Cognitive Radio Network Architecture: Part I - General Structure

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ABSTRACT
Cognitive radio has been considered as a key technology for future wireless communications and mobile computing. We note the cognitive radios can form cognitive radio networks (CRN) by extending the radio link features to network layer functions and above. We categorize CRN architecture into several structures and classify the unidirectional links in such structures, to pave the way for future systematic CRN research.

Categories and Subject Descriptors

C. Computer Systems Organization C.2 COMPUTER-COMMUNICATION NETWORKS C.2.1 Network Architecture and Design Subjects: Wireless communication

General Terms
Design

Keywords
Cognitive Radio, Cognitive Radio Network, Ubiquitous Computing, Wireless Networks, Heterogeneous Wireless Networks

1. INTRODUCTION
Among diverse wireless technology supporting Internet access and other stream traffic services [7], a different vision is to integrate different wireless systems/networks and to appropriately use one of them based on the communication environments and the application requirements, based on reconfigurable communication and networking. Cognitive radio pioneered by J. Mitola III [12-13] from software defined radio (SDR) was originally considered to improve spectrum utilization and FCC endorsed such an idea shortly [1]. Upon to this scenario, cognitive radio is primarily a link-level technology for dynamic access of radio spectrum for physical layer radio transmission, as a sort of configurable wireless communication technology. However, cognitive radio provides not only spectrum advantages but also networking "macro-scale diversity" above link-layer to bridge our integrated re-configurable system/networking vision. We call such a scenario for future wireless networks as cognitive radio networks (CRN), which is pretty much consistent of Haykin's definition of cognitive radio [10]:

> *Cognitive radio is an intelligent wireless communication system that is aware of its surrounding environment (i.e., outside world), 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 communication whenever and wherever needed; efficient utilization of the radio spectrum.*

In other words, once cognitive radios can find the opportunities using the "spectrum holes" for communications, cognitive radio networking to transport packets on top of cognitive radio links is a must to successfully facilitate useful applications and services. A mobile terminal with cognitive radio capabilities can sense the communication environments (e.g. spectrum holes, geographic location, available wire/wireless communication system or networks, available services), analyze and learn information from the environments with user's preferences and demands, and reconfigure itself by adjusting system parameters conforming to certain policies and regulations. For example, when a cognitive radio mobile terminal sensed that there are WiFi and GSM systems nearby while spectrum holes exist in the frequency band of digital TV, it may decide to download files from a certain WiFi AP, make a phone call through GSM system and communicate with other cognitive radio users using those spectrum holes. A cognitive radio terminal could also negotiate with other spectrum and/or network users to enable more efficient spectrum and network utilization. The negotiation procedure may be facilitated from the support of network/infrastructure sides or just proceed in an ad hoc manner.

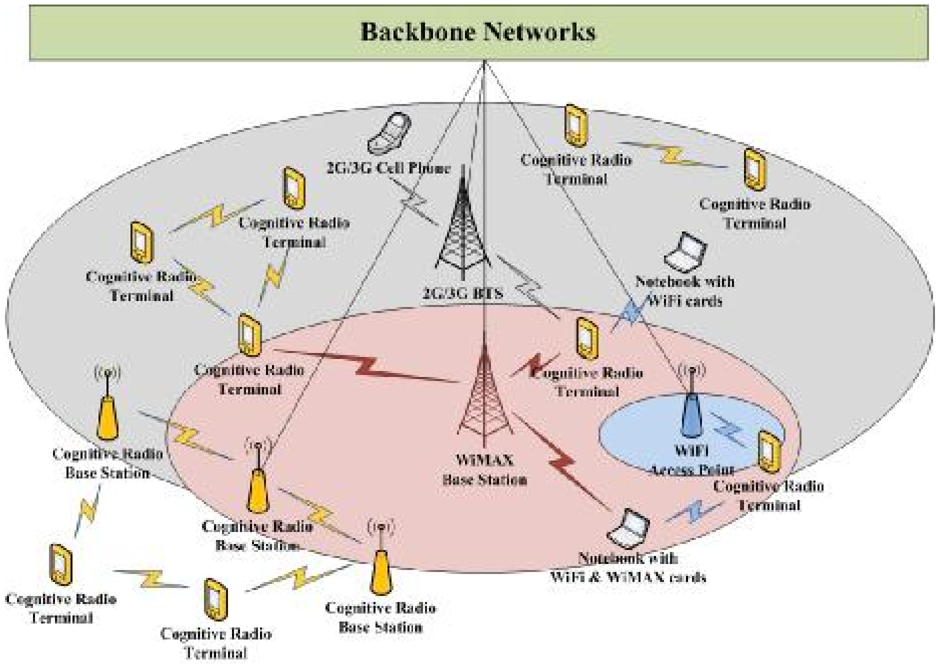

Figure 1. Ubiquitous Cognitive Radio Heterogeneous

Cognitive radio technology could also facilitate interoperability among different communication systems in which frequency bands and/or transmission formats differ [1].

2. TERMINAL CAPABILITY OF COGNITIVE RADIO NETWORKS

The capabilities of cognitive radios as nodes of CRN can be classified according to their functionalities. A cognitive radio shall sense the environment (cognitive capability), analyze and learn sensed information (self-organized capability) and adapt to the environment (reconfigurable capabilities).

2.1 Cognitive Capability

2.1.1 Spectrum Sensing

A cognitive radio can sense spectrum and detect "spectrum holes" which are those frequency bands not used by the licensed users or having limited interference with them.

2.1.2 Spectrum Sharing

A cognitive radio could incorporate a mechanism that would enable sharing of spectrum under the terms of an agreement between a licensee and a third party. Parties may eventually be able to negotiate for spectrum use on an ad hoc or real-time basis, without the need for prior agreements between all parties.

2.1.3 Location Identification

The ability to determine its location and the location of other transmitters, and then select the appropriate operating parameters such as the power and frequency allowed at its location. In bands such as those used for satellite downlinks that are receive-only and do not transmit a signal, location technology may be an appropriate method of avoiding interference because sensing technology would not be able to identify the locations of nearby receivers.

2.1.4 Network/System Discovery

For a cognitive radio terminal to determine the best way to communicate, it shall first discover available networks around it. These networks are reachable either via directed one hop communication or via multi-hop relay nodes. For example, when a cognitive radio terminal has to make a phone call, it shall discover if there is GSM BTSs or WiFi APs nearby. If there is no directed communication link between the terminal and the BTSs/APs but through other cognitive radio terminals some access networks are reachable, it can still make a call in this circumstance. The ability to discovery one hop or multi-hop away access networks is important.

2.1.5 Service Discovery

Service discovery usually accompanies with network/system discovery. Network or system operators provide their services through their access networks. A cognitive radio terminal shall find appropriate services to fulfill its demands.

2.2 Reconfigurable Capability

2.2.1 Frequency Agility

It is the ability of a radio to change its operating frequency. This ability usually combines with a method to dynamically select the appropriate operating frequency based on the sensing of signals from other transmitters or on some other method.

2.2.2 Dynamic Frequency Selection

It is defined in the rules as a mechanism that dynamically detects signals from other radio frequency systems and avoids co-channel operation with those systems. The methods that a device could use to decide when to change frequency or polarization could include spectrum sensing, geographic location monitoring, or an instruction from a network or another device.

2.2.3 Adaptive Modulation/Coding
Adaptive modulation techniques can modify transmission characteristics and waveforms to provide opportunities for improved spectrum access and more intensive use of spectrum while "working around" other signals that are present. A cognitive radio could select the appropriate modulation type for use with a particular transmission system to permit interoperability between systems.

2.2.4 Transmit Power Control
Transmit power control is a feature that enables a device to dynamically switch between several transmission power levels in the data transmission process. It allows transmission at the allowable limits when necessary, but reduces the transmitter power to a lower level to allow greater sharing of spectrum when higher power operation is not necessary.

2.2.5 Dynamic System/Network Access
For a cognitive radio terminal to access multiple communication systems/networks which run different protocols, the ability to reconfigure itself to be compatible with these systems is necessary.

2.3 Self-Organized Capability

2.3.1 Spectrum/Radio Resource Management
To efficiently manage and organize spectrum holes information among cognitive radios, good spectrum management scheme is necessary.

2.3.2 Mobility and Connection Management
Due to the heterogeneity of CRNs, routing and topology information is more and more complex. Good mobility and connection management can help neighborhood discovery, detect available Internet access and support vertical handoffs, which help cognitive radios to select route and networks.

2.3.3 Trust/Security Management
Since CRNs are heterogeneous networks in nature, various heterogeneities (e.g. wireless access technologies, system/network operators) introduce lots of security issues. Trust is thus a prerequisite for securing operations in CRNs.

3. ARCHITECTURE OF COGNITIVE RADIO NETWORK
In addition to spectrum sensing to effective improve spectrum utilization, a cognitive radio in CRN can sense available networks and communication systems around it. A Cognitive Radio Network (CRN) is thus not just another network to interconnect cognitive radios. The CRNs are composed of various kinds of communication systems and networks, and can be viewed as s sort of heterogeneous networks. The heterogeneity exists in wireless access technologies, networks, user terminals, applications, and service providers [9]. The design of cognitive radio network architecture is toward the objective of improving the entire network utilization, rather than just link spectral efficiency. From the users' perspective, the network utilization means that they can always fulfill their demands anytime and anywhere through accessing CRNs. From the operators' perspective, they can provide better services to mobile users, and allocate radio and network resources to deliver more packets per unit bandwidth in a more efficient way.

3.1 Network Architecture
The CRNs can be deployed in network-centric, distributed, ad hoc, and mesh architectures, and serve the needs of both licensed and unlicensed applications. The basic components of CRNs are ***mobile station*** (MS), ***base station/access point*** (BSs/APs) and ***backbone/core networks***. These three basic components compose three kinds of network architectures in the CRNs: Infrastructure, Ad-hoc and Mesh architectures, which are introduced as follows.

3.1.1 Infrastructure Architecture
In the Infrastructure architecture, a MS can only access a BS/AP in the one-hop manner. MSs under the transmission range of the same BS/AP shall communicate with each other through the BS/AP. Communications between different cells are routed through backbone/core networks. The BS/AP may be able to execute one or multiple communication standards/protocols to fulfill different demands from MSs. A cognitive radio terminal can also access different kinds of communication systems through their BS or AP.

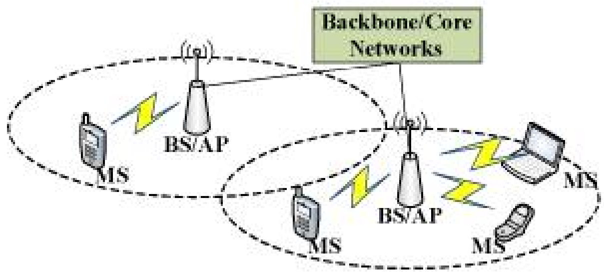

Figure 2. Infrastructure Architecture

3.1.2 Ad-hoc Architecture
There is no infrastructure support (or defined) in ad-hoc architecture. If an MS recognizes that there are some other MS nearby and are connectable through certain communication standards/protocols, they can set up a link and thus form an ad hoc network. Note that links between nodes may be set up by different communication technology. Two cognitive radio terminals can either communicate with each other by using existing communication protocols (e.g. WiFi, Bluetooth) or

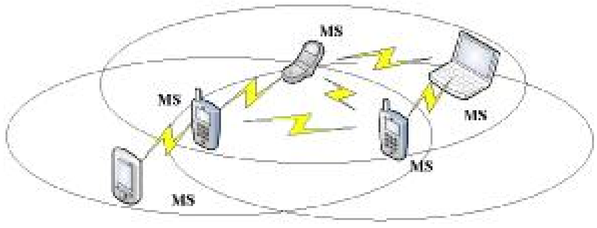

Figure 3. Ad-hoc Architecture

dynamically using spectrum holes.

3.1.3 *Mesh Architecture*

This architecture is a combination of Infrastructure and Ad Hoc architectures by enabling the wireless connections between BSs/APs, which is similar to the Hybrid Wireless Mesh Networks [5]. BSs/APs work as wireless routers and form wireless backbones [5]. MSs can either access the BSs/APs directly or use other MSs as multi-hop relay nodes. Some BSs/APs may connect to the wired backbone/core networks and function as gateways. Since BSs/APs can be deployed without necessarily connecting to wired backbone or core networks, it is more flexible and less costly in planning the locations of BSs/APs. For BSs/APs having cognitive radio capabilities, they may use spectrum holes to communicate each other. Due to potentially lots of spectrum holes available, the capacity of wireless communication links among cognitive radio BSs/APs may be enough to serve as wireless backbone.

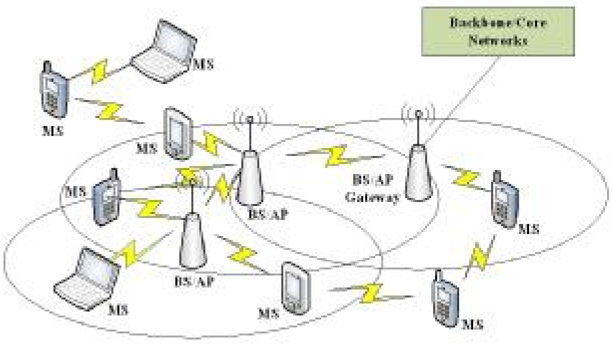

Figure 4. Mesh Architecture Networks

3.2 Primary System and Cognitive Radio System

There are two kinds of wireless communication systems in CRNs: Primary System and Cognitive Radio System, which are classified by their priorities on frequency bands. A primary system is referred to an existing system which operates in one or many *fixed* frequency bands. Various kinds of primary systems work either in licensed or unlicensed bands and are explained as follows.

3.2.1 *Primary System in Licensed Bands*

A primary system operated in the licensed band has the highest priority to use that frequency band (e.g. 2G/3G cellular, digital TV broadcast). Other unlicensed users/systems can neither interfere with the primary system in an intolerable way nor occupy the license band.

3.2.2 *Primary System in Unlicensed Bands*

A primary system operating in the unlicensed band (e.g. ISM band) called unlicensed band primary system. Various primary systems should use the band compatibly. Specifically, primary systems operating in the same unlicensed band shall *coexist* with each other while considering that the interference to each other. These primary systems may have different levels of priorities which may depend on some regulations.

A cognitive radio system neither has a fixed operating frequency band nor has privilege to access that band. Entities of this system communicate with each other by dynamically using spectrum holes. There are two components in CR systems: Cognitive Radio Base Station (CR-BS) and Cognitive Radio Mobile Station (CR-MS).

3.2.3 *Cognitive Radio Base Station (CR-BS)*

A CR-BS is a fixed component in the cognitive radio system and has cognitive radio capabilities. It represents the infrastructure side of the CR system and provides supports (e.g. spectrum holes management, mobility management, security management) to CR-MSs. It provides a gateway for CR-MSs to access the backbone networks (e.g. Internet). CR-BSs can also form a mesh wireless backbone network by enabling wireless communications between them, and some of them act as gateway routers if they are connected with wired backbone networks. If a CR-BS can run PR system protocols, it can provide access network services to PR-MSs.

3.2.4 *Cognitive Radio Mobile Station (CR-MS)*

A CR-MS is a portable device with cognitive radio capabilities. It can reconfigure itself in order to connect to different communication systems. It can sense spectrum holes and dynamically use them to communicate with CR-MS or CR-BS.

3.3 Links in CRNs

Since the Cognitive Radio System can provide interoperability among different communication systems, some inter-system connections should be enabled. We list all possibilities in Table

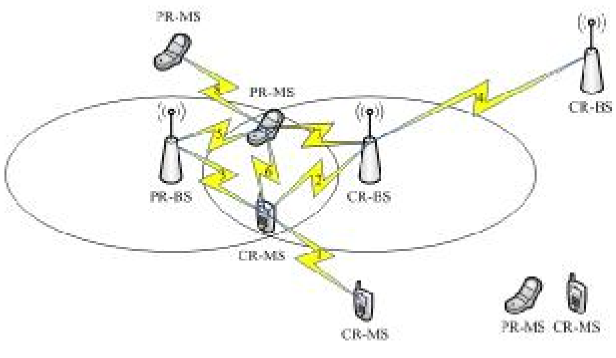

Figure 5. Links in CRNs

1 and show them in Figure 5.

Table 1. Possible Uni-directional Links in CRN

Rx \ Tx	CR-MS	CR-BS	PR-MS	PR-BS
CR-MS	●	●	●	●
CR-BS	●	●	●	
PR-MS	●	●	●	●
PR-BS	●		●	●

●: Possible link

3.3.1 CR-MS ß à CR-MS

A CR-MS can communicate with other CR-MSs in direct links. They may cooperatively sense spectrum holes in different frequency bands which may be licensed or unlicensed and utilize it as their operating frequency band. A common control channel may be necessary for them to exchange spectrum hole information.

3.3.2 CR-MS ß à CR-BS

A CR-BS can dynamically sense available frequency band around it and gather other MSs' sensing results and provide one-hop access to CR-MSs under its coverage area. This may need cooperative sensing technique. Under the coordination of CR-BS, the CR-MS can either access the backbone networks or communicate with other communication systems.

3.3.3 CR-MS ß à PR-BS

If there is a need for a CR-MS to connect to a PR-BS, it will reconfigure itself and become one part of the primary system (i.e. PR-MS). In this case, it will become a primary user on that band.

3.3.4 CR-BS ß à CR-BS

While enabling direct wireless links between CR-BSs, they can form a mesh wireless backbone network. Because of their cognitive radio capability, they can dynamically choose operating frequency band and communicate with each other. Since the CR-BS may have much more air interfaces, the link capacity between CR-BSs may be large. Another benefit of this kind of link is the reduced cost in placing the CR-BSs. This is because that setting up a CR-BS in some environment with a physical wired link is not feasible.

3.3.5 PR-MS ß à PR-BS

It is the typical one-hop connection between mobile stations and base stations. The PR-BS is responsible for coordinating communications in its coverage and providing backbone network access to the PR-MS.

3.3.6 PR-MS ß à CR-MS

In order to provide interoperability between different communication systems, this kind of link may be necessary. In this case, the CR-MS shall reconfigure itself to be one part of the primary system.

3.3.7 PR-MS ß à CR-BS

In order to provide interoperability between different communication systems, this kind of link may be necessary. If the CR-BS can run the protocol of primary system, it can provide access service to the PR-MS.

3.3.8 PR-MS ß à PR-MS

Including this link enables the possibility of ad hoc connections between PR-MSs.

4. CONCLUDING REMARKS

In this paper, we introduce the cognitive radio network (CRN) architecture to extend networking efficiency from cognitive radios' spectral efficiency. CRN can be considered as infrastructured, ad hoc, and mesh structure in terms of network topology. We also identified possible "uni-directional" links among these network structures, while such uni-directional links are resulted from the special nature of CRN operation. We hope this effort to pave the way for future CRN systematic research.

5. ACKNOWLEDGMENTS

This research is supported in part by the National Science Council, Taiwan ROC, under the contracts NSC 96-2219-E-002-008 and NSC 95-2923-I-002-001-MY2, and in part by the I2R, A-STAR, Singapore, and in part by the MAGNET Beyond Project, European Union.

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