Cognitive Radio Definitions and Nomenclature

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History

V0.02. Initial versions of this document were generated in the Cognitive Radio WG prior to January, 2007. John Grosspietsch was listed as the contact person.

V0.03. Pete Cook has undertaken the task of preparing it for publication, and generated the version numbered 0.0.3.0 in January, 2007.

V0.04 Modifications reflecting P1900.1 efforts. 9 October 2007.

V0.05 A set of modifications to address concerns about the relationship between cognitive radio and software defined radio. The disclaimer clarifies the intent of the document.

V0.06 Editing and modifications reflecting current literature. February 2008

V0.07 Added a set of definitions to reflect differences between Cognitive Radio Network and Cognitive Network. March 2008

V0.08 based on WG telecom on May 7, we agreed to 1) reinsert paragraph numbering, 2) refresh the table of contents, 3) revise the heading from "The SDRF Cognitive Radio Definitions" to "The SDRF Cognitive Radio Extended Definitions" and the two corresponding sentences under that to reflect that these definitions are not identical, 4) correct errors in the geolocation paragraph.

Contributors to this Report

Throughout the process of creating this document, we have noted discussions within the Cognitive Radio Working Group members that led to the conclusions and recommendations of this report. The following list is an acknowledgement of the key contributors and corresponding organizations at the time of the contributions responsible for the creation of this document:

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1 Executive Summary

"Cognitive radio" is a term that has caught the attention of a wide range of stakeholders in the wireless industry. Unfortunately it has been applied in an inconsistent manner, often as the ideal solution for the problems of that specific sector.

In this document we identify many different aspects of cognitive radio, and place them into a coherent framework. We then arrive at a very general definition of cognitive radio as a radio aware of its environment, internal state, and location, which autonomously adjusts its operations to achieve desired objectives in response to unexpected changes in these characteristics. Such a radio will also often incorporate software defined radio functionality.

We then identify a number of elements of cognitive radio capability, and discuss spectrum efficiency and network implications. We propose a conceptual model for cognitive software defined radio architecture, and present a detailed list of radio parameters, as well as an extended bibliography of publications in the area.

Cognitive radio is not a single piece of apparatus. It is a technology that can incorporate components spread across a network. It offers great promise for improving system efficiency, spectrum utilization, more effective applications, reduction in interference, improved service, and reduced complexity of usage for users.

2 Disclaimer

This document represents work done over several years, with some significant gaps in the effort due to sequential contributions by key participants. Because it contains a substantial body of significant material, the decision was made in this version to move the document forward to make the content available for use of Software Defined Radio Forum members. This document is a compendium of a wide range of applications and technologies, not all of which are mutually consistent, so it does not represent a normative position of the Software Defined Radio Forum.

3 Purpose and Scope

The purpose of this document is to identify components and collect working definitions for many of the technologies and techniques related to cognitive radios as they are used within the SDR Forum Cognitive Radio Working Group and across the wireless marketplace. It is hoped that these descriptions can be used by others in the communications industry as a baseline for further mutual understanding and technology development.

The SDR Forum Cognitive Radio working group has set out in its charter the goal of preparing a definitions and nomenclature document that defines some of the terms used in discussions of technical aspects of cognitive radio.

The scope of the document is limited to discussion of the benefits of cognitive radio, the implications for software defined radio technology, architectural elements of a cognitive SDR radio, and definitions of specific terms and techniques as they may be used in conjunction with cognitive radios.

The SDR Forum is an international, nonprofit organization dedicated to promoting the development, deployment, and use of SDR technologies for advanced wireless systems. Its mission is to accelerate the proliferation of SDR in wireless networks to support the needs of civil, commercial, and military market sectors. Over 120 entities throughout the world are members of the forum, including operators, suppliers/manufacturers, policy makers, technologists, and academia, and the organization strives to carry out studies and develop views on software defined radio that are representative of all three ITU regions.

4 Introduction

Interest is rapidly growing in lowering barriers to spectrum access and improving spectrum efficiency. The introduction of software-defined radios and the realization that new levels of computational performance applied to radios creates exciting new possibilities for wireless devices. This has resulted in explosive growth in interest in cognitive radios. The term *cognitive radio* was first used by Joe Mitola [1]. The concept and the term *cognitive radio* quickly caught the interest of many in the communications field.

Cognitive radio technology enables a number of capabilities to improve the usefulness and effectiveness of wireless communications. Those functions include:

- Exploit locally vacant or unused radio channels, or ranges of radio spectrum, to provide new paths to spectrum access.
- Roam across borders and perform self-adjustment to stay in compliance with all local radio operations and emissions regulations.
- Negotiate as a broker on behalf of the radio user with multiple service providers to give network access best matched to the user needs at the lowest cost.
- Adapt itself without user intervention to save battery power or to reduce interference to other users.
- Make use of location awareness to ensure that radio emissions do not interfere with licensed broadcasters.
- Understand and follow the actions and choices taken by their users to become more responsive and anticipate user needs over time.
- Formulate and issue queries, one radio to another.
- Execute commands sent by another radio.
- Fuse contradictory or complementary information.

This proliferation of the term *cognitive radio* is validation of the strong interest in the industry and government for communications systems that can operate with more intelligence and improved performance. This interest leads to a need for a common terminology for manufacturers, regulators, researchers, and users all to be able to advance the development of cognitive radios. This document provides definitions of terms and nomenclature used within the SDR Forum Cognitive Radio Working Group when discussing cognitive radios. Definitions of the key methods, techniques and special capabilities of different classes of cognitive radios are described. Definitions of techniques for improving access to spectrum and improving spectrum efficiency are also included.

This document is organized as follows;

- Section 4 discusses the benefits that multiple forms of awareness could bring to cognitive radios. This section describes a conceptual model for the architecture of a cognitive software defined radio. Section 4 also presents a more detailed discussion of the various levels of capabilities that different types of cognitive radios may possess.
- In Section 5, many of the elements and components that may be used in a cognitive radio are described.
- Section 6 describes how these elements can be used to improve performance and improve efficiency.
- In Section 7 a high level view of how cognitive radios can themselves can be elements of larger systems or networks and the benefits that may arise.
- In Section 8 some network aspects of cognitive radio are discussed
- In Section 9 some system aspects of cognitive radio are discussed
- Section 10 provides conclusions
- Section 11 provides references and a bibliography

4.1 SDR and the Benefits of Cognitive SDR

Cognitive radios promise many new and exciting benefits for radio users. Software defined radios are a natural platform on which to build in new cognitive features. In keeping with the interests and objectives of the Software Defined Radio Forum, most of this discussion assumes software defined radio functionality as a foundation for development of cognitive radio functionality. In this section, we describe some of the benefits of cognitive radios and how software defined radios are a natural step in the development of cognitive radios.

Interoperability and Coexistence

Interoperability refers to the need for users, often from different government agencies or offices, to be able to communicate even though they have been issued wireless devices that may be incompatible in assigned operating frequency range or type of air interface employed. In public safety applications, cognitive radios aware of the identity of other first responders, or more specifically, aware of the other types of first responder radios that are present, can improve communications in emergency situations. Frequency agile and protocol flexible software-defined radio platforms with cognitive capabilities are potentially capable of reducing interoperability issues by providing seamless system operation in highly fragmented, multi-terminal/multi-frequency communication environments. As a result, cognitive radios enable seamless communication between and among different first response teams such as firemen, policemen and ambulance services – something that has become even more important in our current world.

A cognitive SDR radio can observe the communications environment to gain awareness of the radio signal environment and adapt its operating parameters to connect with other systems or radios present.

The military services could also benefit from reliable communication between different organizations employing incompatible communication equipment. Joint and combined military operations benefit from radios that are able to configure themselves to provide seamless communication.

Unrestricted roaming for consumers using different types of wireless services such as GSM, CDMA, and WCDMA in addition to WLAN networks could become more common with the introduction of cognitive radios and systems. These consumer radios could listen for the presence of access networks and select the carrier that best meets a user's needs.

Management of identity and authentication are also important aspects of interoperability. The identity of the users of radios who wish to join a network needs to be assured. Authentication that the devices themselves are suitable and authorized for use on a network is critical. The SDR Forum Public Safety SIG has explored some of these issues in greater detail and has published a document describing improvements in interoperability [12]. In addition, the SDR Security WG has discussed identity and authentication in their document, currently in development as SDRF-06-W-0002-V0.42.

Reduced demand on user, reduced user control burden

Another potential benefit of cognitive radios is the reduction and simplification of the tasks needed to set up and use a radio. Cognitive radios aware of a user's goals and priorities, and capable of independently acting, could simplify the operation of radios. A flexible SDR radio needs some form of input or command to set the operating frequency, power level, modulation, bandwidth, and possibly many other radio parameters. For example, filters may need to be tuned and different subsystems may need to be switched in to enable certain operating modes. Software routines may need to be selected, loaded and run to facilitate operation using a new waveform. Enhanced flexibility in a wireless device offers a greater number of possible options and settings. There is value in significantly reducing the burden of technical know how on the part of the user using cognitive functionality. Users should be able to utilize the capability of the radio with a minimum level of detail over radio operating parameters, with the radio making appropriate choices among options.

Greater spectrum efficiency through improved access

The term *spectrum efficiency*, as used in the SDR Forum Cognitive Radio Working Group, refers to increasing the efficiency of how spectrum is assigned and used to support one or more wireless services in one or more geographical locations in either a concurrent or time-based manner. . New methods provide ways of accessing spectrum that would have been excluded by regulatory policy and licensing rules in the past. One scenario involves use of licensed spectrum by unlicensed users using protocols and etiquettes to minimize the potential for interference to licensed users.

Wireless devices that are aware of their spectral environment provide benefits by being able to access previously unused, unavailable, or restricted spectrum segments that may be available for usage in other geographical areas or under other regulatory regimes. Spectral awareness may enable the use of this spectrum without causing interference to the radios originally operating in the spectrum. Radio spectrum is perceived to be a scarce resource: there may be a shortage of spectrum available for dedicated allocation without displacing current users. Interest is high to find ways to use spectrum more efficiently. Utilization levels vary widely between services and geographic areas, with some having substantial amounts of "white space", or unused spectrum segments at any point in time. Radios capable of exploiting unused or lightly-used spectrum without introducing interference will improve efficiency of spectrum utilization.

Improved application interface for communications tasks

A Cognitive SDR radio can provide communications services that allow users to designate a priority or a value for each particular communications task. For example, email might be given a higher priority than streaming video. Cognitive radios could be aware of the requirements that different applications on a radio have for data throughput rates, latencies, and quality of service (QoS) levels. These services become increasingly important as users multiplex applications (e.g. streaming audio and video while simultaneously text messaging) and executing applications in parallel. The cognitive SDR can support communications by using prioritized connection use rules (i.e. drop streaming audio if incoming call), time of transmission optimization (i.e. batch low priority uploads/downloads until low cost, high bandwidth connections), appropriate channel bandwidth to match endpoint coding/decoding schemes, and adaptive compression to balance bandwidth usage (i.e. increase compression in voice over IP (VOIP) conference call scenario). The cognitive SDR can also gracefully degrade the supplied services according to environmental conditions such as link quality changes, interference, and energy-source degradation in order to help maximize the useful operating lifetime of the device

Dynamic Regulatory Compliance

Radios that are aware of their locations and current regulatory jurisdiction can update and maintain compliance with local regulations. This is important for radios that are likely to cross borders. This awareness combined with the ability to update a radio's "knowledge" of regulatory rules could allow regulations to adapt more quickly to new technologies.

Radio performance optimization

A radio that is aware of its internal state can improve its performance compared to a traditional radio. For example, a radio aware of its remaining energy level could adapt its data rates or modulation type to maximize its operating time. A radio that was aware that its decoder was operating near the limits of its abilities may adapt its data rate or bandwidth to increase the operating margins of the communications link.

User based Cognitive Adaptation

An additional level of cognition may be the radio's awareness of its user. Soft biometrics enables an SDR/CR node to recognize user identity. Sensors for medical triage and first responder health may indicate to a wearable SDR/CR the health of its user, enabling the radio to adjust even its physical layer (power) or network layer (routing parameters from forwarding to flooding) to call for help if a first responder is in need. The robotics industry is developing robots for health care, and these robots will have different priorities for use of wireless services for various forms of service and assistance. Although the radio itself would not take on the job of assessing the state of the user, the cognitive radio that is user-aware may autonomously adjust air interface, application, and protocol stack agility to provide the most appropriate mode of communications on a scale of assured connectivity to better bandwidth without the user having to explicitly program or control the SDR. The extension of such intelligence into ad-hoc networks via user-aware cognitive radios would bring increased user-state-dependent wireless agility to home networks, military, humanitarian relief, first responder, and other networks where there is not necessarily a single service provider.

4.2 SDR and Cognitive Radio Conceptual Architecture

Cognitive radios are capable of making decisions and selecting or modifying the operating parameters of a radio. In the most abstract view of the Cognitive Radio Working Group, there are two major subsystems in a cognitive SDR radio; a cognitive unit that makes decisions based on various inputs and a flexible SDR unit whose operating software provides a range of possible operating modes.

The Cognitive Radio Working Group developed a conceptual model that uses a layered architecture where the SDR radio is at the base and is closest to the physical RF channel. The cognitive layer is above the SDR layer and below the application layer. One goal of this architecture is to hide the complexity of the SDR radio from the applications. The combination of a cognitive "engine" and the SDR together comprise a "cognitive radio" or a cognitive SDR radio. The cognitive layer acts to optimize or control the SDR with minimal user interaction or oversight. In this model the cognitive engine accepts inputs, makes decisions and inferences from a pool of current and historical contextual knowledge and issues control or configuration commands to the flexible-architecture SDR radio.

The basic function of a cognitive radio is matching the radio link requirements of a higher layer application or user need with the available device, spectral and infrastructure resources. The cognitive layer could also be aware of the data rates and quality of service requirements of the application.

The cognitive layer would be aware of the radio's hardware resources and capabilities. It would store an inventory of the software modulation schemes available and the capabilities and characteristics of these modulation and spectrum access schemes. The cognitive layer could know the measurement utilities available to allow it to collect information to feed the decision process.

In this model the rules or decision algorithms are stored separately from the engines to enable them to be updated easily. The cognitive function is further separated into two parts as shown in the block diagram in Figure 1 below. The first labeled the "cognitive engine" tries to find a solution or optimize a performance goal based on inputs received from other parts of the radio. These other parts can supply information that is the basis for "awareness" as described above.

The second engine is the "policy engine" and is used to ensure that the solution is in compliance with regulatory rules and other policies external to the radio. Each of these engines has a separate rule-set or algorithm-set. The reason we have shown them separately is that these subsystems perform two different tasks. The policy engine isolates policy or regulatory rules from the operational capability rules of the radio as regulatory policies apply to all radios. The purpose of the policy engine is to veto, if necessary, adaptation choices made by the cognitive engine.

Cognitive rules are likely to be written to be compatible with the specific capabilities of a particular radio. The cognitive engine strives to find ways to adapt the radio to best meet a goal or a set of priorities based in awareness of both internal and external conditions. This view is a conceptual one and implementations may in practice share processing hardware and memory.

The cognitive layer, using the available radio resources, could monitor RF environment and gain awareness of external users and the presence of unused spectrum. It could monitor and be aware of the presence of relay nodes or infrastructure access points that the radio could use. It could also utilize other criteria in the decision process, such as whether to maximize battery life or minimize operating expense.

It is envisioned that in the future, advanced cognitive SDR radios could learn and innovate, meaning they test new hypotheses, store and recall adaptations that resulted in successful outcomes in addition to those that may not have improved performance in future, similar situations.

The inputs come from both the lower SDR layer and from the upper application layers. The SDR, or special monitoring subsystems, provide inputs including the status and current capabilities of the radio and the results of spectrum scans. The upper layers will provide inputs including information about the desired data rates, QoS and inputs from other sensors such as GPS based location.

The decisions can be simple or complex. The decision making activity can also make use of some memory along with the external inputs. This makes it possible for the radio to learn and possibly improve the quality or speed of its decisions. Decisions can be derived using declarative languages combined with inference engines. In other systems, decision systems can be implemented using game theoretic or genetic algorithms. Of course, simple *if-then-else* decision trees can be implemented in imperative languages such as C or Java.

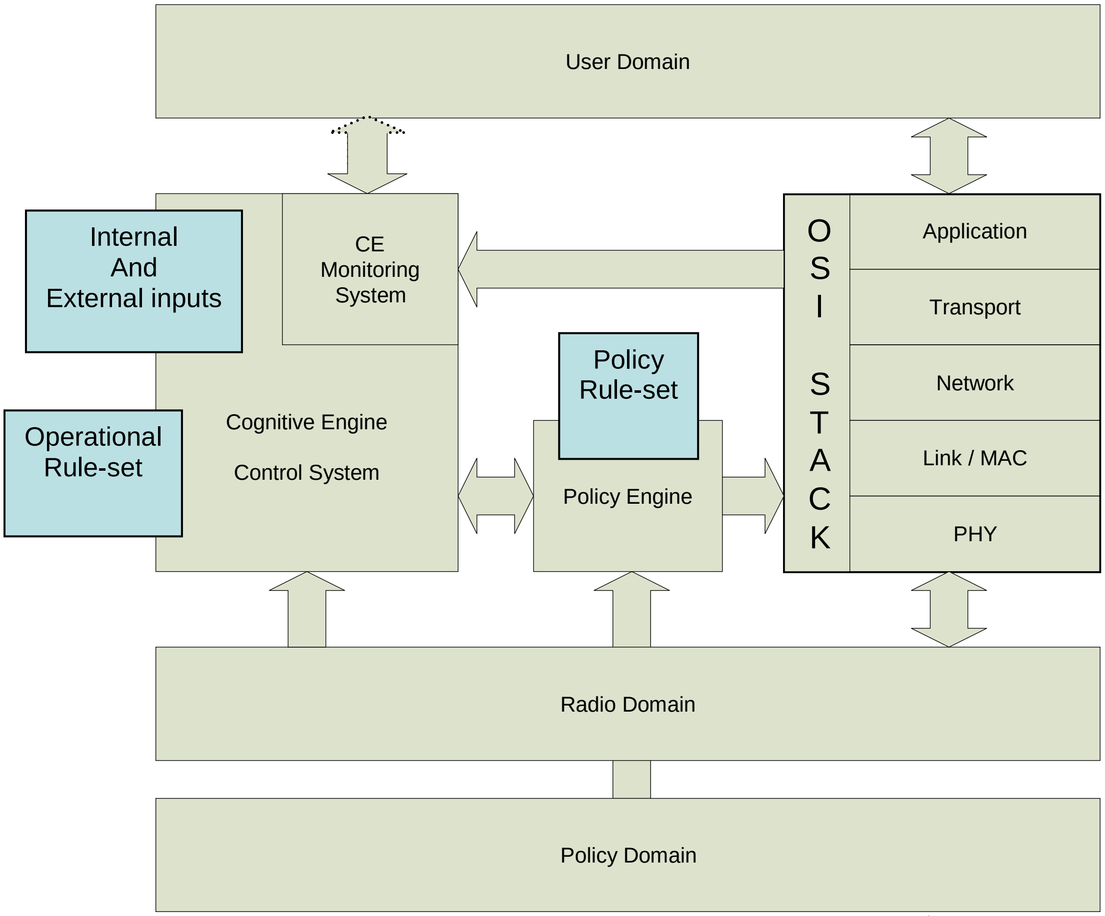

Figure 1: *Conceptual view of Cognitive SDR Radio Architecture*[1]

A less flexible hardware radio may have some degree of cognitive ability but will be limited by the ability of hardware to adapt to different frequencies and modulations. A radio that can operate on only a handful of channels in a single band using a single modulation will have limited "interference avoidance" ability if all the channels are occupied. A radio that can only connect to a single radio network cannot change modes to avoid congestion.

To the extent allowed by the RF hardware a cognitive SDR radio may be capable of multitasking and can simultaneously receive and spectrum scan.

The interface between the cognitive layer and the application layer can be a simple known list or array of available modes or a highly abstracted interface. The abstracted interface of the cognitive layer would appear to applications in terms of a client requesting a communications service possibly with particular latencies or data rates.

[1] B. Fette, *Cognitive Radio Technology*, Elsevier 2006, Chapter 7, p 222 (Originally from T. Rondeau and C. Bostian).

5 Cognitive Radio Definitions and Nomenclature

If the technical community in general and the SDR Forum in particular (especially the CR WG & SIG) are to have a coherent dialogue in defining, developing, and promoting this nascent technology, then a sound unambiguous definition is needed. In this section, a working definition of the cognitive radio is developed progressing in technical depth in the context of multiple perspectives, various authors and evolving to the SDR Forum formal definitions.

Definitions of Various Industry Leaders & Standards Bodies

Dr. Joe Mitola coined the term in the late 1990's [1] and has since refined and distilled it most recently [2] to the following, stating that a CR is—

A really smart radio that would be self-, RF- and user-aware, and that would include language technology and machine vision along with a lot of high-fidelity knowledge of the radio environment.

Since the coining of that term, a number of definitions have been offered for CR over the last 5-7 years or so by industry leaders, including international standards bodies, technologists arguing before the FCC, academia, and others. These are presented in this section, which demonstrate strong similarities, but still differences that are significant enough to warrant the SDRF CRWG attempting to conceive a definition acceptable to most.

The Institute of Electrical & Electronic Engineers (IEEE): The IEEE-USA Board of Directors released a position statement in 2003 [3] that states the following:

A cognitive radio is a radio frequency transmitter/receiver that is designed to intelligently detect whether a particular segment of the radio spectrum is currently in use, and to jump into (and out of, as necessary) the temporarily-unused spectrum very rapidly, without interfering with the transmissions of other authorized users. CR is a relatively new technology, so we recognize that both technical and policy questions must be answered before full CR implementation can proceed.

Intel Corporation: A principal engineer at Intel gave a presentation on adaptive and cognitive radios at an Intel Developers Conference in early 2004 [4]. This presentation expanded the IEEE definition of a CR stating that CRs can be defined by characteristics:

*Radios that automatically find and access un-used (*sic*) spectrum across different networks (licensed and un-licensed [5] including the features of optimization and adaption)*

- *Optimization: Find the best link (in space, time) based on user requirements, e.g., cost per unit throughput, latency*
- *Continuously Adapt: Seamlessly roam across the networks always maintaining the "best link" possible*

New York State Office for Technology: In the published presentation to the US's FCC by NY's Office for Technology [6], the statewide wireless network of that office offers a number of useful definitions and perspectives about CR that distills into the following:

(CR) is a subset of software defined radio (SDR) technologies ... (and) learns from its environment and modifies its behavior based on what it learns.

ITU's Radio Communication Study Group: In an SDR-oriented report, the ITU offered the following definition for CR [7]:

A radio or system that senses, and is aware of, its operational environment and can dynamically and autonomously adjust its radio operating parameters accordingly.

Dr. Paul Kolodzy: Dr. Kolodzy[2] presented a succinct yet complete definition of CR at The Wireless Network Security Center (WiNSeC) of the Stevens Institute of Technology [8]. He defines a CR by its attribute:

[2] Dr. Kolodzy has much experience in the field of wireless communications, having served in various capacities over the last twenty years. Most notably this has included serving as the Director of WiNSeC, the

A CR has the ability to become aware if its environment and forms an "opinion" based upon that information … and can act on it.

The Global Standards Collaboration (GSC): The following definition was offered last year at the GSC conference in Sophia Antipolas, France [9], stating that a CR is—

A radio or system that senses and is aware of its operational environment and can be trained to dynamically and autonomously adjust its radio operating parameters accordingly.

Definitions in Popular & Technical Literature

Despite the potential impact of CR on wireless communications and technologies, there has been no noticeable mention of SDR or CR in the mainstream press including popular American weekly magazines such as *Time*, *US News & World Report*, and *Newsweek*. SDR but not CR has had one mention—back in July 2003 in the UK's *Guardian Unlimited* (online edition of *The Guardian*)[3]. One popular paper publication that is not mainstream because it targets the technology-savvy part of the general public is *Wired* (its circulation is one-fifth of *Time*'s), did have a substantive but passing reference to CR back in April 2003[4], but not since. However, web searches on the terms "Cognitive Radio" performed over years 2006-2008 have shown explosive rise in "hits", now numbering in the area of 90,000.

There have been definitions coined and quoted in both the *EETimes* and *Scientific American* that should be mentioned, since the *EETimes* is a respected voice of the technical industry and *Scientific American* is a reputable, general audience science magazine. The *EETimes* has often quoted Dr. Joe Mitola[5]. But perhaps of more interest is not a definition but the more populist description of CR as described in the March 2006 issue of *Scientific American* [10]:

Cognitive radio is an emerging smart wireless communications technology that will be able to find and connect with any nearby open radio frequency to best serve the user…. Adaptive software will enable these intelligent devices to reconfigure their functions to meet the demands of communications networks or consumers as needed...based on the ability to sense and remember various factors such as the radio-frequency spectrum, user behavior, or network state in different transmission environments at any one place and time.

IEEE Intelligent Systems magazine states that "Cognitive radios are adaptive and extremely programmable, learning users' preferences and automatically adjusting to changes in the operating environment."[6] By the way, this does *not* include cordless telephones.[7] A more technical, AI-slanted and analytically-oriented definition of CR is offered by Professor Simon Haykin in an invited paper published in the *IEEE Journal of Selected Areas in Communications* [11]:

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[8] to learn from

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Senior Spectrum Policy Advisor at the FCC, the Director of Spectrum Policy Task Force charged with developing the next generation spectrum policy and the Program Manager at DARPA in the Advanced Technology Office managing R&D for communications programs to develop generation-after-next capabilities.

[3] http://technology.guardian.co.uk/online/story/0,,994679,00.html.

[4] http://www.wired.com/news/politics/1,58601-0.html. "Author Howard Rheingold believes the freedom of technologists to innovate is under attack as never before.…Rheingold cited attempts to lock the public into using technologies that may not serve them as well as ones yet to be deployed, for example, cognitive radio, which makes intelligent use of a wide swath of the radio spectrum. At present, cognitive radio isn't possible because exclusive use of 56565 (*sic*) radio spectrum has been sold to the highest bidder. 'Incumbents (are) using their political or economic power to push back or thwart newcomers,' he said."

[5] Patrick Mannion quoting Dr. Joe Mitola in a 12/05/2005 article in EE Times, which can be found at http://www.eetimes.com/news/latest/showArticle.jhtml?articleID=174900299

[6] *IEEE Intelligent Systems* magazine, May/June 2003 issue;

[7] From Michael Marcus's column on "Regulatory & Policy Issues" in the May 2005 issue of *IEEE Communications Magazine*.

[8] "Understanding-by-building" is a term for a next generation artificial intelligence framework.

the environment and adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operation 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.*

The FCC expanded its definition of an SDR to include cognition not specifically but by beneficence. FCC document FCC 05-57 was a “rule change for smart radios,” i.e., performance can be improved and interference reduced if wireless systems were aware of other RF signals in their environment.[9]

5.2 The SDR Forum Cognitive Radio Nomenclature

SDR Forum and IEEE P1900.1 have developed harmonized definitions of Software Defined Radio, Adaptive Radio and Cognitive Radio[10]. The following material is intended to expand and elaborate upon these definitions to provide the reader with better insight than the formal definitions allow..

Introduction

This section is intended to communicate a set of definitions in the area of software defined radio and cognitive radio. These definitions have been developed to communicate to practitioners in the field, the position of the Software Defined Radio Forum with regards to these technologies.

Some of the definitions have multiple versions. This structure is to recognize situations where normal industry terminology is at variation with the desired logical definitions. It is intended to facilitate technical discussion by avoiding difference of opinion arising from presuppositions based on differing definitions. All definitions within this document relate to wireless communications.

Radio

a) Technology for wirelessly transmitting or receiving electromagnetic radiation to facilitate transfer of information.
b) System or device incorporating technology as defined in (a).
c) A general term applied to the use of radio waves. [11]

Radio Node

A wireless device point of presence incorporating a radio transmitter or receiver.

Software

Modifiable instructions executed by a programmable processing device.

Physical Layer

The layer within the wireless protocol in which processing of RF, IF, or baseband signals including channel coding occurs. It is the lowest layer of the ISO 7-layer model as adapted for wireless transmission and reception.

Data Link Layer

The protocol responsible for reliable frame transmission over a wireless link through the employment of proper error detection and control procedures and medium access control.

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[9] FCC certification according to FCC 05-57 is still with respect to the software content of the radio and not to any self-proclaimed cognizance.
[10] SDR Forum Definitions Document: SDRF – 06-R-0011-V0.5.1, 20 September 2007
[11] ITU-R Radio Regulations, Article 1 (Terms and Definitions, Section 1.4)

Software Controlled

Software controlled refers to the use of software processing within the radio system or device to select the parameters of operation.

Software Defined

Software defined refers to the use of software processing within the radio system or device to implement operating (but not control) functions.

Software Controlled Radio

Radio in which some or all of the *physical layer* functions are *Software Controlled*.

Software Defined Radio (SDR)

Radio in which some or all of the *physical layer* functions are *Software Defined*.

Adaptive Radio

Radio in which communications systems have a means of monitoring their own performance and a means of varying their own parameters by closed-loop action to improve their performance.

Cognitive radio refers to both an engineering paradigm for designing wireless systems and the implementations of that paradigm. Because cognition is normally associated with human thought processes, the cognitive radio community has adopted several terms from human psychology to describe cognitive radio whose meaning is unclear in an engineering setting. To resolve this, the following also defines these related terms in a manner applicable to wireless engineering.

Cognitive Radio (design paradigm - 1)

An approach to wireless engineering wherein the radio, radio network, or wireless system is endowed with *awareness*, *reason*, and *agency* to *intelligently* adapt operational aspects of the radio, radio network, or wireless system.

We now discuss the terms used in the above definition:

Awareness

a) The *perception* and retention of radio-related information
b) The functionality with which a radio maintains internal information about its location, spectrum environment, or internal state, and is able to detect changes in that information. Radio awareness is required for supporting the *cognitive control mechanism*.
c) The perception and retention of information by a radio

Typical types of information used in a cognitive radio include location, environmental information, and internal states.

Perception

The process of acquiring, classifying, and organizing information.

Note that there are many different potential sources of information that may be acquired. Some sources may be internal (e.g., a measurement of an amplifier bias current); some may be external (e.g., information from a networked database); some information may be about itself (e.g., the radio's own location); and some information may be about other radios (e.g., the interference experienced by another radio).

Reason

The application of logic and analysis to information.

The term "cognitive" radio comes in part from the combination of awareness and reasoning capabilities.

Cognition

The capacity to *perceive*, retains, and *reason* about information.

Agency

The capacity to make and implement choices.

Intelligence

Exhibiting behavior consistent with a purposeful goal.

While a system could be cognitive without exhibiting agency (e.g., a brain in a jar), or could have cognition and agency without intelligence (e.g., a person who makes all of his/her choices by a flip of a coin), all three aspects are critical to the cognitive radio design paradigm.

Using these definitions, the cognitive radio design paradigm can be equivalently defined as follows.

Cognitive Radio (design paradigm - 2)[12]

An approach to wireless engineering wherein the radio, radio network, or wireless system is endowed with the capacities to:

- acquire, classify, and organize information (aware)
- retain information (aware)
- apply logic and analysis to information (reason)
- make and implement choices (agency) about operational aspects of the radio, network, or wireless system in a manner consistent with a purposeful goal (intelligent).

Because there are far too many ways that the cognitive radio paradigm can be applied to list all possible implementations, the subsequent text only defines the three classes of implementations most commonly discussed at the time this document was created – cognitive radio, cognitive network, and cognitive radio network.

Cognitive radio (implementation)

a) A radio designed according to the cognitive radio engineering paradigm.

b) Cognitive radio as defined in (a) that utilizes *Software Defined Radio*, *Adaptive Radio*, and other technologies.

c) A radio endowed with the capacities: to acquire, classify, retain, and organize information, to apply logic and analysis to information, and to make and implement choices about operational aspects of the radio in a manner consistent with a purposeful goal.

d) A radio, radio network, or wireless system designed according to the cognitive radio engineering paradigm.

e) Note that cognitive radio does not explicitly refer to a specific realization of a radio. A mobile could be a cognitive radio; a base station could be a cognitive radio; a mesh node could be a cognitive radio; etc.. Also, having a capacity does not imply that the capability is always used. For instance a mobile cognitive radio might have its operation directed by a network at some times and be self-directed at other times. In all cases, the mobile cognitive radio remains a cognitive radio because it has the requisite capacities even when not actively exercised.

[12] These capacities can be readily mapped to the components of the cognition cycle. For instance perception captures the processes of observation and orientation; agency and reasoning implies the decision and action processes, and learning is the retention of the results of reasoning.

Cognitive network

a) A network designed according to the cognitive radio engineering paradigm.

b) A network endowed with the capacities: to acquire, classify, retain, and organize information, to apply logic and analysis to information, and to make and implement choices about operational aspects of the network in a manner consistent with a purposeful goal.

c) Example: An enterprise WiFi network wherein "thin" access points take in sensing information which is then passed to a networked controller; which then assigns channels to the access points.

Note that the centralization of the capacities for cognition and agency is not critical to the concept of a cognitive network. Instead these capacities could be implemented as distributed processes.

Cognitive Control Mechanism

Cognitive control mechanism is the mechanism through which cognitive radio decisions are implemented.

Policy

a) A set of rules governing radio system behavior. Policies may originate from regulators, manufacturers, developers, network and system operators, and system users.
b) A machine interpretable instantiation of policy as defined in (a)

Policy-Based Radio

Radio in which the behavior of communications systems is governed by machine-interpretable policies that are modifiable

Transmitter

Apparatus producing radio-frequency energy for the purpose of radio communication.

Receiver

A device that accepts a radio signal and delivers information extracted from it.

Air Interface

The subset of *waveform* functions designed to establish communication between two radio terminals. This is the *waveform* equivalent of the *wireless physical layer* and the *wireless data link layer*.

Waveform

a) The set of transformations applied to information to be transmitted and the corresponding set of transformations to convert received signals back to their information content.
b) Representation of a signal in space
c) The representation of transmitted RF signal plus optional additional radio functions up to and including all network layers.

5.3 Attributes of Cognitive Radio

The above definitions provide good boundaries for a working definition of a CR because it provides multiple valid perspectives of parties with vested interests in this technology. A number of attributes have been mentioned in the preceding section, which are now distilled. Therefore, depending on the perspective of who is defining a CR, it would possess any or all of the capabilities described in the following sections.

Aware

First of all, the CR possesses awareness. It can sense, store, recall, disseminate, and make inferences from information derived from its RF environment, geolocation, contextual, and is able to sense its current internal states.

Adjustable

The operating characteristics of the CR can change in response to its environment, of which it is aware. It can change its emissions (frequency, power, & modulation) in real-time without user intervention in response to unexpected changes to its environment, or to save battery power or reduce interference to other users. Also, since the CR is spatially aware, it can cross political borders and adjust itself to stay in compliance with all local radio operation and emissions regulations.

Automatic operation

The CR does not require user intervention in order to be adjustable. Fundamentally, it may have to perform spectrum sensing and exploitation to be adjustable. On its own the CR can exploit locally vacant or unused radio channels or ranges of radio spectrum to provide new paths to spectrum access, based on rules originating from local policy constraints.

Adaptive

The CR can understand and follow the actions and choices taken by its user and over time learn to become more responsive and to anticipate his needs.

6 Cognitive Radio Elements

In this section, we describe some of the elements or capabilities that may be found in a cognitive radio. These elements are used to provide inputs or constraints to the cognitive and policy engines.

6.1 Sensing and Sensors

A cognitive radio requires current information regarding its awareness of its environment, its internal state, node capabilities, and current needs of its user. Environmental sensing may be local and self contained in a radio or remotely performed elsewhere in the network. In collaborative sensing for example, some other device or system collects information about a radios environment and that information may be relayed to the user's radio.

Spectrum Sensing

Spectrum sensing refers to the action of a wireless device measuring characteristics of received signals, which may include RF energy levels as part of the process of determining if a particular section of spectrum is occupied.

Sensing in the spectrum domain is the detection of some signal features indicating the presence (or absence) of other users/services. These can include signal energy, periodic features (pilots, preambles, chip rates), likely identity of the other users/services, estimation of interference-tolerance capabilities and estimation of the duration of spectrum occupancy.

Collaboration and Spectrum Sensing

In cognitive radio systems, two or more wireless nodes combining their capabilities and spectrum-usage resources using negotiated or prior arrangements, is a common way for cognitive radios to have a more global sense of spectrum usage. Delegation of spectrum-usage tasks based on the expected global value of this action allows the network to select more globally optimal choices in minimizing interference over a larger region.

The implementation of a collaborative communications solution may be more effective than individual 'greedy/selfish' approaches. The first stage of a collaborative approach is to identify and form the ad hoc network using underlay and overlay communications. The capabilities and objectives of each node can then be assessed and a leader (if required) is elected. A consensus formation process is initiated, and during the implementation of the strategy, monitoring and strategy-update mechanisms accommodate change.

Advanced Collaborative Sensing

Individual cognitive radio devices could combine cognition capabilities and information to achieve a set of goals that benefit all participants or reach a global consensus regarding a particular scenario. One example of this application is a distributed sensor mesh network used to build a map of the wireless activity in a wide area for frequency planning and allocation, device detection and movement pattern monitoring.

Inferred vs. Explicit sensing

Inferred sensing refers to the act of monitoring performance indirectly through measures such as frame error rate.

Explicit sensing refers to the act of explicitly taking steps and including circuits and devices to be able to directly measure an environmental quantity.

Sensing Examples

Commonly used measures (observable parameters) that may be useful in a cognitive radio are shown in figure 2 below:

Link quality measurements in Physical layer:

Bit-error-rate (BER)
Frame error rate (FER)
Signal-to-noise-ratio (SNR)
Received signal strength (RSS)
Signal-to-noise-plus-interference-ratio (SINR)

Radio channel parameters (including path loss, long and short term fading)

Noise power
Noise plus interference power
Peak-to-average power ratio (PAPR)
Error vector magnitude (EVM)
Cyclostationary features

Link Quality measurements in MAC layer:

Frame error rate (CRC check)
ARQ request rate (for data communication)

Other possible measures in network layers:

Mean and peak packet delay (for data communication)
Routing table or routing path change rate (for ad-hoc and sensor networks)
Absolute and relative location of nodes (location awareness), velocity of nodes, direction of movement

Channel selectivity measures in Physical layer:

Time selectivity of channel (Doppler spread)
Frequency selectivity of the channel (Delay spread)
Space selectivity of the channel (Angle spread)
LOS and NLOS measure of the channel

Situation (context) awareness:

User's needs, preferences, activity, and circumstances
User's behavior (e.g. tasks, habits)
Location, time, temperature, physical circumstances, and other ambient conditions
User's perception of the services

Figure 2: *Commonly Useful Metrics Used by Cognitive Radios for Sensing and Awareness*

6.2 Awareness

Aware implies the ability to integrate sensations from the environment with one's immediate goals in order to guide behavior or draw conclusions. We recognize *Cognizant* as a formal equivalent of *aware* and the root of the name “Cognitive Radio”. *Conscious* emphasizes the recognition of something sensed or felt. Cognitive radios are aware (conscious) radios with the following senses, and the ability to respond to those sensors.

RF/Environment Awareness

Physical quantities including received voltage and ambient temperature fall in this class. Received radio frequency energy is a measure of how much a section of spectrum is occupied at a point in space. Cognitive radio uses spectrum awareness to optimize performance and spectrum utilization by a number of factors based on orthogonality in the dimensions of time, frequency, code, or modulation.

Network Awareness

Identification of all the sources and infrastructures in current geographical area capable of servicing the user and compatible with the radio constitutes network awareness. This also involves being aware of subtle nuances within the network’s structure such as the data links, transport, routing paths and management layers. Network awareness also includes network characteristics such as the QoS, frame error rate, frame delay etc.

Location Awareness

Geographical location identification by a radio constitutes location awareness. Location awareness is significant, particularly for international and coalition communications. This awareness provides the radio ability to discern local infrastructure or policy, primary incumbent transmitters and receivers, terrain, altitude, propagation channels, and the location of network members.

User Awareness

The ability to interpret a user’s needs, preferences, service and operating requirements constitutes user awareness. User awareness drastically simplifies the task of providing, choosing, and using a suitable wireless network service. The users are able to benefit from a targeted solution or a finite range of sufficient solutions, rather than simply being overloaded with choices. This also includes user speech, language and biometrics awareness.

Hardware Awareness

The available wireless device processing power, real time operating system and remaining energy fall in this category of hardware awareness. This also includes DSPs, RF and multimedia chipsets in the wireless device that, among other functions, manage modulation, cryptography, protocols, and source coding for voice, data, and imagery. High-density FPGAs are also important resources of a radio enabling reconfiguration and provide capability to change waveforms and adjust performance characteristics, frequency, power, and other attributes. Cognitive radios need to be aware of the processing functionality and capability in order to keep size and power consumption to a minimum.

Policy Awareness

The ability to operate legally and agilely across multiple bands and in multiple different places using policies as a means to check whether you're legal and eligible constitutes policy awareness. The policies can include regulatory and system specific policies. Hard/soft-wired policies can determine when spectrum is considered as opportunity as well as providing constraints on using these spectrum opportunities.

Figure 3 depicts how many of these different domains of awareness can influence the decisions of the policy engine. In this figure, the environmental domain encapsulates external information and sensing resources including (and not limited to) ambient and temperature differentials, acceleration and shock, air quality, radiation, geolocation and trajectories. The radio domain includes information from spectrum sensing outcomes, wireless network activity, and node capabilities. The policy domain concerns the rules, constraints and operational guidelines for node and network operation. The social and economic domain refers to the different business and deployment models that may be employed. As an example, the wireless node may be deployed in a developing area to facilitate low-cost or free connectivity, or may be deployed in a revenue-rich, time-poor context in a business district. Regarding the user domain, this includes the actions of the user, patterns of behavior, and current and historical wireless service requirements. The influence of one or more domains can be weighted according to the relevance of each domain in the use-case or user context.

The policy engine can then base its outcomes using the combined set of weighted information regarding the different domains. In Fig. 3, information from all the domains is illustrated as being equally weighted and the policy engine outcomes are therefore biased equally for all domains. Increasing the weighting towards a domain increases the sensitivity or importance of information derived from that domain; decreasing the weighting for a domain decreases the sensitivity or importance of that domain in the decision-making process.

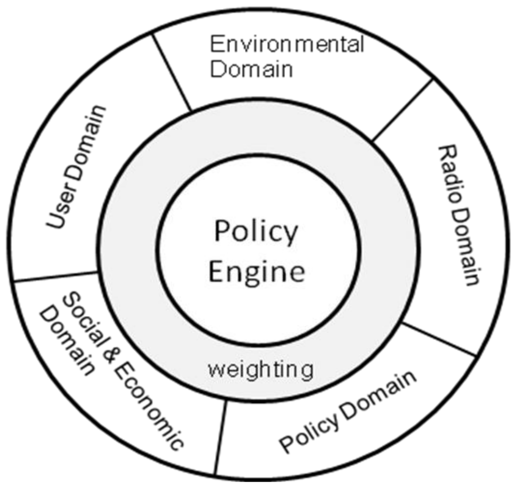

Figure 3: *Domains of awareness that can influence a cognitive radio policy engine* [13]

Other awareness items

Awareness of available routing paths, especially in a dynamic environment, is useful for optimizing the performance of ad-hoc networks.

6.3 Adaptation

- Adaptive: Capability to alter operational characteristics (to environment)
- Aware: Ability to interpret and derive understanding of input data
- Automatic: Not requiring user intervention

Simple Deterministic Rules Based Adaptation

This type of system follows fixed rules. A response to an "input" is repeatable and predictable. These systems are easy to "type accept" and relatively straightforward to test. This may be considered as a set of rules coded as a simple sequence of if-then-else rules without any inference.

Policy based radio

A policy based radio has embedded within it a set of rules or policies which describe under what conditions it may operate. Limitations such as frequency, power level, time-of-day, location and others are controlled or governed by the embedded rule set. A critical difference between a policy based radio and a cognitive radio is that a cognitive radio in some sense learns while the policy based radio does not. That is, given a

[13] Source: Dr. Keith Nolan, Centre for Telecommunications Value-Chain Research.

set of input conditions, a policy based radio should always arrive at the same conclusion regarding how the radio should operate. On the other hand, a cognitive radio may learn more about the environment or learn about its parameter selection performance by recording its experience, and therefore may react differently when provided with the same set of input conditions.

The sets of rules may be very complicated depending on the capability of the radio and on the ability of the user or owner to transport the radio into or across other regulatory jurisdictions. Inference engines developed in the artificial intelligence community may be used for the more complex cases.

Complex Inference Engine Based Adaptation: Ambiguous Rules

Rules derived from legal, natural language expressions of legislation, regulations and policies can be ambiguous or impossible to express in a concise un-ambiguous machine readable form. Higher level expressions beyond a set of simple non-overlapping “if-then-else” rules may be required.

Specific languages and tools have been developed by artificial intelligence researchers to both express complex rules and to process a set of inputs against these rules to arrive at a decision about frequency, waveforms, protocols or other utilization decisions. Web ontology language (OWL), DAML, and OIL are languages commonly used for policy analysis and reasoning.

Cognitive Radio Adaptation Examples

Figure 4 shows some of the aspects of a wireless node that are subject to adaptation:

Link and network adaptation:

Physical layer writable parameters

Transmitted power
Channel coding rate and type
Modulation order
Carrier frequency
Cyclic prefix size (in OFDM based systems)
FFT size, or number of carriers (in OFDM based systems)
Number of pulses per bit (in impulse radio based Ultrawideband systems)
Pulse-to-pulse interval, i.e. Duty cycle (in UWB systems)
Antenna parameters in multi-antenna systems (like antenna powers, switching antenna elements, antenna selection, beam-forming coefficients etc.)
RF impairment compensation parameters
Etc. (many other system specific writable parameters)

Mac layer writable parameters

Channel coding rate and type
Packet size and type
Interleaving length and type
Channel/slot/code allocation
Bandwidth (like number of slots, number of codes, number of carrier, number of frequency bands, etc.)
Carrier allocation in multi-carrier systems, band allocation in multi-band systems

Other writable parameters

Cell assignment (in hierarchical cellular)
Routing path/algorithm (for multi-hop networks)
Source coding rate and type
Scheduling algorithm
Clustering parameters (for clustering based routing and network topology)

Related to context awareness:

Service personalization (to adapt services to the context such as user preferences, user location, network and terminal capabilities)

Receiver adaptation:

Channel estimation, synchronization, frequency offset parameters adaptation
Soft information generation adaptation
Equalization/demodulation parameters adaptation
Interference/noise cancellation parameters adaptation
Receiver antenna selection/combining adaptation
Receiver filter adaptation

Constraints in employing adaptation:

Constant BER (Ensuring the desired BER requirement satisfied)
Constant FER
Maximizing the overall system throughput
Minimizing the network power dissipation (especially critical for power efficient network design like wireless sensors networks)
Minimizing the average and peak delay
Maximizing the system capacity
Maximizing the user's perception of the video/speech quality or other services

Figure 4: *Example parametric controls that may be exerted by a Cognitive Radio*

6.4 Learning

Advanced Cognitive Radios may include learning.

Learning in the context of cognitive radio means that the quality of decisions and adaptations improves with time such that when presented with a set of environmental test stimuli the decisions arrived at are not constant and repeatable, they improve with experience. This capability does raise new issues related to testing and "type acceptance". The main issue is that the radio may respond differently when presented with an identical set of conditions.

6.5 Machine Reasoning

This is another term for the action of a radio using awareness of its state or environment to select an adaptation of its operating characteristics. Reasoning is the act of inferring knowledge based on inputs.

6.6 Optimization

Cognitive SDR Radios will attempt to adapt in ways to optimize their performance or to optimize their usefulness for users.

7 Spectrum Efficiency and Specific Cognitive Radio Techniques

7.1 Spectrum Efficiency

The prospect of increasing the efficiency of how frequency spectrum is used has been one of the key factors that have increased interest in cognitive radio.

Efficiency measures and metrics

An exact, mathematical, engineering definition of spectrum efficiency has proven to be elusive. Link or modulation efficiency is often expressed in units of bits-per-second-per-Hz or alternatively bits-per-second-per-Hz-per square kilometer. A link with a larger value of bits-per-second-per-Hz is considered a more efficient link. This unit of efficiency does not capture some of the effects of creating an RF transmission. While useful for comparing individual links this metric does not directly capture the impact of any given transmitter on the ability of another user to use spectrum. The communications link also consumes transmitted power and also captures the geographical area "illuminated" by the radio energy. The illuminated area creates a zone where other users cannot receive signals at the illuminated RF frequencies. Efficiency must take into account the entire ensemble of users.

In many contexts, efficiency is the ratio of a unit of a desired output to the total amount of resources consumed to produce that unit of output. In a communications system, one possible output is the total information content (bits) received by all users in a geographical area. The total spectrum resources consumed is a four (or five) dimensional volume of spatial x and y (and possibly z), frequency and time. Other resources include transmitter power.

More research in this area is highly recommended.

Spectrum Sharing (secondary users in licensed spectrum)

Spectrum sharing is the method where spectrum that has been assigned to a license holder is made available to other users on a secondary, non-interfering basis. The secondary users may have arrangements with the license holders that are arrived at through some kind of cooperation agreement. The secondary users may, by following a set of rules designed to prevent the possibility of interference, access the spectrum either with the cooperation of, or alternatively without the knowledge of license holders depending on the relevant policies and protocols.

Spectrum Pooling

Spectrum pooling refers to the act of multiple spectrum license holders combing or pooling their spectrum allocations with agreements in place describing means for access, roaming, billing, . Generally, the spectrum footprints overlap, and possibly the needs of all users are served by a common infrastructure. For example, many taxicab dispatch activities can be shared with dispatch of other service organizations through common transmitters, common repeaters, and common antennas.

7.2 Geolocation

Geolocation based cognitive radio describes a system where a radio uses knowledge of its own location to select an operating frequency or network such that interference is avoided. Geolocation can also support other cognitive functions.

Geolocation generally refers to a service on either the client or within the network which can determine a user's real world geographic location, and can be used for time-series velocity, historical and estimated path. For cognitive radios, geolocation services can be implemented through either database lookup or triangulation of various beacons, such as GPS, cell, WiFi, or even Bluetooth. Geolocation information provides a basis for a number of higher level cognitive functions such as determining available network types, policies, and position reporting for emergency requests.

Network-side geolocation services can be derived from triangulation of transmit power levels at various access points or from geolocation-capable radio reports. Network uses of geolocation information for cognitive radios include network load balancing (i.e. AP assignment, peer to peer, mesh or relay formation), network handoff, and location determination for emergency services.

7.3 Dynamic Frequency Selection (DFS)

Dynamic frequency selection refers to the act or ability to dynamically choose an operating center frequency. Prior to transmitting a radio may attempt to detect the presence of other, possibly licensed, radios and avoid operating on frequencies that could cause interference with other radios or other systems.

DFS can also be described as a general term used to describe mitigation techniques that allow, amongst others, detection and avoidance of co-channel interference with other radios in the same system or with respect to other systems.

7.4 Adaptive Bandwidth Control

Describes the ability of a radio to expand or contract its operating emission bandwidth.

7.5 Transmit Power Control

Describes the technique where a radio using feedback or some other means to increase or decrease the input power to the antenna. Transmit power control may also involve the reception of interference information from other co-channel systems.

7.6 Radiation Pattern Control, Directional Antennas

Directional and steer-able antennas are used to control radiation patterns and reduce interference. Controllable radio patterns can be combined with awareness of the directions of desired receivers and the directions of potential victims of interference to improve performance.

7.7 Beacons, Physical and Virtual

Beacons are external sources of information that are used to control access of secondary users to a section of spectrum. Beacons can be single carrier radio transmitters delivering information including the availability of spectrum, or they may also be used for waveform parametric guidance, policy updates, location awareness, and other information useful to local users.

Beacons may be virtual or logical in the sense of a allocating a few dedicated bits in an existing data stream on an existing radio signal.

Beacons may be used to signal the availability of spectrum, that is, if the beacon is heard then the corresponding spectrum is free for use. This method provides a degree of safety in the event the beacon is shadowed or otherwise not received.

Beacons may also be used to signal the presence of a primary user and therefore signal the unavailability of spectrum.

7.8 Spectrum Leasing

Refers to the act of a secondary user entering into a leasing or renting agreement with a primary user for access to spectrum. Leasing may also refer to otherwise reimbursing a license holder in exchange for access and use of the license holder's spectrum. Leases may be long or short term in length. Leases may be cancellable or revocable.

7.9 Advanced Cognitive Radio Topics/Features

Energy (battery) awareness (See CASIG Glossary)

Refers to including knowledge or awareness of the remaining amount of energy in a radio's power supply (e.g. available battery charge) to influence decisions about which operating mode or frequency to use.

Self-correction, Fault tolerance

Refers to the ability of a radio to discover that, for some reason, something is wrong, and that it can reconfigure itself and thereby recover and re-establish communications.

Recovery after incorrect decision, error condition sensing

It is expected that cognitive radios will in some situations adapt their operating characteristics in a way that worsens performance or possibly increases the likelihood of causing interference. Decisions should be followed up with checks where possible to detect these situations and initiate corrective action. Awareness of error conditions could be part of the input set of the cognitive engine.

Negotiation

Negotiation refers to radios that can adapt to new operating characteristics based not only on knowledge of their own priorities and goals and environmental state. Radios and networks that can share knowledge and negotiate with each other to select mutually optimal operating characteristics may perform better. A negotiation language that can express the concepts of and "offer" and "counter-offer" may prove useful

7.10 Testing and Verification of CR and CR rules

The rule-sets and engines of a cognitive radio need to be tested prior to their release. The level of complexity of large rule sets may complicate the testing process. More work in this area is needed.

7.11 CR Software Assurance

Refers to ensuring that the rules or policies or decision software is from a valid source and has not been compromised or tampered with. Keys, trust relationships, and signatures may all play a role in software assurance.

8 Network Aspects

Radios are used in conjunction with other radios and radio networks to provide communication services. In this section some cognitive radio aspects that involve elements beyond an individual radio are discussed.

8.1 QOS and Priorities

For networks supporting cognitive radios, the definition of Quality of Service can extend beyond the traditional parameters of bandwidth, error rate, jitter, and latency. For example, QoS parameters could be extended to support emergency traffic prioritization (i.e. VoIP on WLAN), client or message-specific fee arrangements, remaining battery life of requesting clients, and either reported or measured client location/direction.

Many current definitions of network QoS approaches are confined to a single network view. As radios are increasingly able to access multiple networks, sometimes in parallel, the network QoS scope can include broadened types of support. For example, a network may offer client reports on current and expected conditions of latency, maximum bandwidth, geographic coverage envelope, etc to cognitive radios which are making assessments of alternate connection types. The network QoS approach may need to facilitate graceful handoff to and from other network types. Or, a network may allow reconfiguration from centralized Access Point (AP) mode to peer-peer mode for specific messages to achieve maximum overall network QoS

8.2 Priority Allocation and Radio Resource Management

Awareness of the state of available energy sources (battery, fuel-cell, bio-energy) enables a cognitive radio to vary its cognition abilities in order to maximize radio operational lifetime. Ancillary cognitive radio services/abilities including environmental and long-term spectral monitoring, message-relaying and collaborative sensing tasks could be deactivated as the energy sources near depletion. Alternatively, the interval between sensing and message relaying tasks could be increased thus reducing overall power consumption. The cognitive radio can then focus its remaining energy resources on high-priority wireless services.

8.3 Message Relaying

In heterogeneous and disaggregated network environments, a cognitive radio can be used to relay message traffic between adjacent yet incompatible wireless devices. This is especially useful for scenarios where the destination node is out of transmission range of the source node. For multi-hop data packet transfers where the RF transmit power of a single cognitive radio device is limited, message-relaying using several wireless devices between the source and destination nodes is therefore possible. Message-relaying can be integrated into the cognitive radio as an underlying ‘invisible’ wireless-service entity that operates in conjunction with the main user service.

8.4 Ad-hoc Network CR Element

A fixed, mobile or nomadic cognitive radio device can act as a bridging node between standalone domains of ad-hoc nodes. Bridging nodes can also be used to form a message-relaying connection between an ad-hoc network domain and a wired network. Each ad-hoc network domain may employ different ad-hoc network protocols therefore the cognitive radio ad-hoc network element would have multi-ad-hoc network protocol-handling capabilities.

8.5 Electronic Payments

An Electronic Payment element incorporated into the cognitive radio architecture could obtain and manage reimbursement for communication services provided in real-time. This could then be used to collect and distribute revenue generated from using wireless services across different network architectures and service providers. One example of a scenario using this scheme is a message-relaying service where a message is passed from source to destination nodes routed through a series of intermediate cognitive radio devices. Each cognitive radio device could then receive micro-payments (a small portion of the original payment by the source node) in return for relaying the message. A payment service could act as an incentive to retain and encourage cooperation within the active cognitive radio devices and users in the wireless network.

8.6 MAC layer bandwidth allocation

One way to get spectral efficiency is to use a MAC based shared physical channel on a user device or relay device. For instance a device may simultaneously need to communicate isochronous voice, data, or sensor information. The MAC layer may have to decide on how to allocate communication capacity among the different sources of information.

8.7 Greater priority for Public Protection

In cases where different classes of users are in contention for spectrum resources there may be situations where certain users are given greater priority by a cognitive radio according to policies in its rule base. The levels of priority may change over time, or as a function of the role of the user and his current situation.

8.8 Graceful Degradation

There are a number of circumstances that can reduce the operating effectiveness of a radio. Among them are a depleted energy source, moving toward the fringes of coverage area, introduction of an interfering signal, and changes in multipath effects. When these problems occur, a cognitive radio can degrade its performance parameters and/or decrease its level of functionality or features to maintain communications at a degraded but sufficient level rather than lose all contact. Doing so in a way as to minimize disruption is referred to as graceful degradation.

9 Aspects of System Environment

For purposes of analyzing how cognitive radio communications systems operate the following five aspects can be used to provide insight into system operations. They are particularly pertinent to development of use cases that are the source of requirements for system architecture and development.

9.1 Physical

This aspect is concerned with the physical world, including issues of geography, geometry, topography, proximity, density, RF propagation characteristics, and locale. What resources are where, and how can they get to where they are needed? How large is the area for which communications coverage is required? For a Public Safety response scene, what is the geometric distribution of injured people, hospitals with capacity available, and transport to move them? How are responders moving over time and how is the geographic layout of the responders changing over time (e.g., expanding a perimeter)?

9.2 Network

This item deals with the technical issues of how information flows and how failed systems are restored, both normally and in response to the emergency. How are radio systems structured, and how do they connect with other networks such as personal area networks, commercial systems such as the telephone network or WiFi/WiMAX capabilities? Is there a need for interoperability? How much bandwidth is needed? What quality of service is needed? What kinds of terminals are available? How do all the different agencies talk with each other and distribute data? Does the network use base stations with an infrastructure, repeaters, direct peer to peer, or an ad hoc mesh? What authentication mechanisms are used in the network? What cryptographic algorithms support communications security?

It is in the network environment aspect that most cognitive radio considerations fall. Cognitive radio technology has prospects for significant improvement in system performance over manual operation.

9.3 Procedural

This issue deals with the role of people in the system. For commercial systems, how do users obtain equipment and accounts to use the system? For public safety, what procedures are followed, including authority, command, control, operating procedures, communications security procedures, and activation of contingency plans? Who develops contingency plans? Who has command and control of the situation? Who authorizes individuals or groups to operate radios? What is the registration process for new communications devices requiring authentication? Who reviews requests for registration? Who reprograms radios?

Cognitive capability in systems serves to reduce the need for human involvement. When properly designed it can even provide better solution of complex problems in less time that a human participant. In effect, the cognitive radio functionality serves to move tasks from the non-real time procedural environment to a real time network and radio environment.

9.4 Regulatory

Regulators administer the use of spectrum, issue licenses for radio operation, resolve issues of interference, and make rules for radio operation. Regulations dictate specific or a range of characteristics including modulation techniques and frequencies of operation. Rules for operation in unlicensed spectrum and the allocation of spectrum for emergency use fall under the remit of the regulatory bodies.

9.5 Economic

Economic considerations dominate commercial systems. Capital expenditures (CAPEX) are needed to purchase and install the system. Operational expenditures (OPEX) are concerned with the cost associated with running it. There is only one significant revenue source, and that is the revenue per user that is paid for system access and use. The challenge is to build out the system so as to adequately support users, to avoid premature installations that could result in significant unused capacity, but efficiently provide for system expansion.

For non-commercial systems, the ability to upgrade systems is very dependent on cost of equipment and availability of funding. Costs are very volume sensitive, so any opportunity to capitalize on the enormous volumes of commercial system equipment can result in cost savings.

9.6 Time

Time is an overarching consideration that applies to all of the other aspects. During the time before a specific event, there is time for establishing organizations, procuring equipment, recruiting and training personnel, building networks, definition of policies and procedures, and development of contingency plans. When an event occurs in the non-commercial sector, the first problem is awareness that something has happened, and learning enough to assess the situation. Then decisions are needed to determine the nature of the response, what resources to commit to it, and what actions to pursue. Operations continue until the emergency is resolved, and then the units involved stand down. After an event is over, an after-action review considers how well the operations were executed, and what can be done to improve preparedness for subsequent emergencies.

10 Conclusions

We have discussed a number of different considerations of the use of Cognitive Radio technology. The challenge is to understand its implications, and make use of its capabilities to specify, design, and operate communications systems that provide users with capabilities they need, enhance their applications, and make them more effective. Gaining more utility from existing spectrum or minimizing the acquisition cost of additional spectrum for additional services is shown to have a huge monetary value. And in the commercial world, time is also critical. Systems must complete their communications tasks within an acceptable time frame to suit the user’s purposes. All of these goals are substantially enabled by cognitive radio capabilities.

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