time or location can be identified. As shown in Fig. 2, CR enables the usage of temporally unused spectrum, referred to as *spectrum hole* or *white space*. Consequently, the best spectrum can be selected, shared with other users, and exploited without interference with the licensed user.
- *Reconfigurability*: A CR can be programmed to transmit and receive on a variety of frequencies, and use different access technologies supported by its hardware design [4]. Through this capability, the best spectrum band and the most appropriate operating parameters can be selected and reconfigured

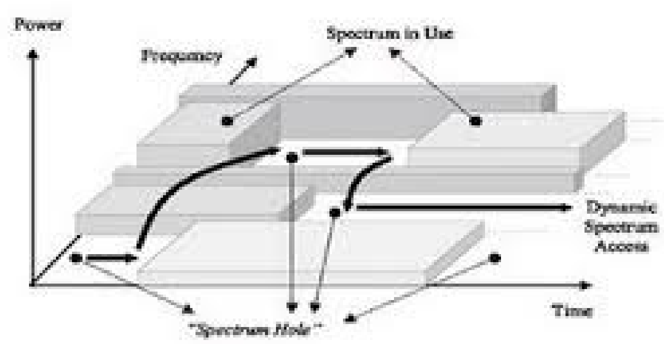
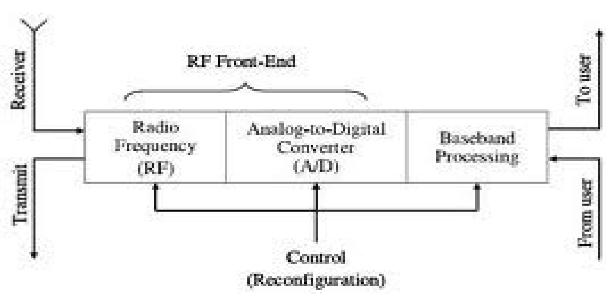


Fig. 2. Overview of cognitive radio: a) the spectrum hole concept



(a)

b) Cognitive Radio Transceiver architecture

In order to provide these capabilities, CR requires a novel radio frequency (RF) transceiver architecture. The main components of a CR transceiver are the radio front-end and the baseband processing unit that were originally proposed for software-defined radio (SDR), as shown in Fig. 2b [4]. In the RF front-end the received signal is amplified, mixed, and analog -to- digital (A/D) converted. In the baseband processing unit, the signal is modulated/demodulated. Each component can be reconfigured via a control bus to adapt to the time-varying RF environment.

The novel characteristic of the CR transceiver is the wideband RF front-end that is capable of simultaneous sensing over a wide frequency range. This functionality is related mainly to the RF hardware technologies, such as wideband antenna, power amplifier, and adaptive filter. RF hardware for the CR should be capable of being tuned to any part of a large range of spectrum. However, because the CR transceiver receives signals from various transmitters operating at different power levels, bandwidths, and locations; the RF front-end should have the capability to detect a weak signal in a large dynamic range, which is a major challenge in CR transceiver design.

3. COGNITIVE RADIO ARCHITECTURE

A comprehensive description of the CR network architecture is essential for the development of communication protocols that address the dynamic spectrum challenges. The CR network architecture is presented in this section.

3.1. Network Components

The components of the CR network architecture, as shown in Fig. 3, can be classified as two groups: the *primary network* and the *CR network*.

The primary network (or licensed network) is referred to as an existing network, where the *primary users* have a license to operate in a certainspectrum band. If primary networks have aninfrastructure, primary user activities are controlledthrough *primary base stations*. Due totheir priority in spectrum access, the operationsof primary users should not be affected by unlicensedusers.

The CR network (also called the dynamic spectrum access network, secondary network, or unlicensed network) does not have a license to operate in a desired band. Hence, additional functionality is required for *CR users* to share the licensed spectrum band. CR networks also can be equipped with *CR base stations* that provide single-hop connection to CR users. Finally, CR networks may include *spectrum brokers* that play a role in distributing the spectrum resources among different CR networks [6].

3.2. Spectrum Heterogeneity

CR users are capable of accessing both the licensed portions of the spectrum used by primary users and the unlicensed portions of the spectrum through wideband access technology. Consequently, the operation types for CR networks can be classified as *licensed band operation*and *unlicensed band operation*.

- *Licensed band operation*: The licensed band is primarily used by the primary network. Hence, CR networks are focused mainly on the detection of primary users in this case. The channel capacity depends on the interference at nearby primary users. Furthermore, if primary users appear in the spectrum band occupied by CR users, CR users should vacate that spectrum band and move to available spectrum immediately.
- *Unlicensed band operation*: In the absence of primary users, CR users have the sameright to access the spectrum. Hence, sophisticated spectrum sharing methods are required for CR users to compete for the unlicensed band.

3.3. Network Heterogeneity

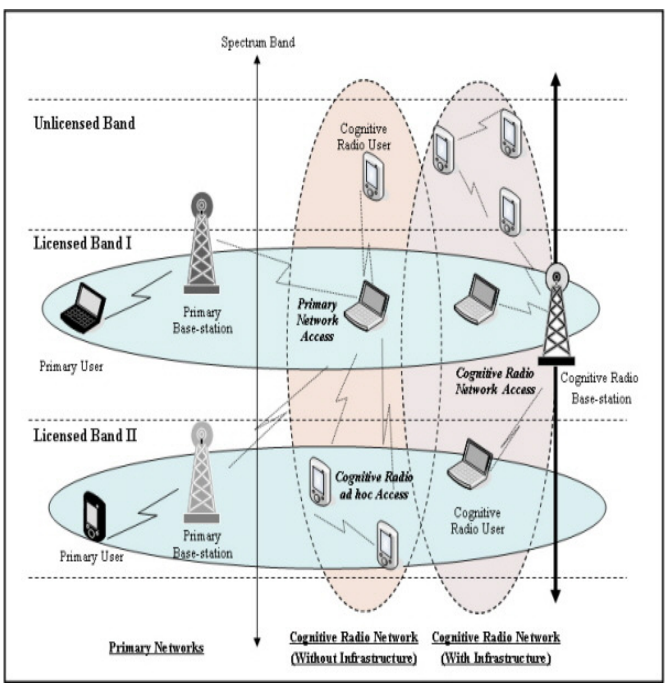
As shown in Fig. 3, the CR users have the opportunity to perform three different access types:

- *CR network access*: CR users can access their own CR base station, on both licensed and unlicensed spectrum bands. Because all interactions occur inside the CR network, their spectrum sharing policy can be independentof that of the primary network.
- *CR ad hoc access*: CR users can communicate with other CR users through an ad hoc connection on both licensed and unlicensed spectrum bands.
- *Primary network access*: CR users can also access the primary base station through the licensed band. Unlike for other access types, CR users require an adaptive medium access control (MAC) protocol, which enables roaming over multiple primary networks with different access technologies. According to the CR architecture shown in Fig. 2, various functionalities are required to support spectrum management in CR networks. An overview of the spectrum management framework and its components is provided next.

4. CHALLENGES FACED BY COGNITIVE RADIOS

CR networks impose unique challenges due to their coexistence with primary networks as well as diverse QoS requirements. Thus, new spectrum management functions are required for CR networks with the following critical design challenges:

- *Self-coexistence:* One of the most important and specific issue of CR is to avoid secondary users to harmfully interfere with primary users. However, self-coexistence is difficult to achieve in CR scenarios because well-defined cellular architectures and frequency allocations are not provided, primary users have non deterministic activities, and neighbouring secondary users compete for the same spectrum holes.
- *QoS awareness*: To decide on an appropriate spectrum band, CR networks should support QoS-aware communication considering the dynamic and heterogeneous spectrum environment.
- *Seamless communication*: CR networks should provide seamless communication. regardless of the appearance of primaryuser.
- *Accurate Sensing:* Sensing aims to determine if a channel is idle or busy in terms of primary user activity.
- *Optimized spectrum decision:* In CR scenarios, secondary users are expected to dynamically choose the best available channels and transmission parameters. For instance, CR MAC protocols should be able to determine the order spectrum bands must be searched for minimizing time and energy that are needed to find a spectrum opportunity.
- *Cross-layer design:* While spectrum sensing is restricted only to the PHY and MAC layers, spectrum management (e.g., spectrum handover, decision making and scheduling) can be related to all upper layers, which makes interaction and coordination between the different layers of the protocol stack necessary.



5. COGNITIVE RADIOS FUNCTIONALITY

To address these challenges, we provide a directory for different functionalities required for spectrum management in CR networks. The spectrum management process consists of four major steps:

- *Spectrum sensing*: A CR user can allocate only an unused portion of the spectrum. Therefore, a CR user should monitor theavailable spectrum bands, capture their information, and then detect spectrum holes.
- *Spectrum decision*: Based on the spectrum availability, CR users can allocate a channel. This allocation not only depends onspectrum availability, but is also determined based on internal (and possibly external) policies.
- *Spectrum sharing*: Because there may be multiple CR users trying to access the spectrum, CR network access should be coordinated to prevent multiple users colliding in overlapping portions of the spectrum.
- *Spectrum mobility*: CR users are regarded as visitors to the spectrum. Hence, if the specific portion of the spectrum in use isrequired by a primary user, the communication must be continued in another vacant portion of the spectrum.

6. CURRENT DEVELOPMENTS

Industry leaders like Nokia have adopted cognitive radio within allocated spectrum bands to more effectively manage heterogeneous spectrum and femtocell dynamics, moving network intelligence to the radios to reduce network overhead while substantially improving user experience for the more innovative integrated telecommunications (cable/ fibre TV, telephone, Internet Service, and wireless) service providers.

The US Defence Information Systems Agency (DISA) is leading their Defence Spectrum Organization (DSO) by moving into the age of dynamic spectrum access (DSA), which is the key near-term contribution of cognitive radio.

The IEEE 1900.5 spectrum use policy language group now is including spatial maps that hopefully will evolve to context-aware space-time maps with machine learning to reduce the time and effort to keep these maps current. For example, sporting events and emergencies distort P1900.5 radio environment maps, but the policy community has not yet reflected this level of adaptability.

7. FUTURE SCOPE

Cognitive radio already is going the way of the radical changes. When a decade ago the researchers formulated and published cognitive radio, that question really was important. During this past decade cognitive radio morphed into DSA, adaptive networks, and heterogeneous networks as communications enablers.

At the same time, user awareness, context aware services, and malleable user interfaces are embracing my vision of embedded cognition supporting the user, simplifying the user's life, embracing communications and computing, fixed and mobile, with fibre cores extending to wearable fashion statements. So as cognition becomes ubiquitous and integrated into everything from home appliances to automobiles, the excitement will morph from cognitive radio to the sentient spaces that such smart devices enable. Those who keep thinking of cognitive radio as if it were an end in itself will go the way of the buggy whip.

8. CONCLUSION

By exploiting the existing wireless spectrum opportunistically, CR networks are being developed to solve current wireless network problems resulting from the limited available spectrum and the inefficiency in spectrum usage. CR networks, equipped with the intrinsic capabilities of cognitive radio, will provide an ultimate *spectrum-aware* communication paradigm in wireless communications. In this survey intrinsic properties, current research challenges, current developmmentsin CR networks are presented. In particular, we investigate novel spectrum management functionalities such as spectrum sensing, spectrum decision, spectrum sharing, and spectrum mobility. Many researchers are currently engaged in developing the communication technologies and protocols required for CR networks. However, to ensure efficient spectrum aware communication, more research is requiredalong the lines introduced in this survey.

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