Working Document Towards a Preliminary Draft New Report on Cognitive Radio in Land Mobile Service

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SOFTWARE DEFINED RADIO FORUM

WORKING DOCUMENT TOWARDS A PRELIMINARY DRAFT NEW REPORT ON COGNITIVE RADIO IN THE LAND MOBILE SERVICE

1. Introduction

The QUESTION ITU-R 241-1/8 “Cognitive radio systems in the mobile service” was approved in October 2007. We note that the ITU-R has been active in studying Software Defined Radio in the land mobile service. The QUESTION ITU-R 224-2/8 “Adaptive antennas” was also approved in October 2007. The technical material generated by other relevant ITU-R Working Parties in response to this Question may have an impact on Cognitive Radio studies.

2. Discussion

The Software Defined Radio Forum (SDRF) is a non-profit organization dedicated to promoting the development, deployment and use of software defined radio technologies for advanced wireless systems. The membership of the SDR Forum consists of commercial, defense, and civil government organizations, and includes wireless service providers, network operators, component and equipment manufacturers, hardware and software developers, regulatory agencies, and academia. Presently numbering more than 100 members, the SDR Forum's membership spans Asia-Pacific, Europe, and North America. In January 2005, the SDRF, under its Technical Committee, chartered a Working Group on Cognitive Radio technology.

Based on over two years of study, the Software Defined Radio Forum is pleased to provide this contribution as its initial response to the QUESTION ITU-R 241-1/8 “Cognitive radio systems in the mobile service”.

3. Proposal

It is proposed that WP5A use Annex 1 as the outline of a Draft New Report on Cognitive Radio and related technologies.

We appreciate the opportunity to respond to these issues and look forward to further review at the 2nd meeting of Working Party 5A.

Annex 1
Working Document for the Preliminary Draft New Report on Cognitive Radio in Land Mobile Service

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1 Cognitive Radio

The following is excerpted from "SDR Forum Cognitive Radio Definitions", SDR Forum Approved Document Number SDRF-06-R-0011-V1.0.0.This document was approved by the SDR Forum in Plenary ballot on November 9, 2007.[1]

1.1 Definition

a) Radio in which communication systems are aware of their environment and internal state and can make decisions about their radio operating behavior based on that information and predefined objectives. The environmental information may or may not include location information related to communication systems.

b) Cognitive Radio (as defined in a.) that utilizes Software Defined Radio, Adaptive Radio, and other technologies to automatically adjust its behavior or operations to achieve desired objectives

2 Closely Related Radio Technologies

The following is also excerpted from "SDR Forum Cognitive Radio Definitions", SDR Forum Approved Document Number SDRF-06-R-0011-V1.0.0, and discusses some of the closely related technologies and their functionalities that may be a part of cognitive radio systems. The material in this section has been developed as a formal position of the SDRF, and is in the process of being harmonized with IEEE P1900.1. Although format changes have been made to permit incorporation here, no changes have been made in the wording of the definitions. This material has not been rectified or harmonized with other portions of this response.

2.1 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 approach of the Software Defined Radio Forum 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.

[1] http://www.sdrforum.org/pages/documentLibrary/documents/SDRF-06-R-0011-V1_0_0.pdf

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2.2 Definitions

2.2.1 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.

2.2.2 Radio Node

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

2.2.3 Software

Modifiable instructions executed by a programmable processing device.

2.2.4 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.

2.2.5 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.

2.2.6 Software Controlled

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

2.2.7 Software Defined

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

2.2.8 Software Controlled Radio

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

2.2.9 Software Defined Radio (SDR)

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

2.2.10 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.

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2.2.11 Intelligent Radio

Cognitive radio that is capable of machine learning.

2.2.12 Radio Awareness

Radio awareness is 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.

2.2.13 Cognitive Control Mechanism

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

2.2.14 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)

2.2.15 Policy-Based Radio

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

2.2.16 Transmitter

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

2.2.17 Receiver

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

2.2.18 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.

2.2.19 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.

3 Key Technical Characteristics, Requirements, Performance and Benefits of Implementation of Cognitive Radio Systems

The following is excerpted from *Cognitive Radio Definitions and Nomenclature*, SDR Forum Working Document SDRF-06-R-0009-V0.05. This working document has been voted out of the Cognitive Radio working group and is in the process of being approved by the SDR Forum membership. The answer to this question may be amended at a later date pending review of comments received during the balloting process. [Editor's Note: Although format changes have been made to permit incorporation here, original wording is largely intact.]

3.1 Introduction

The preceding definitions (see 2.2) provide good boundaries for a working definition of a CR because they provide multiple valid perspectives of parties with vested interests in this technology. The following discusses the characteristics, requirements and the benefits associated with the implementation of cognitive radio systems.

3.2 Characteristics and Requirements

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 one or more of the capabilities described in the following.

3.2.1 Aware

First of all, the CR possesses awareness. It understands its RF environment and associated spectrum use policies.

3.2.2 Adjustable

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 to save battery power or reduce interference to other users.

3.2.3 Autonomous

The CR does not require user intervention in order to be adjustable. Fundamentally, it must perform spectrum exploration 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, within its local policy constraints.

3.3 Benefits

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.

3.3.1 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 radios that are incompatible in operating frequency or air interface. Cognitive Radios that are 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. Being frequency and protocol agile, Software Defined Radio platforms with cognitive capabilities are potentially capable of solving the technical radio and system interoperability problems 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 post-9/11 world.

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

Public services, including military services, could also benefit from reliable communication between different organizations employing incompatible communication equipment. Public service operations benefit from radios that are able to configure themselves to provide seamless communication.

Unrestricted roaming for consumers using different types of phones such as GSM, CDMA, and WCDMA as well as 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.

The SDR Forum Public Safety SIG has explored some of these issues in greater detail and has published a document describing improvements in interoperability.[2]

3.3.2 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 that are aware of a radio user's goals and priorities, and capable of independently acting, could simplify the user 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. The greater the flexibility of a radio, the greater the number of possible options and settings. Users often would prefer not to become experts in complex radio setup and optimization. There is value in lifting the burden of setting parameters by hand or through a graphic user interface. Users should be able to specify the level of detailed control they desire over radio operating parameters, with the radio making appropriate choices among options the user chooses to ignore.

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[2] SDRF-06-A-0001-V0.00 Software Defined Radio Technology for Public Safety, http://www.sdrforum.org/pages/documentLibrary/documents/SDRF-06-P-0001-V1_0_0%20_Public_Safety.pdf

3.3.3 Greater Spectrum Efficiency through Improved Access

Radios that are aware of their spectral environment provide benefits by accessing previously unused, unavailable, or forbidden spectrum. Spectral awareness may enable the use of this spectrum without causing interference to the radios operating in the spectrum. Radio spectrum is a scarce resource: there is little 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 channel-minutes. Radios capable of exploiting unused or lightly used spectrum without introducing interference will improve efficiency of spectrum utilization.

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 protect against interference with licensed users.

3.3.4 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 while simultaneously text messaging) and execute 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 codecs, and adaptive compression to balance bandwidth usage (i.e. increase compression in VOIP conference call scenario).

The Cognitive SDR can also gracefully degrade (i.e., doing so in a way as to minimize disruption) the supplied services according to environmental conditions such as link quality changes, interference, and battery degradation.

3.3.5 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.

3.3.6 Self-correction, Fault tolerance

Refers to the ability of a radio to discover that as a result of local conditions, it has lost communications and must recover and re-establish communications.

3.3.7 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.

3.3.8 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 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 AP mode to Peer-peer mode for specific messages to achieve maximum overall network QoS

3.3.9 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 operation 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.

3.3.10 Message Relaying

In heterogeneous and disaggregated network environments, 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.

3.3.11 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 also be employing different ad-hoc network protocols therefore the cognitive radio ad-hoc network element would have multi-ad-hoc network protocol-handling capabilities.

3.3.12 MAC Layer Bandwidth Allocation

This is the 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.

3.3.13 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.

3.3.14 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 to maintain communications at a lower level rather than lose all contact. Doing so in a way as to minimize disruption is referred to as graceful degradation.

4 Potential Applications of Cognitive Radio Systems and Their Impact on Spectrum Management

The following is also excerpted from *Cognitive Radio Definitions and Nomenclature*, SDR Forum Working Document SDRF-06-R-0009-V0.05. This working document has been voted out of the Cognitive Radio working group and is in the process of being approved by the SDR Forum membership. The answer to this question may be amended at a later date pending review of comments received during the balloting process. [Editor’s Note: Although format changes have been made to permit incorporation here, original wording is largely intact.]

4.1 Introduction

The preceding discussion of benefits of cognitive radio identified many potential applications. The following discusses applications of cognitive radio as they specifically relate to spectrum management with regard to improving spectrum efficiency, dynamic frequency selection, adaptive bandwidth control, transmit power control, radiation pattern control, spectrum leasing, and networking aspects.

4.2 Improving Spectrum Efficiency

One of the factors that have elevated interest in Cognitive Radios is the potential for improving spectral efficiency.

Spectrum efficiency is a measure of how the spectrum segment of interest is being utilized obtained from a user-defined cost function. This cost function is a ratio of the measurable gains derived from the spectrum usage to the cost of identification, characterization, and usage of the spectrum segment of interest

In this section some specific techniques that may improve spectral efficiency are described.

4.2.1 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 without the knowledge of license holders.

4.3 Dynamic Frequency Selection (DFS)

Describes the technique where prior to transmitting, a radio attempts 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 be defined 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.

4.4 Adaptive Bandwidth Control

Describes the ability of a radio to expand or contract its operating emission bandwidth to avoid interfering with other radios.

4.5 Transmit Power Control

Describes the technique where a radio using feedback or some other means uses the least practical amount of transmitted power to minimize interference. Transmit power control may also involve the reception of interference information from other co-channel systems.

4.6 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.

4.7 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 cancelable or revocable.

4.8 Network Aspects

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

4.8.1 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 operation 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.

4.8.2 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.

4.8.3 MAC layer bandwidth allocation

This is the 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.

5 Operational Implications of Cognitive Radio Systems

[Editors Note: Additional inputs are required. The SDR Forum intends to submit an answer to this question at a later date.]

5.1 Privacy

5.2 Authentication

5.3 Other

6 Cognitive Capabilities which could Facilitate Coexistence with Existing Systems

Cognitive radio nodes and cognitive wireless networks (CWN), collectively “cognitive radios,” may have the capability to observe spectrum activity and act appropriately in order to coexist with existing systems. This cooperative behavior is commonly governed by software policies that define constraints from very restrictive to permissive.

[Editors note: Additional inputs are required. The SDR Forum intends to submit additional material to respond to this question at a later date.]

Annex 1

7 Spectrum Sharing Techniques to Ensure Coexistence with Other Users

[Editors Note: The following represents early SDR Forum work on Spectrum Sharing Techniques to Ensure Coexistence with Other Users. It is intended for discussion purposes only. The SDR Forum intends to continue to work on this topic and provide an amended answer to this question at a later date.]

7.1 Introduction

Two systems are said to coexist with one another if the operation of each system could negatively impact the performance of the other and the operation of one system does not preclude the operation of the other.

Most spectrum-sharing techniques emphasize a closely related coexistence objective – minimizing the negative impact of one system on the performance of another. For radio systems, minimizing negative impact generally means minimizing interference, but different coexistence metrics can be applied at different layers and the exact impact of interference is dependent on the signalling features of both systems. Besides being characteristic of a “polite” cognitive radio system, an assurance that a cognitive radio system will minimize the negative impact on other users is likely necessary to assuage the fears of primary users. Additionally, when considering coexisting cognitive radio systems, minimizing the interference between systems will generally (subject to certain constraints) maximize both systems’ performance.

If we focus primarily on layer 1 and 2 coexistence issues, coexistence of radio systems implies spectrum sharing. To share spectrum, radio systems’ operational parameters are implemented so both systems have some access to the spectrum, possibly interference-free. While many parameters such as transmitted power (e.g., transmit power control), frequency (e.g., dynamic frequency selection) and time (e.g., predictive scheduling) directly impact coexistence metrics and are obvious candidates for cognitive radio control, many other parameters can be set to ensure and enhance coexistence such as route selection (choosing routes to minimize interference), network association (preferentially connecting to a network with greater protective measures), and application layer parameters (such as reducing video quality which reduces occupied bandwidth). Conceptually, virtually every parameter, setting, and/or process which influences the transceiver operations of a radio can be controlled to ensure or enhance the coexistence of cognitive radio systems with other users.

Traditional radio systems and cognitive radio systems can set the same parameters or processes to maximize coexistence. But in traditional radio systems, operational parameters and the processes to control them have been defined statically prior to deployment, e.g., the frequency reuse patterns defined by spectrum regulators and service providers. Of course, because traditional systems are unable to leverage situation dependent information, these spectrum sharing techniques led to significant spectrum under-utilization. By providing the means to gather locally relevant information and implement design (decision) processes to adapt operational parameters to ensure that its operation does not degrade other users below a minimal performance level, a cognitive radio system provides the possibility for radio system coexistence with relatively improved spectrum utilization/efficiency. In some domains (e.g. government), the reuse patterns may not be as well defined, resulting in additional spectrum management complexity.

Because the ability to process information and adapt its operation based on that information are the key differences between a cognitive and a traditional system, this response focuses on the techniques by which a cognitive radio system defines its parameters and gains locally relevant information.

7.2 Design/Decision Processes

The following subsections decompose the large number of possible design and decision processes into a manageable set of classifications of techniques which have been proposed to design/decide cognitive radio operational parameters to facilitate coexistence with other users. Rather than viewing these as discrete mutually exclusive categorizations, we believe that varying mixes of the following techniques will be utilized in most systems.

7.2.1 Static Partitioning (Assignment)

Static spectrum partitioning divides the spectrum into a set of predefined and orthogonal channels and assigns these channels to different radio systems. This partitioning can occur along a variety of different dimensions such as by space, frequency, or time. Static spectrum partitioning is the spectrum sharing technique which has been used for decades to allow the sharing of spectrum between different applications and radio technologies (e.g., the static spectrum partitioning between FM, AM, TV, cellular, public safety, and government spectrum). This approach best ensures a predefined limit on interference between radio systems but is the slowest to adapt to the changing spectral needs of society and generally leads to underutilized spectrum.

7.2.2 Dynamic Spectrum Sharing

With dynamic partitioning, transmission patterns change frequently, but transmissions remain orthogonally partitioned. Examples of dynamic orthogonal partitioning include transmission scheduled services (e.g., EVDO or WiMAX where a base station (BS) schedules transmissions of its subscribers, or 802.16h where BS's collaborate to schedule orthogonal transmissions), spectrum markets and auctions. In public safety and government domains, the standards that are in place do not necessarily facilitate dynamic spectrum sharing across enterprises (e.g. different public safety organizations) to the degree that 3G enterprises can employ EVDO for dynamic spectrum sharing within an enterprise (e.g. a single commercial service provider).

7.2.3 Hybrid Schemes

Note that the more flexible a dynamic partitioning scheme is, the greater the need for software defined radios. Also note that static allocations necessarily are unable to capture and capitalize on temporal variations. Finally, note that one primary reason for including static partitioning in our list of available design/decision techniques is to make explicit the fact that all traditional coexistence techniques can be applied to cognitive radio. That is to say, cognitive radio augments the set of tools/techniques available for ensuring the coexistence of radio systems. Primary and secondary users may share spectrum with different hybrid schemes than ISM band users, for example.

7.2.4 Centralized and Distributed Control

Differentiating between centralized and distributed systems is frequently a function of scale. At a sufficiently small scale every system is centralized (even if the controlling entity only controls the allocation for a single radio or single link) and at a sufficiently large scale, systems are necessarily distributed. For example, national frequency allocations look distributed at an international level and enterprise allocation systems look distributed in areas with multiple enterprises deployed.

Because centralized systems eliminate the possibility of resource conflicts, a centralized algorithm should perform at least as well as a distributed system in theory. In practice, the presence of large numbers of radios and rapid variations in local operating conditions and user needs (localized information) frequently lead to situations where the information processing and communications requirements make a centralized system impractical or degrade its performance. It is hard to define a bright dividing line where conditions favour either a distributed system or a centralized system, but as the amount of information needed to implement the system grows (e.g., more rapidly changing channel environments, more users, more user variation, more varying topologies), the more likely it is that a practical distributed system can be designed which outperforms a practical centralized solution.

Also note that while static partitions are more amenable to centralized allocation techniques, static allocations can still have a degree of distribution in the allocation process. For example, see the spectrum allocation decisions of the FCC and the NTIA.

7.2.4.1 Centralized Control

In a centralized scheme, the coexistence of users is managed by a single entity. Examples of centralized control include national spectrum allocations, intra-cell scheduling, traditional enterprise spectrum management systems, and various proposed centralized optimization routines (e.g., local searches, network wide genetic algorithms).

7.2.4.2 Distributed Control

In a distributed scheme, coexistence is managed by multiple entities who generally (though not always) have conflicting priorities and operate with different information sets. Examples of distributed control for coexistence include the 802.11 CSMA/CA algorithm, inter-cell power control effects (e.g., cell breathing), graph-coloring algorithms, and algorithms rooted in game theory.

7.2.5 Cooperative and Non-cooperative Processes

In a distributed system, coexistence decisions can be made either cooperatively or non-cooperatively. When made cooperatively, decisions are made by a group of entities (with potentially conflicting objectives) and the decisions bind subsequent actions of those entities. Examples of cooperative processes include 802.16h and 802.22 inter-BS allocations.

When made non-cooperatively, the coexistence decisions of one cognitive radio system are made independently of other systems, though possibly with input from other spectrum controlling entities.[3] Examples of non-cooperative processes include the 802.11 CSMA-CA algorithm, the white space coalition's proposed approach to coexistence for low-power transmitters, and most proposed algorithms rooted in game-theory.

Cooperative and non-cooperative approaches exhibit many of the same tradeoffs as seen between centralized and distributed algorithms. Namely that as networks scale in numbers of decision makers and in terms of information variance, cooperation becomes more difficult to implement efficiently, but in theory, a cooperative process can outperform a non-cooperative process due to the elimination of resource conflicts.

7.2.6 Procedural and Non-Procedural Processes

Coexistence techniques can be defined procedurally with a well-defined algorithmic definition or non-procedurally with only generalized principles or operational guidelines. Many currently considered or proposed coexistence techniques are defined procedurally, i.e., prescribing particular actions in response to particular events.

Examples of procedural algorithms include how power is stepped up or down in response to SINR variations, the 802.11 CSMA-CA algorithm which controls WiFi transmission times, or scheduling algorithms defined for varying standards.

However, coexistence can also be achieved and enhanced without specifying what action should be taken in response to an event. For example policy definitions frequently place restrictions on operational parameters, but the specific action a radio should take may be unspecified; a game theoretic coexistence technique defines objective / utility functions for the radios but leaves decision processes largely undefined; and a radio etiquette may define principles of operation which the radio must consider when making its decisions but will generally not define what action should be taken in every situation.

Note that non-procedural processes could be implemented as some system's decision process, e.g., a system could adapt transmit power policy based on the number of users or a system could specify changes to radio objectives as the mix of users changes. A degree of control must be exercised by regulators and spectrum managers, and this may include the specification of policies in a formal policy language, or in less formal spectrum usage rules according to which manufacturers may employ industry standard or proprietary policy languages for legal conformance to regulatory intent.

The sections below offer further elaboration regarding information processing and distributed processing implications of this answer.

7.3 Information Processing

The processes described in the preceding classifications can only be guaranteed to perform well when armed with reasonably accurate information. In general the higher the quality of the available information (i.e., more timely and more accurate), the better the decision and design processes will perform. Thus, the processes by which cognitive radio systems gain information are intricately linked to any technique intended to ensure and enhance coexistence with other users.

[3] If spectrum controlling entities first consulted with each other and then were free to act in any way they saw fit (i.e., without being bound to a group decision), this would also be an example of a non-cooperative process.

Information processing in a cognitive radio is defined by two complementary processes – observation and orientation. An observation process gathers raw data and an orientation process assigns meaning to the data. Examples of observation processes include power spectral density measurements to detect the presence of signals; cyclostationarity techniques to extract signal characteristics (e.g., modulation and bandwidth); and trilateration to infer transmitter location. Examples of orientation processes include ontological reasoning processes and classifiers (e.g., neural nets or hidden Markov models).

While almost any piece of layer 1 and layer 2 information could be applied to coexistence algorithms, some of the more commonly cited gathered information types include the presence and location of other users, other users' signalling parameters, and environmental propagation characteristics. To give a feel for the wide range of information which could be applied to coexistence consider that user preferences could be used to anticipate how interference impacts perceived performance, radio performance characteristics could be used to predict performance impact, and biometric information could be used to authenticate that another user has priority. As such, an exhaustive listing of the kinds of information that a cognitive radio system may find useful for promoting coexistence is perhaps impossible. Instead, the following classifies the means by which cognitive radio systems can generate the information needed for its decision processes.

7.3.1 Collaborative and Non-Collaborative Information Processing

In collaborative information processing, multiple systems collaborate on the observation and/or orientation processes. In contrast, a system implementing a non-collaborative information processing technique must rely solely on its own capabilities.

Because the variance of an estimation of a process is reduced as the number of independent samples used to make the estimation increases, collaborative information processing will generally improve information accuracy. Further, because of hidden node effects and variances in device capabilities, collaborative techniques can make information available to cognitive radio systems which would otherwise be unavailable. Examples of proposed collaborative information processing techniques include the collaborative detection techniques proposed for 802.22 and various proposed database techniques such as the Radio Environment Map. Both of these techniques are largely focused on collaborative observation processes, but collaborative orientation processes such as data fusion and distributed processing could also be employed.[4]

Note that collaborative information processing techniques will generally yield superior performance to non-collaborative techniques, but practical considerations (e.g., a rapidly changing phenomenon or limited processing resources or bandwidth) may make collaborative techniques unfeasible. Also note that our definition of collaborative information processing does not restrict collaboration to cognitive radio systems. In fact, many of the most promising collaborative techniques involve collaboration with a system which does not implement any radio functions. For example, 802.11y and various proposals for the TV band coexistence assume the existence of databases which store and make available the location and characteristics of fixed protected users so that a cognitive

[4] SETI @ Home – an example of distributed processing - is arguably the largest example of a collaborative orientation process. However, SETI @ Home will not satisfy most definitions of a cognitive radio system and any coexistence benefits which might be gained via SETI @ Home are only theoretical at this point.

radio capable of only observing its own location can be aware of the presence of protected users. Likewise, the structure of collaborative information processing can take on many forms, e.g., between peers of cognitive radio systems, in a hierarchical system (ala 802.22), in a client/server information pull mode (like 802.11y's proposed database), or in an information push mode (as in proposed information beacons which can supply both observation and orientation information).

7.3.2 Cooperative and Non-Cooperative Information Processing

In cooperative information processing, the observed user actively aids the observing cognitive radio system while in non-cooperative processing a cognitive radio system has to gain relevant information without help from the user.

Out of necessity, most proposed techniques for gaining information about legacy systems (e.g., TV or satellite) adopt a non-cooperative approach with cooperative techniques utilized more frequently for coexistence between cognitive radio systems (such as has been proposed for systems utilizing a Radio Environment Map). However, this need not be the case as with the proper inducements, legacy users could augment their existing systems to aid cognitive radio systems' observation/orientation processes. For instance, coexistence between public safety systems and commercial systems seems a natural candidate for cooperation and different agencies are making databases available for fixed transmitters (making those databases examples of cooperative collaborative information processing).

7.3.3 Pre-Programmed and Augmented Information

Pre-programmed information refers to information which is available to a cognitive radio system prior to deployment. Augmented information refers to information which only became available to the radio after deployment by means other than a software upgrade. Note that with collaboration, pre-programmed information for one radio may be augmented information for another.

All cognitive radios will come pre-programmed with some internally available information which we term innate information. For cognitive radio systems, innate information generally corresponds to pre-programmed models such as environmental models, radio operation models, and signalling models (e.g., what combination of observed signal parameters implies the existence of a particular class of users), but could define very specific pieces of information such as the IP address for a key database or expected locations for particular users. Other examples of pre-programmed information might include the fixed transmitter databases proposed for use with varying standards.

Note that while cognitive radio systems will eventually be capable of reprogramming and programming new internal models (thereby augmenting that information), for most applications being considered today, internal models should be viewed as pre-programmed information.

7.3.4 Observed and Predicted Information

Most coexistence techniques react to observations of the current environment (or more accurately, the recent past). However, in time-varying situations, reacting to observations of the recent past necessarily leads to spectral inefficiencies. Greater efficiencies can be achieved when conditions are accurately predicted to occur before they are observable. For instance, when spectrum will be unoccupied when the primary user is a TV station which regularly powers down at night or a signal with a regular time-slot structure can be readily predicted which allows cognitive radio systems to optimize for how the spectrum *will be* as opposed to how it *was*. Similarly, many other potential types of information can be predicted such as location based on observed velocity and transmit frequency for a regularly hopped transmitter or the presence of a fade based on past experience. Information prediction can even be extended to non-deterministic processes as long as the processes exhibit some degree of stationarity. For example hidden-Markov models have been applied to predict spectrum and occupy spectral holes created by random back offs of 802.11 systems.

7.4 Joint Processing

While the preceding largely discussed cognitive radio decision and information gathering processes as separate entities or at least implied that information gathering processes operate independently of decision processes, this need not be the case. Certainly, the choice to operate in different bands in the presence of different users could require the use of different information gathering processes. Further, decision processes and information gathering processes could be jointly designed so that the actions by a cognitive radio enable or enhance information gathering. For instance, a cognitive radio system could coordinate regular periods where the radios do not transmit to minimize interference when attempting to detect incumbent users (e.g., the extended quiet periods proposed in 802.16h) or could transmit special signals to gain information about the environment (e.g., ranging in sensor networks or channel sounding to identify channel models). In general, any of the preceding classifications of cognitive radio decision processes and information gathering processes could be applied to the development of a joint processing solution.

8 Increased Efficient Use of Electromagnetic Spectrum by Cognitive Radio Systems

[Editors Note: The following represents early SDR Forum work on Increased Efficient Use of Electromagnetic Spectrum by Cognitive radio Systems. It is intended for discussion purposes only. The SDR Forum intends to continue to work on this topic and provide an amended answer to this question at a later date.]

Cognitive radio systems promote the efficient use of radio spectrum by enabling cooperative communications and automated radio resource management.

8.1 Cooperative Communications

Beyond merely taking into account the existence of other radios in its environment and working with and/or around them, a cognitive radio can work with other radios to improve spectral efficiency. For example in the proposed 802.16h amendment, transmission times are coordinated to reduce collisions thereby reducing retransmissions and improving net throughput. This strategy may apply across radio access techniques in heterogeneous networks by cognitive radios as well. Such radios can work together to effect a single more efficient transceiver as proposed in collaborative MIMO. More intense processing or information databases can be distributed across idle radios which could allow lower complexity radios to leverage higher complexity and more spectrally efficient waveforms.

8.2 Automated Radio Resource Management

Beyond the techniques described for multi-user diversity and intelligent link coding, cognitive radios could also effectively manage radio resources in ways which have impact far beyond their immediate purview. For instance, how channels are allocated across a network can have a significant impact on aggregate system performance and aggregate system spectral efficiency. Cognitive radios which automate radio resource management, whether via centralized, distributed but cooperative, or distributed techniques, working around non-cooperative techniques, can bring the benefits of radio resource management to networks that currently lack a clear means for performing radio resource management (e.g., consumer WiFi deployments). Similarly, automating radio resource management means that network optimization need not be discarded when conditions change due to updated policy definitions or a changing operating environment.