COGNITIVE RADIO AND DYNAMIC SPECTRUM SHARING

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ABSTRACT

Evolutionary technological developments have sought to improve spectral efficiency by increasing the number of users in each frequency band. Revolutionary technological advancements, however, have introduced cognitive radios, which promise more efficient spectrum utilization through environmental awareness. This technology builds on the accomplishments of Software Defined Radio, which replaces the classical heterodyne radio with a digital signal processor. By using advanced computing power to sense the existing radio frequency (RF) environment, cognitive radios become aware of and can respond to that environment. This intelligence allows communications devices to modify their behavior to optimize spectrum utilization in real time. However, RF devices must still operate within the boundaries set by rules and regulations. Cognitive radio may help improve spectrum management by moving it from the sclerotic framework of regulations to the flexible realm of networks and devices, thereby enabling dynamic spectrum sharing and improving spectrum utilization.

1. INTRODUCTION

The proliferation of wireless communications services has caused a concurrent increase in the demand for and congestion of radio frequency (RF) spectrum. This congestion has put a premium on the cost of spectrum and has created a battle between the public, private, and military sectors over frequency ownership. Studies have shown, however, that spectral utilization is relatively low when examined not just by frequency domain, but across the spatial and temporal domains. [1] Thus, an intelligent device aware of its surroundings and able to adapt to the existing RF environment in consideration of all three domains, may be able to utilize spectrum more efficiently by dynamically sharing spectral resources.

This type of real-time spectrum monitoring and transmission method alteration requires that certain technical and operational situations exist. The device must be capable of sensing its operating environment, determining the best transmission method, and reconfiguring itself to the ideal state. In essence the device must be cognitively aware of its surroundings and able to make decisions about when and how to transmit.

This paper examines the technical and operational environments that radios exist within and how cognitive technology may improve the efficiency and effectiveness of their communications.

2. COGNITIVE RADIO – A BRIEF HISTORY

A Software Defined Radio (SDR) is a transmitter in which operating parameters, including transmission frequency, modulation type, and maximum radiated or conducted output power can be altered without making any hardware changes.

The classical method of demodulating high frequency signals is to shift the signal's frequency down in one or two steps before feeding it to a demodulator. The frequency shifting is necessary because the demodulation is more stable and easier to implement at lower frequencies. The demodulator block is designed to perform a fixed set of services (e.g., modulation and demodulation, encryption and decryption) chosen at design time.

Advances in computer design and digital signal processing (DSP) make it possible to replace the classic demodulator with a component that dynamically supports multiple systems, protocols, and interfaces. The signal in this case is sampled by a high-speed analog-to-digital converter (ADC) and all the processing required to extract the useful signal is performed by a computer. This new approach enables an unprecedented flexibility in modulation and encryption capabilities because the digital signal processing module can be reprogrammed. Furthermore, the separation of the hardware platform from the functionality allows the emergence of standards for the hardware platform which, in turn, offers tremendous benefits for the development and deployment of SDR devices.

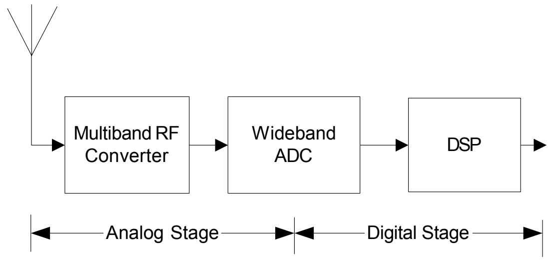

Figure 1. Major Building Blocks of an SDR Device

The concept of Cognitive Radio (CR) emerged as an extension of SDR technology. Definitions vary, but most experts agree that a CR device should have the following characteristics: 1) aware of its environment, 2) capable of altering its physical behavior to adapt to its current environment, 3) learns from previous experiences, and 4) deals with situations unknown at the time of the radio's design. In practice, we consider multiple levels of cognition, the simplest being a pre-programmed device that has no model-based reasoning, but can sense its operating environment and make some decisions about which built-in capabilities to use at a given time. An example of such a device is a multi-band, multi-protocol cellular telephone. Higher levels of cognition – which are not available today – would allow a cognitive radio to negotiate the parameters of the communication with other radios or base stations.

3. THE OPERATIONAL ENVIRONMENT

All RF devices operate under a strict set of rules dictating the operational environment for radio transmitters including operating frequency, effective radiated power limits, antenna height, emission type, and bandwidth limitation, among others. At present, various rules and regulations apply to a multitude of services and differ by frequency band, geographic location, service type, and spectrum management model. The following subsections present an overview of the spectrum management arena within the United States and its current effects on the RF environment.

3.1 Regulatory Bodies

The United States operates in a bifurcated spectrum management system where the Federal Communications Commission (FCC) governs commercial wireless communications users and state and local government spectrum users, while the National Telecommunications and Information Administration (NTIA) regulates all Federal Government spectrum users. Additionally, the U.S. must conform to any applicable International Telecommunication Union (ITU) regulations as set forth during the biennial World Radio Communication Conferences.

The FCC enforces regulations generated from the process set forth in the Administrative Procedures Act, [2] which provides for a transparent rulemaking process enabling any entity to publicly file comments or submit information to the FCC regarding an existing or potential rule. Although the FCC sets time limits on the open comment period, it is not obligated to respond to the comments under any set timeframe, often making the process quite lengthy. The FCC is charged with acting in the public's "best interest," a somewhat nebulous statutory term whose definition is often considerably debated during the course of a proceeding.

Conversely, the NTIA's spectrum management process is not as open and transparent. All frequency assignments are coordinated through the government-only Interdepartment Radio Advisory Committee, and are regularly classified for the sake of national security. Federal wireless users are subject to the rules set forth by the IRAC in the *NTIA Manual of Regulations & Procedures for Federal Radio Frequency Management*, commonly referred to as the Red Book.

The ITU's Radiocommunication Sector coordinates spectrum use on an international level, seeking to globally harmonize RF spectrum bands and to reduce harmful interference between countries to improve the use of RF services. Because the U.S. has two international borders, and due to the fact that communication service commerce is truly an international arena, it is necessary that the FCC and NTIA participate in the ITU process and adhere to its outcomes.

Any cognitive device would be subject to the rules and regulations set forth by these regulatory bodies, under every operating condition of the device. As the device reconfigures itself, it must be aware of, or able to download software defining the rules associated with its operating status and geographic location.

3.2. Three Spectrum Management Models

Within the U.S., three spectrum management models exist – command and control, exclusive use, and unlicensed use, often referred to as "spectrum commons." Rules governing spectrum use under these models are as widely varied as the motivations for providing the services that they regulate.

The command and control model has been the traditional spectrum management model in the U.S. for more than 70 years. The principle behind it is that RF spectrum is divided into frequency bands, in which specific channels are licensed to specific users for specific services. These frequency bands are subject to explicit usage rules governing the designated RF service or transmission type.

Under the exclusive use model a licensee is authorized to use a specific frequency band or channel for whatever service or purpose they desire. These rights are subject to general emission rules that are designed not to interfere with neighboring spectrum users. In return for not interfering with other users, licensees are afforded the freedom to use their spectrum however they choose, much like property rights.

RF devices governed by the tenets of the spectrum commons, which typically refers to unlicensed frequency bands, operate on a first-come, first-serve basis. Devices transmitting in this band are subject to certain emission rules, but are not guaranteed any interference protection rights or the exclusive use of dedicated channels. [1]

Any cognitive device could operate on spectrum that is governed by these models, and as such, must be aware of, or able to download software describing the unique rules of each.

3.3 Current Limitations

The increased demand for and use of traditional wireless services and applications have strained the spectrum management regime. Multi-billion dollar commercial spectrum auctions provide a source of revenue for the U.S. Treasury, the use of unlicensed spectrum bands has exploded and will soon cause severe congestion problems, and the command and control governance of public safety spectrum has been questioned because of low, non-peak time utilization rates.

Unlicensed spectrum use provides no interference protection rights, and as the band becomes increasingly congested, quality of service will fall. Under the command and control model, entities that require dedicated, 100 percent exclusive use spectrum, i.e., public safety agencies, must have immediate access to all of their assigned frequencies in an incident response situation. At all other times, however, their spectrum is not being fully utilized and is therefore not fully efficient. The exclusive use model affords spectrum licensees the flexibility to use their spectrum as the market demands, provided that use does not interfere with other wireless services. Spectrum access negotiation, however, is limited to the speed with which that two or more parties can agree on terms and conditions.

4. COGNITION AND DYNAMIC SPECTRUM SHARING

SDR and CR technology advancements have the potential to alleviate the limitations in the frequency, spatial, and temporal domains and provide for real-time spectrum access negotiation and transactions, thus facilitating dynamic spectrum sharing. We have discussed the technical and operational environments for RF devices and now move into the details of how Cognitive Radio and Dynamic Spectrum Sharing can improve those environments.

4.1. DSS Defined

The US Spectrum Allocation Chart shows a very fragmented portioning of the radio spectrum. As the number of wireless technologies, products, and users increases, many applications need more bandwidth. The cellular and Industrial, Scientific, and Medical (referred to as ISM) bands are presently over-utilized. In contrast, television and land mobile radio bands are most often under-utilized, primarily during periods of off-peak use. Studies show that spectrum is not used uniformly across the space and time domains. The FCC Spectrum Task Force reports utilization rates between 15–85 percent. These numbers underline the need for technology that exploits areas of low utilization.

Dynamic Spectrum Sharing (DSS) is a collection of techniques for better utilizing radio spectrum as a function of time, space, and context. There are two distinct ways of sharing radio spectrum:

Underlay: In this model, spectrum is used by a second party at the same time as the primary licensee, but with the intent of causing as little interference as possible. Ultra Wideband (UWB) technologies are particularly suited for this type of spectrum sharing because signals are spread over large swaths of spectrum and the signal strength is around the RF noise level (this allows a UWB signal to operate on occupied spectrum with a very low power output, and not cause any interference). This model relies on measuring the ambient noise and the interference caused in the operating range and maintaining it under a predefined threshold (the interference temperature threshold).

Overlay: In this model, spectrum is shared explicitly in one of three ways:

- **Opportunistic**, where spectrum is used whenever the licensee does not use it
- **Cooperative**, where frequencies are allocated centrally based on real-time negotiation with the licensee
- **Mixed,** where sharing is cooperative when possible and opportunistically otherwise.

The fundamental capability in spectrum awareness alone, while essential in all the spectrum sharing models, is not sufficient for the more sophisticated cooperative sharing mode. Higher levels of cognition are necessary.

- **Radio self-awareness** – the radio has knowledge of its internal and network architectures and can make flexible decisions on how to best take advantage of the architecture.
- **Planning capabilities** – the radio follows goals as a function of time, space, and context.
- **Negotiation capabilities** – the radio can negotiate alternatives with other radios in the environment.

At this level of cognition, the radio could modify its physical layer behavior not only to use available spectrum but also to satisfy higher-level application requirements. Networks would be able to leverage the radio's cognition abilities to achieve an unprecedented level of flexibility and reconfigurability. Such a network could achieve high levels of cooperation between all its components and thereby more efficiently and effectively utilize spectral resources.

4.2 Enabling factors

The idea of CR devices developed naturally as an extension of SDR technology. The general-purpose computing capability that is essential to the SDR architecture can be harnessed to provide the functionality needed for "cognition", as defined at the beginning of this paper. As this computing power increases, more sophisticated cognition algorithms can be implemented.

Equally important for the cognition process is environment sensing. While there are many ways of sensing the external world, being aware of the surrounding radio environment calls for smart antennas, which are capable of sensing across wide bands of the radio spectrum. These types of antennas are being developed in an effort to improve the frequency agility of SDR.

4.3 Hurdles and obstacles

Several obstacles must be overcome before cognitive radio implementation can become practical. In the underlay sharing model, the radio needs to be aware of the ambient RF noise level as a function of both space and time. With today's technology it is fairly difficult to measure the interference temperature threshold given that in real-life situations, directional and omni-directional RF sources can coexist.

The overlay spectrum sharing mode calls for higher computing power and more sophisticated radio reconfigurability than current technology offers. Efficient spectrum negotiation algorithms have yet to be developed.

Security is also a major concern. In an environment where radios can decide how spectral resources are used, proper authentication is vital. Rogue players have the potential to cause major communication disruption. Mechanisms must be developed to identify and incapacitate these devices. One of the defining characteristics of SDR and cognitive radio is the ability to gain or modify functionality through over-the-air software downloads. Robust security measures are necessary to accomplish this goal.

5. THE FUTURE OF COGNITIVE RADIO

CR devices have the potential to dramatically change the wireless communications landscape. When this technology matures, RF devices will be able to determine the most appropriate transmission method, maximizing the efficient and effective use of spectrum. New, real-time negotiation capabilities will effectively render spectrum a tradable commodity, opening up new markets and competition for an in-demand resource.

As noted above, however, several hurdles must be passed to make high-level CR technology viable. The time frames for commercial availability of this technology are fluid and depend greatly on the speed with which technological advancements can be accomplished.

5.1 Near term environment

SDR technology is a burgeoning field and several devices exist that fall under the broad definitions of the terms software defined or cognitive. It is expected that advances in the core technologies of SDR devices will continue at a steady pace, as the benefits of such technology are more effectively communicated to the wireless industry. Additionally, authorities have taken an active role in establishing regulatory frameworks to build business cases. Interference temperature metric development will provide a standard for sensing and determining allowable RF emissions, the FCC's secondary markets proceeding has paved the way for negotiation of spectrum as a commodity, and the regulations governing SDR and CR devices were created to be relatively flexible until more is known about how best to treat these technologies.

5.2 Long term environment

While SDR technology is developing, the aspects of any such RF device that will make it truly cognitive may be a longer way off. Advances still must be made in areas that allow for higher level cognition, including learning capabilities, decision making technologies, negotiation techniques, and spectrum etiquette rules. It is very possible, though, that as the associated CR-enabling technologies develop and mature, they pave the way for environmentally aware, reconfigurable, truly cognitive devices to replace traditional hardware based radios, completing the migration towards the flexible realm of devices and networks.

6. REFERENCES

[1] FCC, "Spectrum Policy Task Force Report," ET Docket No. 02-135, pp. 35-53, released November 7, 2002.
[2] Title 5, United States Code, Administrative Procedures Act, Chapter 5, Sections 511-599.