Quantifying the Benefits of Cognitive Radio

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TERMS, CONDITIONS & NOTICES

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Executive Summary

To promote a better understanding of Software Defined Radio (SDR) and Cognitive Radio (CR) within the Wireless Innovation Forum (WInnF) and the broader technical, regulatory, and business communities, this document reports the results of an extensive survey performed by the WInnF Cognitive Radio Work Group (CRWG) on open and public CR literature. The intent is to document the "hard numbers" that researchers and developers have reported so researchers and developers can better assess the value proposition of CR.

Across the world, there is a general consensus that cognitive radio has the potential to radically improve the performance, efficiency, and reliability of existing wireless networks and will enable transformative new applications such as dynamic spectrum access (DSA) and real-time spectrum markets. For some, this enthusiasm is tempered by a feeling that cognitive radio is an unproven commodity whose benefit remains more hype than substance. In an earlier study produced for OFCOM in 2007 by QinetiQ[1], it was reported that the introduction of CR into the commercial cellular bands could be justified if it would yield a 3.7% efficiency gain in call volume and that this "*required efficiency gain is close to the minimum we expect from our simulations*." Alone, that result seems to imply that CR will be a commercial success.

To further establish the value proposition of CR and to separate the hype from the substance, the CRWG reviewed over 300 papers from a diverse range of conferences, e.g., the SDR Conference, DySPAN, CrownCom, Milcom, patents, and textbooks. Over 100 papers satisfied our selection criteria of papers that touted their technologies as "cognitive radio", compared performance with a non-cognitive radio implementation, and provided hard numbers. Key CR results from each identified source were extracted and summarized in Section 2 and detailed results were included in the body of the report to facilitate comparisons between various approaches while Appendix B provides additional context to describe how the original authors' generated the cited results.

Section 3 reviews how CR could help address the needs of commercial, public safety, and military users. For commercial users, Section 4 considers how revenues could be increased by reducing deployment costs (e.g., self-organizing networks) and finding additional revenue streams for spectrum (e.g., spectrum markets and auctions); capacity could be increased by allowing leveraging femto-cells which utilize several CR techniques to reuse a provider's own spectrum, size, weight and power could be improved by applying CR-related "green radio" techniques.

Drawing from documents created by the WinnF Public Safety Special Interest Group (PSSIG) Use Cases on the London Bombing Scenario and Chemical Plant Scenario, Section 3 shows CR could help with coverage issues, enhance spectrum availability, better support dynamic prioritization, support interfaces to civilian responders, improve interoperability and resource management, and help synthesize sensor network information.

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[1] QinetiQ, "Cognitive Radio Technology A Study for Ofcom – Volume 1," February 12, 2007. Available online: http://www.ofcom.org.uk/research/technology/research/emer_tech/cograd/

After identifying communications-related needs of the military community published in recent proceedings, Section 3 examines how DSA and spectrum management applications could help reduce the lengthy times required to plan and set up networks by using and improving spectrum access and capacity, though distribution of key material remains an issue and spectrum demand will continue to increase exponentially. The military user community is also exploring CR applications towards achieving "spectral dominance" wherein CR is applied to electronic warfare applications.

While the document identified many CR technologies that would be beneficial to commercial, defense, and public safety applications, Section 4 reviews issues and risks posed by CR of which developers, users, and regulators should be aware. First, depending on the implementation, CR implementations can grow quite complex, significantly reducing potential SWAP gains while making verifying software implementations a more complicated task. Likewise, hidden node and spoofing issues should be expected to arise from sensing-based CR schemes, though external sources of information such as Cognitive Pilot Channels and CR databases can help alleviate these. Likewise the coexistence of many CR systems will pose new issues as systems react to one another's decisions; this is currently being studied for the TVWS under 802.19.1. Because of the larger range of stimuli, greater freedom in adaptation, greater system interdependence, and the deployment in new operational scenarios, testing and certifying CRs promises to be challenging. For TVWS CR, this is currently being explored by the WInnF Test and Measurement Group. Because CR is much more sensitive to the outside world, there are many new avenues for attack (e.g., primary user emulation, learning-based attacks, cognitive "viruses", compromised information sources, and interrupted control channels; some of these issues were addressed by the WInnF Security Working Group in a report entitled, "Securing Software Reconfigurable Communication Devices." While many different regulatory regimes have been proposed for CR, regime uncertainty is currently limiting further TVWS development, but this has to be tempered against the large impact that regulations have on market development.

Contributors

This document was drafted by the Cognitive Radio Work Group of the Wireless Innovation Forum and got valuable contributions from the following member representatives:

Ihsan Akbar, *Harris*

Pete Cook, *Hypres*,

Bruce Fette, *General Dynamics C4S*

John Fitton, *Harris*

Matt Holmes, *Diversified Technology Incorporated*

Vince Kovarik, *Harris*

Al Kunze, *SPAWAR*

Neal Mellen, *TDK*

Rekha Menon, *Harris*

Joe Mitola, *Stevens Institute*

James Neel, *Cognitive Radio Technologies*

John Polson, *General Dynamics C4S*

Jim Rodenkirch, *Diversified Technology Incorporated*

Qun Shi, *ITT*

Richard Taylor, *Harris*

Dandan Wang, *Huawei*

Quantifying the Benefits of Cognitive Radio

1 Motivation, Methodologies, and Background to Survey

In an effort to promote a better understanding of Software Defined Radio (SDR) and Cognitive Radio (CR) within the Wireless Innovation Forum (WInnF) and the broader technical, regulatory, and business communities, this document reports the results of an extensive survey performed by the WInnF Cognitive Radio Work Group (CRWG) on open and public CR literature. The intent is to document the "hard numbers" that researchers and developers have reported.

This report first synthesizes the survey results by the technologies and applications enabled by CR. To provide domain-relevant context to the readers, the document reviews many of the key issues facing the three largest market segments represented by the members of the WInnF – military, commercial, and public safety – and describes how the surveyed CR technologies address the needs of these communities. Finally, this document concludes with a discussion of potential issues that will need to be addressed when integrating cognitive radio technologies into existing and future wireless systems. Because of the breadth and depth of this document, each section is written to facilitate stand-alone review so the reader can focus on the issues and applications of greatest concern. However, cross-references to other sections are provided for more detailed analysis. The cited technical publications are summarized in Appendix B.

The remainder of this section is organized as follows.

- Section 1.1 gives an overview of the Wireless Innovation Forum and the Cognitive Radio Work Group
- Section 1.2 provides an overview of cognitive radio
- Section 1.3 reviews some of the key motivations of this document
- Section 1.4 presents the motivating context for this work
- Section 1.4 covers the organization for the remainder of this document.
- Section 1.5 summarizes key findings from the survey

1.1 The Wireless Innovation Forum and Cognitive Radio Work Group

The Wireless Innovation Forum[2] (WInnF) is an international, nonprofit organization, dedicated to promoting the development, deployment, and use of innovative wireless technologies, including SDR to support the needs of civil, commercial, and military market sectors. Over 120 entities throughout the world are members of WInnF, including operators, suppliers / manufacturers, policy makers, technologists, and academia. WInnF strives to carry out studies and develop views on wireless innovations that are representative of all three International Telecommunication Union (ITU) regions.

[2] Formerly the Software Defined Radio Forum or SDR Forum.

The CRWG is a technical group within the WInnF that provides the industry with guidance to help standardize terminology, architectures, interfaces, use cases, policies and etiquettes for cognitive radio.

1.2 Cognitive Radio Overview

As noted in an earlier CRWG document[3], cognitive radio (CR) refers to both an engineering paradigm for designing wireless systems and the implementations of that paradigm. Thus when this report refers to CR, the report can be referring to particular devices/systems or to broad classes of processes consistent with the CR engineering paradigm. For some clarity, we earlier defined the CR paradigm as:

> 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.

Note that learning is also a commonly attributed aspect of cognitive radio and learning is implicitly part of this definition as learning is the application of logic and analysis to retained information for the purposes of making and implementing better (more intelligent) choices about the operational aspects of the radio, network, or system.

Because cognition is normally associated with human thought processes, the CR community has adopted several terms from human psychology, whose meaning is unclear in an engineering setting, to describe CR, , e.g., "aware" or "reason" in the preceding. To resolve this, the earlier report also defined CR in a manner which would be more familiar for a wireless engineer as: [3]

> "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*).

A CR or cognitive network was then defined as a radio or network "designed according to the cognitive radio engineering paradigm". Other definitions including some earlier definitions for cognitive radio are presented in Appendix A.

[3] Cognitive Radio Definitions and Nomenclature," SDRF 06-P-0009-V1.0.0, 2008

Emboldened by the expansive possibilities enabled by incorporating artificial intelligence into wireless networks, researchers have proposed numerous new capabilities and applications and identified ways in which cognitive radio can improve the performance of existing applications or systems. These include the following applications listed in Table 1 and Figure 1. Some of these applications are discussed in more detail in Section 2.

Table 1: Cognitive radio enables new applications and improves performance of existing systems

Proposed New Applications Enabled by CR	Performance Metrics Improved by CR
• Dynamic spectrum access • Self-organizing networks • Cognitive jamming systems • Cognitive gateways / bridges • Real-time spectrum markets • Synthetic (Cooperative) MIMO • Cognitive spectrum management • Cognitive routing	• Improving spectrum utilization & efficiency • Improving interoperability between legacy and emerging systems • Improving link reliability • Less expensive radios • Enhancing SDR techniques • Extended battery life • Extended coverage

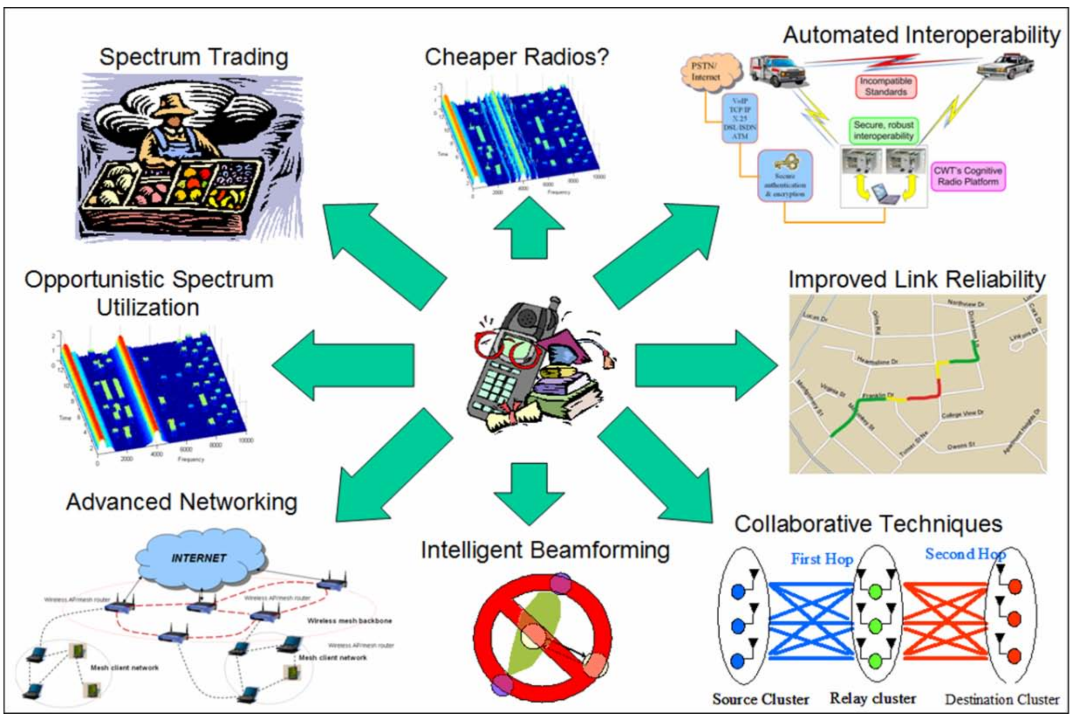

Figure 1: Cognitive radio is seen as enabling many new applications[4]

[4] Figure 1.6 in J. Neel, "Analysis and design of cognitive radio networks and distributed radio resource management algorithms," Virginia Tech, PhD Dissertation, Sep. 2006.

1.3 Report Motivation

Across the world, regulators and businesses are evaluating how and if they should include CR and CR-enabled applications in their development path as there is a general consensus that cognitive radio has the potential to radically improve the performance, efficiency, and reliability of existing wireless networks and will enable transformative new applications such as dynamic spectrum access (DSA) and real-time spectrum markets. For some, this enthusiasm is tempered by a feeling that cognitive radio is an unproven commodity whose benefit remains more hype than substance.

However, while not considering the general benefits of CR, many different authors and sources have investigated how CR could improve their particular use case(s). For instance, in a study produced for OFCOM in 2007 by QinetiQ[5], it was reported that the introduction of CR into the commercial cellular bands could be justified if it would yield a 3.7% efficiency gain in call volume and that this "*required efficiency gain is close to the minimum we expect from our simulations*." Alone, that result seems to imply that CR will be a commercial success.

CR is also being assessed for deployment in other bands and other applications, perhaps most notably in the application of dynamic spectrum access (DSA) to support secondary spectrum access in the US TV UHF 2-51 (fixed) and 21-51 (portable)[6] channels. This is proposed to allow for the deployment of "WiFi on Steroids" and a myriad of different use cases. Likewise, CR is seen as a critical technology for facilitating the automated interoperability and improved performance of public safety systems[7] and increasing spectral availability and network reliability for military networks.[8] Similarly, the recently published FCC National Broadband Plan[9] identified CR as a key enabling technology for increasing spectrum availability and usage efficiency and encouraged the FCC to expeditiously complete the final specification of the white space regulations.

1.4 Methodologies

This project set forth with the following goals:

- Survey and document the reported quantifiable benefits of CR
- Identify how the surveyed technologies can address problems facing the wireless community today

[5] QinetiQ, "Cognitive Radio Technology A Study for Ofcom – Volume 1," February 12, 2007. Available online: http://www.ofcom.org.uk/research/technology/research/emer_tech/cograd/
[6] FCC 08-260, *Second Report and Order and Memorandum Opinion and Order*. November 14, 2008. Available online: http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-08-260A1.pdf
[7] Public Safety Special Interest Group, "Use Cases for Cognitive Applications in Public Safety Communications Systems: Chemical Plant Explosion Scenario," *WINNF-09-P-0015-V1.0.0*, February 12, 2010.
[8] J. Hoppe, "S&TCD Activities in Cognitive Policy and Antennas," JTRS Science and Technology Forum (JSTeF) 3, January 26-30, 2009.
[9] Federal Communications Commission, "Connecting America: The National Broadband Plan," March 2010, Available online: http://www.broadband.gov/plan/.

- Highlight potential issues that will need to be addressed when deploying the surveyed technologies or applications.

The processes we followed to achieve each of these goals is described in the following sections.

1.4.1 Process for Identifying Quantified Benefits

As highlighted in Figure 2, the CRWG followed a five step process for identifying published quantifiable benefits of CR. The results of this process are presented in Section 2 and the process is explained in more detail in the following.

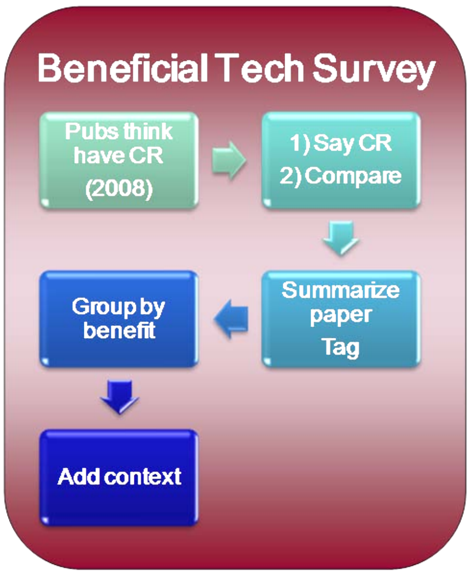

Figure 2: Steps in Survey of Quantified Technical Benefits of Cognitive Radio

1. *Identify within the group membership what open publication sources were available and likely to be related to cognitive radio.*

While many interesting and likely valuable algorithms are currently being internally developed by the WInnF and CRWG membership, we wanted to create a document where the interested reader could fully explore an algorithm or application that seemed relevant to their domain and so that the results of this document presented in this document could be independently verified.

We restricted ourselves to only those publication sources which the group membership had on hand because the CRWG is ultimately a group of interested volunteers with limited funding. Nonetheless, we were able to survey the following fairly extensive set of sources:

- Cognitive Radio Oriented Wireless Networks (CrownCom)
- Dynamic Spectrum Access Networks (DySPAN) 2005, 2007, 2008
- Milcom 2004, 2005, 2006, 2007, 2008

- SDR Technical Conference 2002, 2003, 2004, 2005, 2006, 2007, 2008
- IEEE Journal publications
- Patents available on Google's patent search service
- Cognitive radio textbooks
- White papers available online

While this was certainly not an exhaustive survey and was somewhat dated even before this report was complete, it should nonetheless give the reader a good feel for the state-of-the-art in CR research and for the benefits enabled by CR. Additional publications as encountered during the writing of this report were also included, but were not surveyed in as systematic fashion as with the preceding sources.

2. *From the set of documents identified in 1, identify the subset of documents that satisfy all of the following criteria.*

a. The paper proposes or reviews a method that is explicitly identified in the paper as "cognitive radio" or as a well known cognitive radio application (e.g., dynamic spectrum access).
b. The paper presents a quantified (measured) benefit of cognitive radio that is compared against a non-cognitive radio system

While these conditions significantly limited the scope of the project, it also allowed us to avoid making judgment calls on a paper-by-basis on what is and is not "cognitive radio" while ensuring that the reported results are representative of the broader community's use of the term "cognitive radio" and are indicative of what cognitive radio adds to existing wireless systems. Some of these definitions are collected in Appendix A.

3. *For each document that remained after step 2, perform the following steps.*

a. Write a brief summary of the algorithm and/or application
b. Extract the quantified benefit reported in the publication
c. Describe the scenario/experiment in which the benefit was measured
d. Tag the paper with identifiers related to application and technology area.

The write-ups that resulted from this step are included in Appendix B of this report. It was our intention that including these summaries would allow the reader to gain initial insight into a particularly promising and relevant application or algorithm discussed in subsequent sections. This also served as the database from which we drew our analysis.

4. *Using the tags and summaries identify key technologies/applications and for each technology, synthesize a summary of technology and its reported benefits from the summaries in step 3.*

It was not our intention to draw comparisons or contrasts between algorithms or to draw judgments as to which algorithm is superior to another. This was motivated by a recognition that different papers or authors will consider different operating scenarios which complicates comparisons and by the fact that a key advantage of cognitive radio is that it is not a one-size-fits-all solution as a CR's algorithm suite could be autonomously tuned to changing conditions.

5. *Provide a meaningful context for each of technologies*

This context is included with each surveyed technology (Section 2) and presented in light of pressing issues in the three considered wireless domains (Section 3). Potential issues are emphasized in its own Section (Section 4). Again, it is the intention of this document to avoid editorializing on the topic of cognitive radio,[10] so this context is sourced to existing publications in the literature.

1.4.2 Process for Identifying how Technologies Apply to Key Markets

As highlighted in Figure 3, the CRWG followed a four step process for identifying how the surveyed technologies apply to key market segments. We limited this portion of the study to only consider military, commercial, and public safety applications. For military and commercial applications we closely followed the process shown in Figure 3, but for public safety applications we primarily mined existing publications from the Public Safety Special Interest Group. The results of this process are presented in Section 3 and the process is explained in more detail in the following.

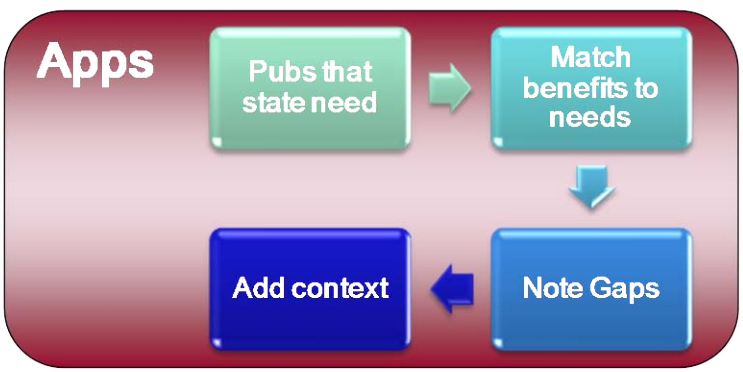

Figure 3: Steps in Identifying how Technologies Apply to Key Markets

1. *Survey existing literature to identify needs of target communities*

While the CRWG has contributors knowledgeable in their respective markets, it was not the goal of this document to produce new opinions of the needs of these markets. So this step was critical to providing a basis for the subsequent steps. Note that no attempt was made to restrict our search to publications advocating for CR, though CR consistently had a large role to play in addressing these needs. These needs were written up with added as the first part of each sub-section in Section 3.

[10] Outside of exercising our editorial judgment in what technologies issues are selected for inclusion and emphasis.

2. *Match benefits to the identified needs*

The surveyed technologies from Section 2 were then reviewed to determine if they could help address the identified needs. Descriptions were added and the quantified benefits were presented to provide guidance for how extensively the needs of these communities could be addressed.

3. *Identify gaps*

While CR can help ameliorate many problems, there are needs that do not have a technical, let alone a CR solution. Further applying a CR technology might only partially address the need or might introduce additional issues that will need to be addressed. These gaps and new issues were then summarized and described in the last sub-section of each application-area write-up.

4. *Add context*

Added context allows the document to address linkages between application and issue areas (e.g., how a technology could support both commercial and military needs) and to better understand expected development timelines and efforts that are working to mature the technologies.

1.4.3 Process for Identifying Risks

As highlighted in Figure 4, the CRWG followed a three step process for identifying risks posed by the surveyed CR technologies. The results of this process are presented in Section 4 and the process is explained in more detail in the following.

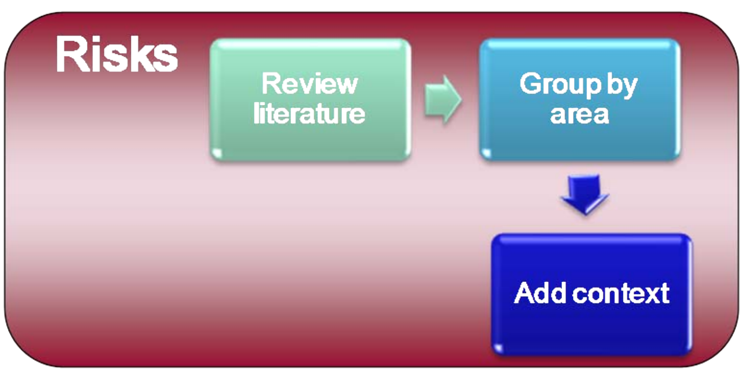

Figure 4: Steps for Identifying Risks Posed by CR Technologies

1. *Survey existing literature to identify risks posed by CR technologies*

While risks were primarily identified by surveying publications, some of the risk discussion is based on individual expertise of the CRWG members.

2. *Synthesize and group the issues reported in the literature*

Each of the risks identified were grouped to facilitate easier reading.

These groupings were then augmented with context that places the risks within the larger application space, tied back to previous sections, and highlighted possible mitigation strategies.

1.5 Findings

Beyond the detailed results on specific technologies and applications presented in subsequent sections, the survey process led the CRWG to draw the following conclusions, which may be of interest to the reader.

- The term "cognitive radio" is used in a widely inconsistent fashion across authors. This is further complicated by submergence as CR becomes "just software" as it is implemented.
- Nonetheless, the number of publications that include the phrase "cognitive radio" has been increasing rapidly.
- There is an ongoing transition from basic research to applied research as CR begins to come to market.
- Dynamic Spectrum Access remains the CR technology that has received the most interest and study.
- However, CR was applied to numerous different applications with varying degrees of sophistication, and a particular increasing interest in cognitive networks and systems applications, but this is not fully reflected in the benefits section due to the process used for this document
- Security has been receiving increased interest, though is still sometimes overlooked.

1.6 Document Organization

The remainder of this document is organized as follows.

- Section 2 presents the quantifiable results of the survey. These are grouped by technology and application areas. To allow each technology or application write-up to be read in a stand-alone fashion, each subsection includes its own references and provides introductory contextual information.
- Section 3 reviews issues currently facing the commercial, military, and public safety domains and describes how surveyed CR technologies can help address these issues.
- Section 4 highlights risks and issues posed by introducing cognitive radio systems.
- Appendix A presents various definitions proposed for cognitive radio in the literature.
- Appendix B collects the summaries and tags generated as part of the paper survey.
- Appendix C defines various acronyms that are used throughout the document.

For quick reference for a specific technology, application, use, or issue, the reader is referred to the table of contents.

2 Cognitive Radio Technologies and Applications

This section presents the quantifiable results of the survey grouped by technology and application area. To allow each technology or application write-up to be read in a stand-alone fashion, each subsection includes its own references and provides introductory contextual information. Each section begins by introducing some context for the topic, continues with a description of the reported quantifiable benefits, and concludes with a listing of references presented in the subsection.

As part of the review information was collected in the following technology and application areas:

- Dynamic Spectrum Access (DSA) (Section 2.1)
- MIMO Applications (Section 2.2)
- Radio Resource Management (Section 2.3)
- Spectrum Markets and Auctions (Section 2.4)
- Single Link Adaptations (Section 2.5)
- New Business Models (Section 2.6)

2.1 Dynamic Spectrum Access (DSA)

2.1.1 Overview and Relationship to Cognitive Radio

Dynamic spectrum access (DSA) is a vital feature of cognitive radio and has received the most interest from the Cognitive Radio (CR) research community. DSA has been defined by SCC41 1900.1 as "*the real-time adjustment of spectrum utilization in response to changing circumstances and objectives*" [1900.1]. In practice, DSA generally implies that spectrum that was once exclusively used by or licensed to a single system's signals (called the incumbent or primary system) is made available to other systems' signals (called secondary systems) as long as the secondary systems' signals do not (significantly) interfere with the primary system's signals. For instance, in its 2008 ruling [FCC_08_260A], the FCC established rules whereby TV-band spectrum could be used by new systems (employing TV Band Devices or TVBDs) as long as these systems implemented certain processes intended to produce a minimal impact on broadcast TV signals (the original TV-band incumbents) and wireless microphone signals.[11] Similar rules are being considered elsewhere for permitting secondary usage of spectrum, e.g., OFCOM which calls this usage "interleaved spectrum" [OFCOM_09].

DSA can be realized using several different approaches such as, but not limited to, opportunistic, coordinated and uncoordinated access of the spectrum. Some of the benefits claimed in the literature for DSA include improved spectrum efficiency, increased spectrum access, increased capacity, and simplifying the management of heterogeneity.

[11] While most wireless microphone signals do not have a licensed right to the TV-band spectrum, the ruling in practice assigned all wireless microphone transmissions primary user status, thus necessitating protection from secondary system transmissions.

DSA is such a key feature of a CR that it is often confused as being the only benefit that a CR provides. However, when originally formulated, cognitive radio centered on self-awareness, user-awareness, and machine learning in addition to radio spectrum awareness and agility [Mitola_99]. The adoption by the FCC of the term cognitive radio for the narrower concept of dynamic spectrum access helped conflate these two terms (CR and DSA) within global radio engineering communities. One disadvantage of moving away from this original formulation is that the sources of information such as location-awareness interfaces from user modalities are deprecated even though these can be much more reliable than the radio alone (e.g., GPS or radio reception templates) and the adaptations more meaningful for the needs at hand. For instance context-sensitive DSA may include awareness of the user's situation, and this was the original intent of the word cognitive (versus merely adaptive).

Significant commercial interest in DSA techniques was initially fuelled by the adoption of rule-making changes by the FCC [FCC_03] that would facilitate the development of cognitive radios that dynamically alter their spectrum access characteristics in response to the operating environment and usage by licensed devices. Since DSA is perceived as a technology that could allow secondary systems to operate in bands which were previously exclusively allocated, it is a popular enabling technology in several emerging wireless standards. For example, the IEEE 802.22 standard for Wireless Regional Area Networks (WRANs) is developing a cognitive radio-based PHY/MAC air-interface for use by license-exempt devices on a non-interfering basis in spectrum that is allocated to the TV Broadcast Service. Another standard initiative for DSA is IEEE 802.11y which enables high powered Wi-Fi equipment (higher-powered than traditional Wi-Fi equipment) to operate as registered secondary users in the same band with legacy satellite services and radar systems in the 3.650 to 3.700 GHz band. IEEE 802.11h [802_11h] was developed to allow WiFi systems to coexist with fixed satellite and radar installations in Europe and is now part of the full 802.11-2007 standard. The Cognitive Networking Alliance (CogNeA) draft protocol is intended for secondary wireless LAN protocols in the TV band for standardization in ECMA [ECMA_09]. Finally, 2010 saw the start of the 802.11af standardization effort. [802.11_af]

To realize DSA functions, a CR (or cognitive network) needs information about its operating environment and governance on how to operate. Information required by a CR to implement DSA primarily refers to radio spectrum information, e.g., what signals are present in its environment, from where are the signals emanating, to where are the signals being sent. There are numerous, different ways proposed to gain this information, such as:

- Sensing to perform signal detection and classification, which may be cooperative to help mitigate hidden node issues,
- The use of databases based on geographical information and known primary user emitter characteristics
- Pilot channels to distribute environmental information and help the bootstrapping problem
- Direct information sharing among secondary devices and between primary and secondary systems.

To improve robustness, many systems employ a combination of these techniques.

The view that the operations of Cognitive Radios employing DSA techniques will be governed by rules expressed as policies is common. Efforts are underway in standards bodies to define languages and/or methods by which policy requirements can be expressed in machine interpretable format (e.g., IEEE SCC41 (1900.5), WInnF Modeling Languages for Mobility (MLM) Work Group). Such a capability could permit over-the-air downloads of policy statements governing DSA operations in a given geographical area. This might be important, for example, for radios spanning multiple regulatory domains and could facilitate earlier deployment by allowing regulator experimentation with DSA rules. However, not all DSA operations need to be governed by machine-interpreted policies. Simpler, lower cost approaches where adherence to policy is incorporated into the radio design are also being pursued, e.g., as in the TV-Band Devices (TVBD) considered in 802.22.

Tactical military networks contain a sizeable wireless network domain with a highly coordinated wireless spectrum access environment. DSA has the potential to introduce more effective spectrum management, particularly in a rapidly evolving battlefield environment involving autonomous net-centric operations, by employing technologies that can "*enable wireless devices to dynamically adapt their spectrum access according to criteria such as policy constraints, spectrum availability, propagation environment, and application performance requirements*." [Zhang_07]. Further, DSA has been identified by the U.S. DoD as a critical technology in addressing current spectrum management gaps and has been called the "*key to adaptive networking*." [Hoppe_09] Filling the current gaps in spectrum management will positively affect autonomous operations by UAVs and tactical robots, e.g., improved and more efficacious surveillance while the UAV platforms operate outside the friendly confines of a highly coordinated wireless spectrum will further aid in keeping the War Fighter out of harm's way.

The 700 MHz block of spectrum has a potential for DSA where it can be highly beneficial in mitigating interference in white spaces (the spectrum left vacant by the FCC to avoid interference among TV channels). The FCC mandated that all the TV bands would switch to digital broadcast in 2009. This allowed a whole block of spectrum available for wireless broadband use (channels 52-69 in the 700 MHz band).

2.1.2 Reported Benefits of DSA

Any DSA-enabled radio must include techniques for gathering adequate information about the operating environment including incumbent device locations and usage. This process might be complicated due to limitations in sensing mechanisms, inaccurate/limited databases and practical deployment issues e.g. the hidden-node problem. Other challenges range from the design of wide-band sensing mechanisms and interference metrics to the design of distributed DSA algorithms that are stable in dynamic environments as well as consideration of security issues.

How these challenges are overcome is not the focus of this section. Rather the following summarizes the reported benefits to using DSA encountered in our survey for increasing spectrum utilization, improving capacity, reducing interference, achieving a fairer spectrum access regime, and enhancing profits of spectrum owners.

2.1.2.1 Techniques to Access Spectrum

DSA research has led to the evolution of various innovative techniques to access spectrum. In [Brik_05], a centralized DSA scheme is described where the central server makes spectrum access decisions based on a radio-map and an administrative policy database. [Pereira_07] proposes a UMTS TDD approach for unlicensed users to access the licensed cellular UMTS spectrum. It is shown that the lower the power transmitted by TDD opportunistic radios, the higher the probability of them to be able to communicate. From Table 2, it is seen that for -30 dBm transmit power, the opportunity duration is equal to the call duration and the probability of transition is only 0.02%.

Table 2: DSA can enable licensed and unlicensed users to share cellular spectrum. Sharing is easier with lower power.. From Table II in [Pereira07].

P_o (dBm) / Transition	-30	-20	-10	0	10
P_{00}	0	0.6162	0.2007	0.5285	0.8069
P_{01}	0	0.1703	0.3838	0.2287	0.1008
P_{02}	0	0.2135	0.4155	0.2428	0.0923
P_{11}	0.9998	0.9791	0.9348	0.6844	0.4454
P_{10}	0	0.0133	0.0242	0.2252	0.4460
P_{12}	0.0002	0.0076	0.0409	0.0904	0.1087
P_{22}	0.9998	0.9765	0.9421	0.7006	0.4191
P_{20}	0	0.0162	0.0226	0.2173	0.4589
P_{21}	0.0002	0.0074	0.0352	0.0821	0.1220

[Bayhan_07] proposes a satellite assisted smart radio network architecture where DSA is accomplished by the satellite, based on information from smart base stations. [Zhang_07] reviews DSA technologies and provides a DSA-based DoD spectrum management framework. [Chen_07] proposes a cluster-based framework to form a distributed wireless mesh network (called a CogMesh network) in the context of open spectrum sharing. The framework employs a novel distributed topology management algorithm.

On a different note, [Brown_07] discusses conditions under which DSA enabled by CRs is viable to provide broadband access in the licensed TV bands. The rural areas show some promising results, however, it is found that the system would fail in dense urban areas. This is primarily because of less unused spectrum in urban areas and also due to the fact that many unlicensed networks are already deployed there.

2.1.2.2 Improvement in Capacity

By increasing access to spectrum, DSA will improve utilization of spectrum and thereby enhance system performance. Spectral measurements indicate significant spectral capacity is underutilized [McHenry_05] and providing non-interfering access to it through the use of CR technology increases effective capacity to enable better military communications. In the form of secondary spectrum access, a DSA enabled system would be expected to avoid interference with legacy users, find open spectrum, comply with regulatory guidance defined in machine-readable policies, and maintain connectivity through dynamic reconfiguration.

DSA is the application most closely associated with CR. xG, a proprietary implementation developed under a DARPA program, is perhaps the best-known realization of DSA. Field test results from xG have been published in [Marshall_06] with key results and program evaluation thresholds summarized from the tests in Table 12.

Table 3: xG Test Results and Evaluation Thresholds From [Marshall_06]

Metric	Threshold	Results
Channel Abandon Time	500 ms	100% in 465 ms
Interference Limit	3 dB	Mean 0.16 dB, Max 0.49 dB
Net Formation	30 s with 6 nodes	90% 3.5 s, 100% 8.68 s
Net Join	5 s	90% 2.07s, 100% 4.36s
Net Re=establish	500 ms	100% 165 ms
Spectrum occupancy	60% with 6 nodes	85% Occupancy @ 83% Confidence

While xG refers to a proprietary technology, the API for xG is available within the defense community so other systems could build to it. This should enable the work of other researchers to be incorporated and to extend this work. For instance, [Nolan_05] describes OFDM-based dynamic spectrum access where narrowband legacy (FM) users are avoided. Gains are shown with respect to a static allocation where all the subcarriers are used for OFDM irrespective of legacy transmission location. Likewise, [Seidel_05] used mesh secondary networks in which secondary nodes use heteromorphic waveforms that allow multiple discontiguous narrow bandwidth spectrum holes to be integrated into a single wideband logical channel. The nodes continually monitor local spectrum usage and adapt their spectrum according to perceived usage as well as according to regulatory policies. Around 70% of the spectrum is used as compared to 2-10% without DSA.

[Zhao_05] employs a framework of Partially Observable Markov Decision Process (POMDP) for DSA. The figure shows the achievable transmission rate with respect to time. It can be seen that due to the cognitive nature of the Markov scheme, the performance improves over time.

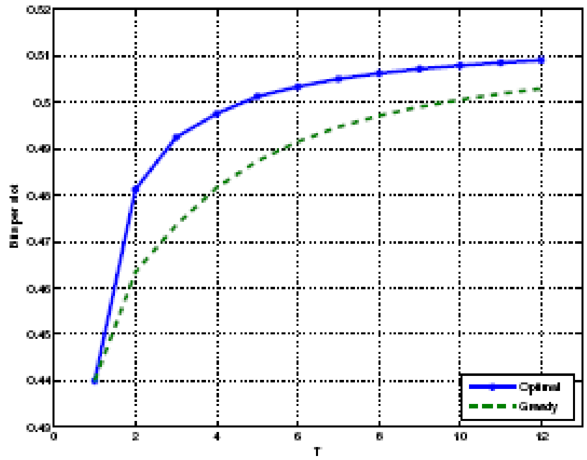

Figure 5: Achievable transmission rate (in bits per slot) over time [Zhao_05]

[Sankaranarayanan_05] discusses ad hoc multi-hop secondary network coexisting with a primary GSM cellular system. Sensing data is obtained at secondary nodes and a control channel is used to coordinates access to unused spectrum. The algorithm efficiently utilizes unused spectrum and achieves spatial reuse of spectrum.

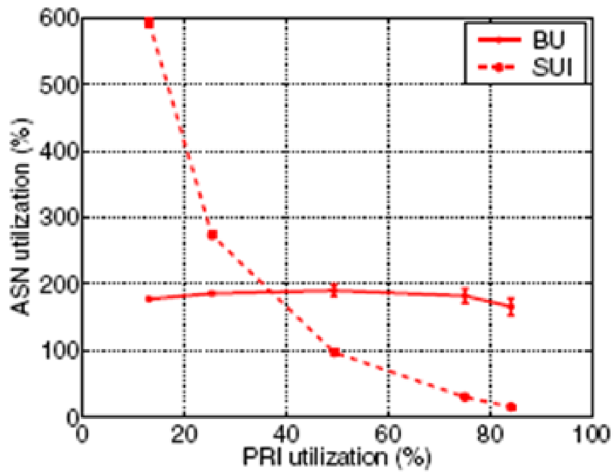

Figure 6: From Figure 10 in [Sankaranarayanan_05]

[Nolan_05] describes OFDM-based dynamic spectrum access where narrowband legacy (FM) users are avoided. Gains are shown with respect to a static allocation where all the subcarriers are used for OFDM irrespective of legacy transmission location.

[Biswas_07] models interference in 802.11-based mesh networks by using distributed conflict graphs at each network interface. For both local and multi-hop traffic, there is an increase in network throughput as compared to common channel assignment. [Ma0_5] studies DSA protocol based on three operational bands: the control channel, the data transmission channel and a busy tone band for avoiding hidden-node issues. The proposed protocol always does better than the best-static allocation protocol (where the entire spectrum is used irrespective of the primary usage) except at very low SNR or when the primary spectrum allocation is close to 1(100%).

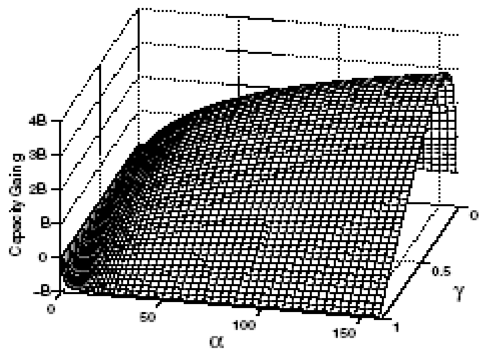

Figure 7: Gain in achievable channel capacity of DOSS over the best static allocation scheme. From Figure 5 in [Ma_05]

[Luo_05] discusses flexible spectrum management and cites papers that show that gains are achieved by using pooling strategies as compared to single system access.

[Hwu_07] considers secondary access in a primary network with a single transmitter and multiple receivers to assess the capacity benefit of using secondary access. Secondary users achieve capacity improvement and it is shown that this capacity improvement depends upon 1) density of primary receivers, 2) distance between primary-secondary transmitters.

[Mody_07] presents machine-learning based DSA. It is shown that the use of non-competitive policy set results in zero interference with the legacy system and a modest increase in the spectrum utilization. In addition, the use of a competitive policy set utilizes machine learning to predict future opportunities, resulting in >90% spectrum utilization at the expense of some interference due to errors in prediction. [Devroye_07] provides an estimate of the rate-region in the presence of a cooperative secondary user. It is shown that the rate-region is more than doubled as compared to when only an individual primary user is present.

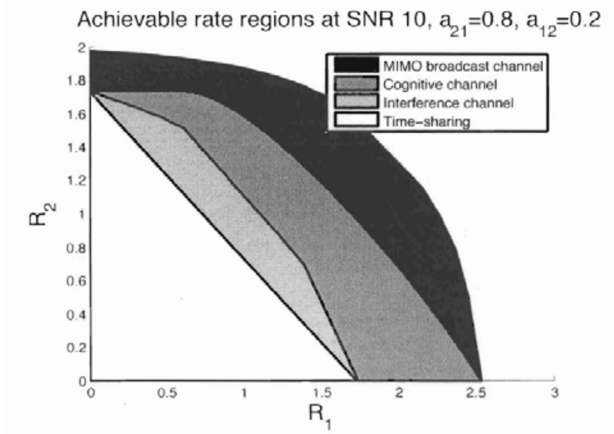

Figure 8: Capacity region of the Gaussian 2x1 MIMO two receiver broadcast channel (outer), cognitive channel (middle), achievable region of the interference channel (second smallest) and time-sharing (innermost) region for Gaussian noise powers N1=N2=1, power constraints P1=P2=10 at the two transmitters, and channel parameters a_{12}=0.8, a_{21}=0.2. From Figure 17.4 in [Devroye_07]

2.1.2.3 Interference Avoidance/ Interference Reduction

DSA research has primarily focused on the secondary utilization of spectrum. This scenario inherently includes strict regulations/restrictions on interference caused to the primary users of the spectrum. This has spawned the development of various innovative interference avoidance/reduction techniques as part of DSA.

[Mishra_07] explores the use of DSA to enable operations of UWB devices in WiMax bands. The paper proposes an energy detector based 'detect and avoid' DSA technique for this scenario. It is shown that the technique can reliably detect WiMax uplink transmissions. It is also shown that incorporating the detect-and-avoid technique with noise estimation, baseband filter compensation and spurious tones can improve the detection sensitivity by 14 dB (Figure 9).

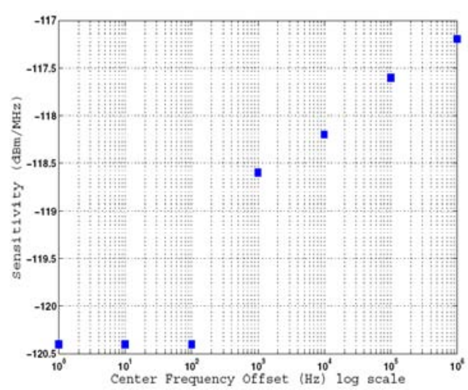

Figure 9: Detection Sensitivity for P_D = 0.9 and P_{FA} = 0.1 of 1.25 MHz WiMAX signal for various values of center frequency estimation error. From Figure 6 in [Misha_07]

[Lacatus_07] presents an OFDM-based DSA which rejects interference and is optimal with respect to the minimum mean squared error criterion.

[Zhao_07] studies the use of DSA in open areas and dense urban areas enabled by a shared database known as a Radio Environment Map (REM) that provides both global and local information sharing. The use of a REM results in less interference to primary/legacy users due to the mitigation of hidden-node and hidden-receiver problems.

[Zheng_05] examined a mobile ad hoc network (MANET) comprised of multiple secondary and primary users. Device centric DSA is used where users observe the interference usage of their neighbors and act independently according to preset spectrum access rules. It is found that the rule-based approach considerably reduces communication costs when compared to collaborative approaches (which offer near-optimal allocation efficiency) while still providing good interference avoidance performance.

[Thilakawardana_07] compares the performance of a genetic algorithm-based DSA scheme and an FSA scheme in hot spots. It is seen the performance degradation of DSA is less than that of FSA with increase in system traffic load.

2.1.2.4 Fairness in Spectrum Access

A possible goal for DSA is to ensure that spectrum is fairly shared by multiple users / systems.

DSA implementations are discussed with respect to this objective in [Ma_07]. The paper introduces a CR implementation of an OFDMA-based system. The methodology employs exclusive carrier assignment (ECA) and Shared Carrier Assignment (SCA) schemes. It is found that ECA is preferred over SCA with non-trivial interference and medium-high SNRs with respect to ensuring proportional fairness as well as achieving optimal throughput.

2.1.2.5 Spectrum trading profits

Spectrum trading enabled by DSA could also generate revenue for agencies and licensed primary users. Some of the research in this area is delineated below:

[Niyato_07] uses Cournot game theory to model the interaction between secondary users who purchase spectrum from a primary user. Strategies to optimize the profit of the secondary users are developed (Figure 10 and Figure 11).

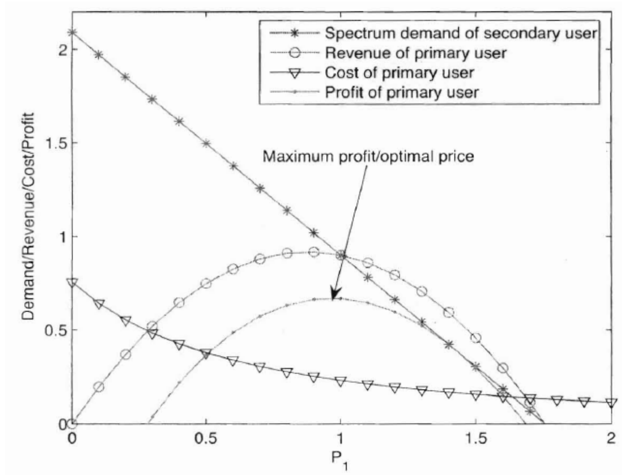

Figure 10: Demand functions of the secondary user, and revenue, cost, and profit of the first primary user. From Figure 14.13 in [Niyato_07]

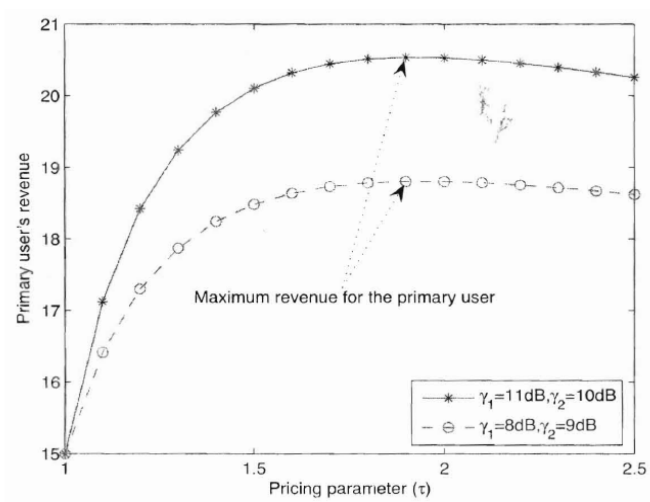

Figure 11: Profit of primary user under different pricing parameters. From Figure 14.11 in [Niyato_07]

[Niyato_07-2] uses Bertrand game theory to model the interaction between multiple secondary users who purchase spectrum from multiple primary users. The point of optimal profit for both parties is identified.

[Niyato_07-3] uses Stackelberg game theory to model the interaction between a primary user (WiMAX user) that sells services to multiple secondary users (WiFi nodes) who in turn sell services to WiFi clients. It is shown that the price to all WiFi nodes is the same irrespective of their demand.

[Tonmukayakul_05] uses agent-based computational economics to model the interaction between transaction costs (associated with leasing costs of the spectrum or other market factors) and the potential interference in the system. The paper shows that secondary usage is favored in a wider range of scenarios than completely unlicensed spectrum usage or exclusive ownership of the spectrum. [Hultell_07] discusses processes for automating financial transactions (auctions) for spectrum access.

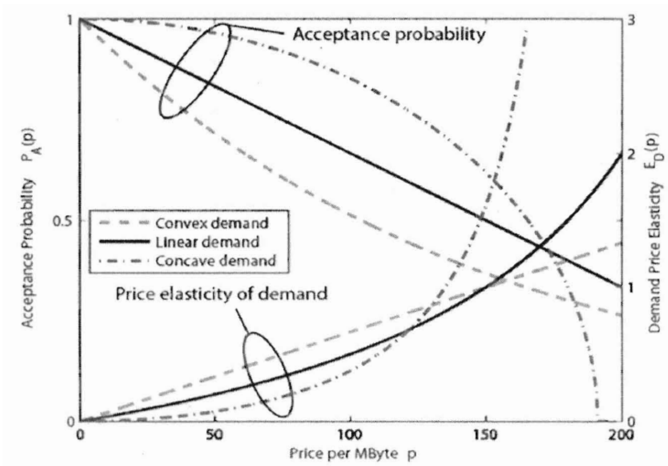

Figure 12: Illustration of the studied normalized demand functions (acceptance probabilities). In the studied example β = 1/150. From Figure 6.5 in [Hultell_07]

2.1.3 DSA References

[802_11h] *IEEE*, IEEE Standard for Information technology — Telecommunications and information exchange between systems —Local and metropolitan area networks— Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications Amendment 5: Spectrum and Transmit Power Management Extensions in the 5 GHz band in Europe," IEEE Std 802.11h™-2003, October 14, 2003. http://standards.ieee.org/getieee802/download/802.11h-2003.pdf

[802.11af] R. Kennedy, P. Eccelsine, "TVWS PAR and 5C," 18, Available online: https://mentor.ieee.org/802.11/dcn/09/11-09-0934-08-tvws-draft-par-and-5c.doc

[1900.1] IEEE, "IEEE Standard Definitions and Concepts for Dynamic Spectrum Access: Terminology Relating to Emerging Wireless Networks, System Functionality, and Spectrum Management IEEE Standard Definitions and Concepts for Dynamic Spectrum Access: Terminology Relating to Emerging Wireless Networks, System Function," IEEE 1900.1-2008, September 26, 2008.

[Bayhan_07] S. Bayhan, G. Gur, F. Alagoz, "Satellite Assisted Spectrum Agility Concept," Milcom 2007.

[Biswas_07] S. Biswas, T. Wu, A. Plummer Jr., "Cognitive Spectrum Assignment Protocol Using Distributed Conflict Graph Construction," Milcom 2007.

[Brik_05] V. Brik, E. Rozner, S. Banerjee, and P. Bahl “DSAP: a protocol for coordinated spectrum access,” DySPAN 2005, Nov. 8-11, 2005. Paper # SP1-9.

[Brown_07] T. Brown and D. Sicker, “Can Cognitive Radio Support Broadband Wireless Access?” DySPAN 07.

[Chen_07] Tao Chen, Honggang Zhang, Gian Mario Maggio, and Imrich Chlamtac, ”CogMesh: A Cluster-based Cognitive Radio Network,” DySPAN 2007, pp 168 – 178.

[Devroye07] Devroye, N., Tarokh, V., Cognitive Wireless Networks, Chapter 17, pp 333-337, Edited by Fitzek & Katz, Springer, 2007

[ECMA_09] ECMA, ”ECMA Standard 392: MAC and PHY for Operation in TV White Space,” December 2009. Available online: http://www.ecma-international.org/publications/files/ECMA-ST/Ecma-392.pdf

[FCC_03] FCC Office of Engineering Technology, Cognitive Radio Technologies Proceeding (CRTP) ET Docket No. 03-108,” 2003-2005. Available online: http://www.fcc.gov/oet/cognitiveradio.

[FCC_08_260A] Second Report and Order and Memorandum and Order in the Matter of Unlicensed Operation in the TV Broadcast Bands and Additional Spectrum for Unlicesd Devices Below 900 MHz and in the 3 GHz Band,” FCC 08-260, November 2008. Available online: http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-08-260A1.pdf

[Hoppe_09] J. Hoppe, “S&TCD Activities in Cognitive Policy and Antennas,” JTRS Science and Technology Forum (JSTeF) 3, January 26-30, 2009.

[Hwu_07] Juite Hwu, Fan Ng, Xiaohua Li, Transmission Power and Capacity of Secondary Users in a Dynamic Spectrum Access Network, Milcom 2007

[Hultell_07] Hultell, J., Zander, J., Markendahl, J., Cognitive Wireless Networks, Chapter 6, pp 122-123 , Edited by Fitzek & Katz, Springer, 2007

[Lacatus_07] Catalin Lacatus, David Akopian, Mehdi Shadaram, Spectrum Assignment for Flexible Rate Cognitive OFDM Systems, Milcom 2007.

[Luo_05] J. Luo, C. Kloeck, K, Moessner, D. Grandblaise, P. Demestichas, G. Dimitrakopoulos, E. Mohyeldin, O. Sallent, P. Cordier. “Inter-operator Flexible Spectrum Management vs. Roaming,” SDR Technical Conference 2005, November 14-18, Orange County, paper # 4.3-04.

[Ma_05] L. Ma, C. Shen, “Dynamic open spectrum sharing MAC protocol for wireless ad hoc networks,” DySPAN 2005, Nov. 8-11, 2005. Paper # TT3-4.

[Ma_07] Y. Ma, “Distributed Spectral Access Schemes for Cognitive Radio Networks,” Milcom 2007.

[Marshall_06] P. Marshall, T. Martin, M. McHenry, P. Kolodzu, “xG Dynamic Spectrum Experiments, Findings and Plans Panel,” DoD Spectrum Summit 2006.

[McHenry_05] M. McHenry, “NSF Spectrum Occupancy Measurements Project Summary”, Aug. 15, 2005. Available online: http://www.sharedspectrum.com/?section=nsf_measurements

[Mishra_07] S. Mishra, S. Brink, R. Mahadevappa, R. Brodersen, “Cognitive Technology for Ultra-Wideband/WiMax Coexistence,” IEEE DySPAN 2007, pp. 179-186.

[Mitola_99] J. Mitola, III, “Cognitive Radio for Flexible Multimedia Communications”, Mobile Multimedia Communications, 1999. (MoMuC '99) 1999 IEEE International Workshop on, pp. 3 –10, 1999.

[Mody_07] A. Mody, et al., “Machine Learning Based Cognitive Communications in White as well as The Gray Space,” Milcom 2007

[Niyato_07] D. Niyato, E. Hossain, Cognitive Wireless Communication Networks, Chapter 14, pp 396-408, Edited by Hossain & Bhargava, Springer, 2007

[Niyato_07-2] D. Niyato, D., Hossain, E., Cognitive Wireless Communication Networks, Chapter 14, pp 407-412, Edited by Hossain & Bhargava, Springer, 2007

[Niyato_07-3] Niyato, D., Hossain, E., Cognitive Wireless Communication Networks, Chapter 14, pp 414-421, Edited by Hossain & Bhargava, Springer, 2007

[Nolan_05] Keith Nolan, Linda Doyle, Donal O’Mahony, Philip Mackenzie. “Fluid Wireless – Dynamic Spectrum Allocation and Spectrum-Monitoring Application Using Reconfigurable Radio and OFDM,” SDR Technical Conference 2005, November 14-18, Orange County, paper # 4.4-04.

[OFCOM_09] “Digital dividend: cognitive access Consultation on licence-exempting

cognitive devices using interleaved spectrum,” February 16, 2009.

[Pereira_07] Artur Pereira, Joaquim Bastos, Paulo Marques, Atílio Gameiro, “Analysis of Communication Opportunities in UMTS Cellular Networks”

[Sankaranarayanan_05] S. Sankaranarayanan, P. Papadimitratos, and A. Mishra, “A bandwidth sharing approach to improve licensed spectrum utilization,” DySPAN 2005, Nov. 8-11, 2005. Paper # TT4-6.

[Seidel_05] S. Seidel and R. Breinig, "Autonomous dynamic spectrum access system behavior and performance," DySPAN 2005, Nov. 8-11, 2005. Paper # TT3-1.

[Thilakawardana_07] D. Thilakawardana, K. Moessner, "Enhancing Spectrum Productivity through Cognitive Radios facilitating Cell-by-Cell Dynamic Spectrum Allocation SDR Forum 2007, Denver CO, Nov 5-9, paper # 3.6-02.

[Tonmukayakul_05] A. Tonmukayakul and M. B H. Weiss, "An agent-based model for secondary use of radio spectrum," DySPAN 2005, Nov. 8-11, 2005. Paper # PT2-2.

[Zhang_07] Dynamic Spectrum Access Enabled DoD Net-centric Spectrum Management

Kevin Zhang, Darcy Swain, Mary Lin, Milcom 2007

[Zhao_05] Q. Zhao, Q.; Tong, L. and Swami, A. "Decentralized cognitive MAC for dynamic spectrum access," DySPAN 2005, Nov. 8-11, 2005. Paper # TT3-6.

[Zhao_07] Y. Zhao, D. Raymond, C. da Silva, J. Reed, S. Midkiff, "Performance Evaluation of Radio Environment Map-Enabled Cognitive Radios Coexisting with Incumbent Users," Milcom 2007.

[Zheng_05] H. Zheng, and L. Cao, "Device-centric spectrum management," DySPAN 2005, Nov. 8-11, 2005. Paper # GS2-2.

2.2 Cognitive Radio and MIMO

Multiple Input Multiple Output (MIMO) smart antenna systems are used in communications for improved performance (such as enhanced data rate or link reliability) and added capability (such as beam forming). Our survey turned up reports of cognitive radio (CR) being used with MIMO to adapt the employed MIMO scheme to the needs of the environment and user during use to create a more effective relaying scheme. These led to reported improvements in link capacity, link reliability, range, network availability and energy usage.

In the following, Section 2.2.1 gives an overview of the use of MIMO with CR. Section 2.2.2 reviews benefits uncovered in the survey for the combination of MIMO and CR. A listing of the references cited in this section is provided in Section 2.2.3.

2.2.1 Overview of MIMO Techniques

Multiple-Input-Multiple-Output (MIMO) techniques encompass a family of smart antenna array techniques including beam forming, spatial multiplexing and diversity coding. For beam forming applications, the inter-antenna timing (phase) of a signal is manipulated to combine energy coherently (or destructively to form a null) in a particular spatial direction. This can be performed at the transmitter, the receiver, or both. For a link, beam forming is used to improve SINR by improving the link budget of the desired signal by steering a beam in its direction and suppressing interference by steering a null in its direction. Within a broader wireless system, this can be used to help realize a spatial division multiple access scheme to greatly increase system capacity.

To understand spatial multiplexing, consider the MIMO system depicted in Figure 13 where there are *M* transmit antennas and *N* receive antennas. If there are *M* transmit antennas and *N* receive antennas, then there *MxN* propagation paths between the antennas in the system which we could represent by an *M*x*N* link gain matrix, *H*, where entry (*m*,*n*) in *H* is the link gain from transmit antenna *m* to receive antenna *n*. In spatial multiplexing, up to *M* different symbols are transmitted over the air, call this vector **x**, which are received as the vector **Y**=**Hx**. The receiver now has a linear system of equations to solve to recover **x**. The receiver's ability to recover **x** is determined by the degree of independence of these equations, i.e., the *rank* of **H**. As the rank of **H** increases, the receiver is able to recover more symbols. Of course, the rank of **H** is controlled by the smaller of *M* and *N* as well as the multipath environment. Interestingly for MIMO systems, the richer the multipath environment (greater the rank of **H** and thus more independent multipath components in the channel), the higher the actual throughput as more independent paths are available to be utilized.

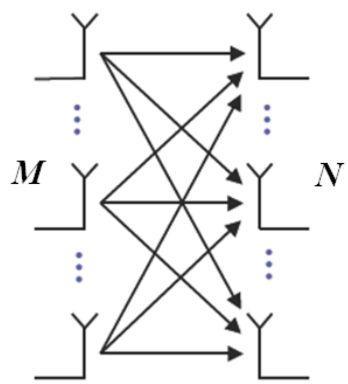

Figure 13: In a MIMO system, there are multiple antennas at the transmitter and multiple antennas at the receiver. If there are *M* transmit antennas and *N* receive antennas, there are *MxN* propagation paths between the antennas in the system.

Spatial multiplexing, then, is the exploitation of the spatial diversity in paths provided by the multipath and the antenna arrays to achieve higher throughputs over a given bandwidth. The size of this increase is a function of the number of antenna elements and the richness of the multipath environment. However in poor signal environments, this same channel independence may instead be used to encode redundant information (diversity coding) to decrease error rates on the data link. A CR could then modify the level of redundancy based on performance requirements and environment. Further, it may be advantageous in some settings (e.g., multipath poor environments) to use a beam forming application instead to increase capacity or link reliability.

One of the earliest MIMO algorithms is the Bell Labs Layered Space-Time Algorithm (BLAST). Foschini ([Foschini_98]) presented this algorithm to cope with fading channels and achieve spatial multiplexing. Alamouti ([Alamouti_98]) introduced simplified block codes that have been adopted by multiple standards. Currently, MIMO is used in 802.11n, LTE, and WiMAX, and MIMO is being discussed for use in 4G systems (LTE Advanced and 802.16m).

MIMO is itself a rich and varied field and it is not the purpose of this section to provide an exhaustive treatment of MIMO. So the interested reader is encouraged to learn more about MIMO from the references at the end of this section, from textbooks such as [Oestges_07] or by following up on some of the techniques listed in Table 4.

Table 4: MIMO includes a wide class of techniques for improving reliability and throughput. N_t is the number of transmit antennas (M) and N_r is the number of receive antennas (N). From [Andrews_07].

Technique	(N_r, N_t)	Feedback?	Rate r^a	Comments
Reliability-Enchancement Techniques ($r \leq 1$)				
Selection combining	$N_r \geq 1$ $N_t = 1$	Open loop	$r = 1$	Increases average SNR by (1 + 1/2 + 1/2 + ... $1/N_r$)
Maximal ratio combining	$N_r \geq 1$ $N_t = 1$	Open loop	$r = 1$	Increases SNR to $\gamma_\Sigma = \gamma_1 + \gamma_2 + ... + \gamma_{Nr}$
Space/time block codes	$N_r \geq 1$ $N_t > 1$	Open loop	$r \leq 1$	Increases SNR to $\gamma_\Sigma = \gamma \|\mathbf{H}\|_F / N_t$
Transmit selection diversity	$N_r \geq 1$ $N_t > 1$	Closed loop: Feedback desired antenna index	$r = 1$ usually ($r < N_t$)	Same SNR as selection combining
DOA beamforming	$N_r \geq 1$ $N_t \geq 1$ $N_r + N_t > 2$	Open loop if $N_t = 1$ Closed loop if $N_t > 1$ or used for interference suppression	$r = 1$	Can suppress up to $(N_r - 1) + (N_t - 1)$ interference signals and increase gain in desired direction. Ineffective in multipath channels
Precoding Techniques				
Linear diversity precoding	$N_r \geq 1$ $N_t > 1$	Closed loop: Feedback channel matrix	$r = 1$	Special case of linear beamforming; only one data stream is sent. Increases SNR to $\gamma_\Sigma = \gamma \|\mathbf{H}\|_F$
Eigenbeamforming	$N_r \geq 1$ $N_t > 1$	Closed loop: Feedback channel matrix	$1 \leq r \leq \min(N_r\text{–L } N_t\text{–L})$	Can be used to both increase desired signal gain and suppress L interfering users
General linear precoding	$N_r > 1$ $N_t > 1$	Closed loop: Feedback channel matrix	$1 \leq r \leq \min(N_r, N_t)$	Similar to eigenbeamforming, but interfering signals generally not suppressed; goal is to send multiple data streams
Spatial Multiplexing				
Open-loop spatial multiplexing	$N_r > 1$ $N_t > 1$	Open loop	$r = \min(N_r, N_t)$	Can receive in a variety of ways: linear receiver (MMSE), ML receiver, sphere decoder. If $N_t > N_r$, select best N_r antennas to send streams
BLAST	$N_r > 1$ $N_t > 1$	Open loop	$r = \min(N_r, N_t)$	Successively decode transmitted streams
General linear precoding	$N_r > 1$ $N_t > 1$	Closed loop: Feedback channel matrix	$1 \leq r \leq \min(N_r, N_t)$	Same as preceding; both a precoding technique and a spatial-multiplexing technique

a. r is similar to the number of streams M but slightly more general, since $r < 1$ is possible for some of the transmit-diversity techniques.

2.2.2 Reported MIMO Benefits

In our literature review, we encountered two primary approaches to combining CR and MIMO techniques:

- Using CR processes to tailor the employed MIMO scheme to the needs of the environment and user at run-time
- Using CR with MIMO to create a more effective relaying scheme.

Depending on the technique implementation, improvements in link capacity, link reliability, range, network availability and energy usage are realized.

2.2.2.1 Cognitive Control of MIMO Resources

As noted by Table 5.3 in [Marshall_06] and reproduced in Table 5, both frequency and spatial diversity can be combined by changing how frequencies (called channels in Table 5) are allocated across an antenna array. For example under the right multipath conditions, using an 8x8 MIMO scheme where all antennas are operating on a single carrier frequency can increase spectral efficiency enough to yield a capacity approximately as large as using 5 parallel carriers. But if more spectrum were available so that the 8x8 system could use 8 parallel carriers, an even greater throughput could be achieved, at the cost of consuming more spectrum.

Table 5: Table 5.3 Alternative approaches for mixed spectral and MIMO adaptation

	Channels Used	Resources	Throughput	Throughput/ Resource	Throughput/ Channel
Pure 8x8 MIMO	1	8	5.04	0.63	5.04
6x6 MIMO	1	6	4.49	0.75	4.49
2 sets of 3x3 MIMO	2	6	5.68	0.95	2.84
2 sets of 4x4 MIMO	2	8	7.18	0.90	3.59
4 sets of 2x2 MIMO	4	8	7.80	0.98	1.95
8 Independent Channels	8	8	8.00	1.00	1.00

Clearly the most advantageous scheme depends on the operating conditions (e.g., spectrum availability, battery life, and computing resource availability) and the goals the CR is working towards (e.g., energy efficiency or throughput). Marshall suggests that cognitive adaptation can be used to optimize which MIMO scheme is employed by selection of the operating points from the trade space (e.g., spectral efficiency for resource efficiency as shown in Figure 14).

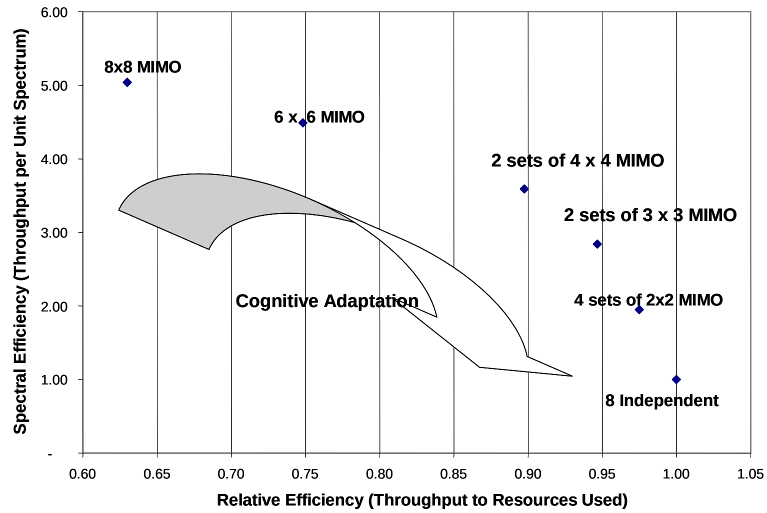

Figure 14: CR can be used to optimize over the MIMO tradespace. From Figure 5.5 in [Marshall_06]

2.2.2.2 Cooperative Techniques

As reported by Devroye and Tarokh ([Devroye_07]), (see Figure 15) a transmitter aided by a cooperative cognitive radio transmits at up to two times the data rate by exploiting the MIMO communications channel.

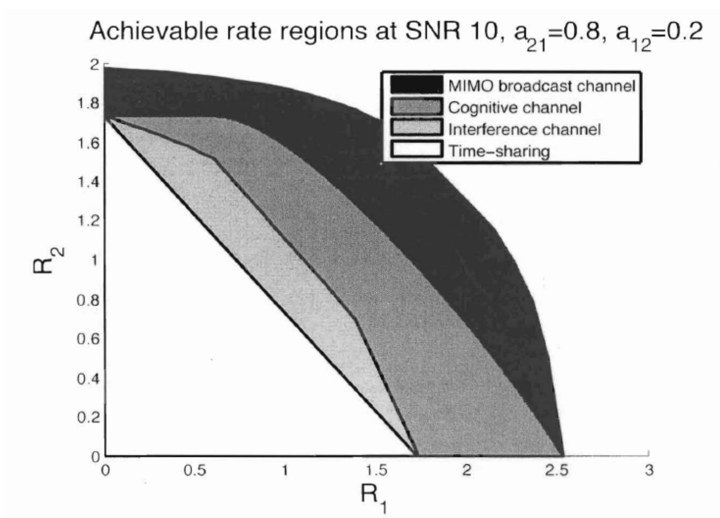

Figure 15: Capacity region of the Gaussian 2x1 MIMO two receiver broadcast channel (outer), cognitive channel (middle), achievable region of the interference channel (second smallest) and time-sharing (innermost) region for Gaussian noise powers N1=N2=1, power constraints P1=P2=10 at the two transmitters, and channel parameters a12=0.8, a21=0.2. From Figure 17.4 in [Devroye_07].

As reported by Lu, Fitzek, and Eggers ([Lu_07]), a cooperative cognitive radio acting as a relay increases the link availability by 50% under certain conditions. The necessary condition is high SNR from the primary node to the destination and from the primary node to the relay node. Therefore, a region populated with cognitive radios that have cooperative MIMO waveform and a cooperative protocol for forwarding traffic can improve network availability.

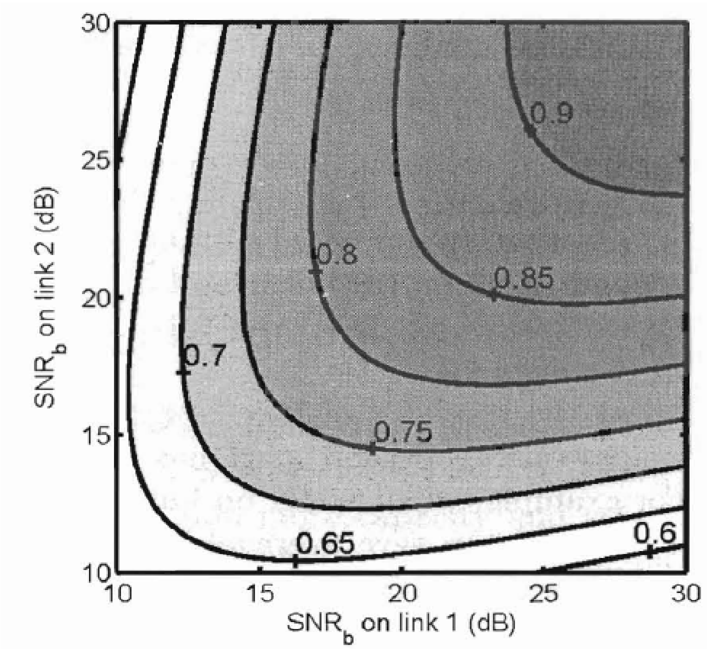

Figure 16: CSR availability when both links satisfy Condition I. SNR_b denotes the mean SNR per branch. From Figure 23.7 in [Lu_07]

As reported by Zhang and Fitzek ([Zhang_07]), WLAN nodes participating in cooperative re-transmission, save between 40% and 48% in energy in a packet-loss rate (PLR) condition of 5%. In a WLAN environment with 128 nodes partitioned into various group sizes and numbers of groups and there is cooperative spatial reuse, the nodes experience various, but significant, savings of energy.

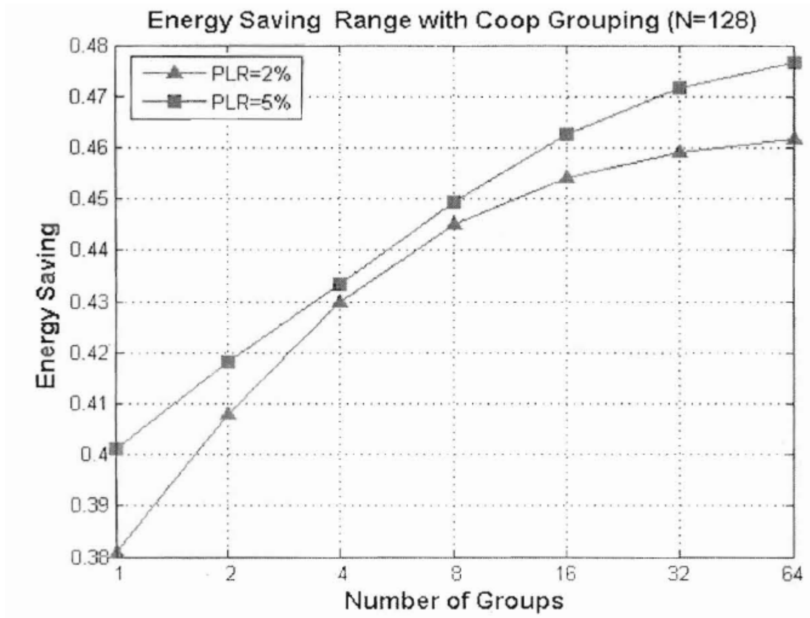

Figure 17: A cooperative retransmission scheme was reported to save energy in a WLAN system as a function of the Packet Loss Ratio (PLR) and the number of groups with a fixed number of nodes (128). However, diminishing returns on groupings is seen. From Figure 25.8 in [Zhang_07]

2.2.3 MIMO References

[Alamouti_98] S. Alamouti, "A Simple Transmit Diversity Technique for Wireless Communications," IEEE JSAC, Vol. 16, No. 8, October 1998.

[Andrews_07] A. Andrews, R. Ghosh, *Fundamentals of WiMAX*, Prentice Hall, 2007.

[Devroye_07] N. Devroye, V. Tarokh, "Fundamental Limits of Cognitive Radio Networks," Chapter 17 in *Cognitive Wireless Networks*, Edited by Fitzek & Katz, Springer, 2007.

[Foschini_98] G.J. Foschini and M.J. Gans ,"On Limits of Wireless Communications in a Fading Environment when Using Multiple Antennas." *Wireless Personal Communications* **6:** 311–335, 1998.c 1998 Kluwer Academic Publishers. Printed in the Netherlands.

[Lu_07] C. Lu, F.H.P. Fitzek, P.C.F., Eggers, Cognitive Wireless Networks, "A Cooperative Schemee Enabling Spatial Reuse in Wireless Networks," Chapter 23 in *Cognitive Wireless Networks*, Edited by Fitzek & Katz, Springer, 2007.

[Marshall_06] P. Marshall, "Spectrum Awareness," Chapter 5 in *Cognitive Radio Technology*, Editor B. Fette, Newnes, 1st Edition, June 2006.

[Oestges_07] C. Oestges, B. Clerckx, *MIMO Wireless Communications,"* Elsevier, 2007.

[Zhang_07] Q. Zhang, F.H.P. Fitzek, "On the Energy Saving Potential in DVB-H Networks Exploiting Cooperation among Mobile Devices," Chapter 24 in *Cognitive Wireless Networks* Edited by Fitzek & Katz, Springer, 2007.

2.3 Radio Resource Management (RRM) and Cognitive Radio

2.3.1 Overview of RRM and its Relationship to Cognitive Radio

This section provides an overview of radio resource management and its relationship to cognitive radio and reviews papers that have proposed using cognitive radio techniques to enhance the management of radio resources.

In a wireless network, a design engineer has control over many variables in the radio domain that will impact device and system performance. Channel allocations between sectors, level crossing rates, call drop thresholds, device power levels assignment, timers and backoff period adjustments, and antenna patterns are all examples of parameters that are adjustable to improve network performance. These choices can be made during the design phase (e.g., specifying a channelization pattern) or they can be tweaked post deployment (e.g., adjusting the orientation of antennas), or they can be changed at run-time based on the current conditions (e.g., adjusting base-station beacon power levels to distribute subscriber loading between cells, scheduling transmission times, adaptive fractional frequency reuse schemes on cell-edges, and dynamic frequency selection or channel allocation). All of these are examples of methods, techniques, or actions taken as part of a radio resource management regime.

By incorporating intelligence and situational awareness into the system, network, or device, many different cognitive radio techniques have been proposed for improving existing or enabling new run-time radio resource management algorithms. More specifically, as the number and type of wireless devices increase (increasing amount of machine-to-machine communications, the access-everywhere paradigm, and generally increasing cellular market penetration), radios will increasingly operate as part of heterogeneous wireless ecosystems whose behavior and needs vary greatly with time and location and where the interactions will likely be so complex that they cannot be perfectly anticipated by the designers. In such a setting, cognitive radio will play a very important role in radio resource management by enabling the devices and systems to learn how to best operate in the context of their evolving environment and the varying needs of the applications (or users) they support.

In this complex ecosystem, it will be important to bring some structure to the environment to simplify the processes a CR uses to make meaningful decisions, lest all of a CR's computational resources be lost to just understanding the world around it. Thus there will be an increasingly important role for cognitive radio standards that span individual wireless protocols as the wireless world evolves. This could be a simple as defining a common set of channels (as with the TVWS) or as complex as formal etiquettes that guide inter-system interactions. Current efforts pursuing such standards include the policy languages being developed in IEEE 1900.5, the meta-languages in the Wireless Innovation Forum's MLM workgroup, the mechanisms for sharing sensing data in 1900.6, the common architectural building blocks of 1900.4, and the TVWS coexistence techniques being considered in IEEE 802.19. None of these will define a CR or a wireless protocol, but they all have the potential to be significant aids to CR processes in the complex wireless ecosystem of the future.

Even with such a structure, the use of cognitive radios as part of radio resource management schemes will pose significant design issues as the interactions of so many intelligent decision makers could yield unexpected emergent behaviors. To address this, many researchers are employing techniques from game theory to model, analyze, and design CR radio resource management schemes. Game theoretic tools allow the designers to characterize expected operating points for the complex system and describe expected behavior (e.g., convergence and stability characterizations). Further, many designers will build their systems to satisfy the parameters of particular game models (e.g., tweaking the allowable adaptations, adjusting system timings, and tweaking the interaction schemes) because that would lead to their systems having certain desirable behavioral properties.

Because virtually every cognitive radio algorithm is arguably some sort of radio resource management scheme (e.g., DSA can be viewed as channel allocation scheme that spans a complex wireless system of primary and secondary users; self-organizing networks necessarily perform many radio resource management functions) this section focuses on the many different cognitive-radio-enabled radio-resource-management schemes not considered elsewhere in Section 2.

2.3.2 Reported Benefits

The following reports the results of applications of CR to radio resource management schemes for bandwidth sharing, power control, interference avoidance enabled channel management, network selection and multi-function radio resource management.

2.3.2.1 Bandwidth Sharing

Several authors considered how cognitive radio techniques could be used to more optimally share a channel among several users. In general, it was found that if the overhead could be tolerated, then schemes whereby nodes cooperate by sharing their observations and consider the impact of their performance on other nodes yielded better performance.

For instance, [Comanciu_07] explores channel access schemes and uses game theory to develop cooperative techniques for sharing a channel and this is shown to outperform networks unable to directly cooperate in terms of highest per user throughput and lowest variance of throughput, specifically reporting increased per user throughput increases of 7% while throughput variance is reduced 15%.

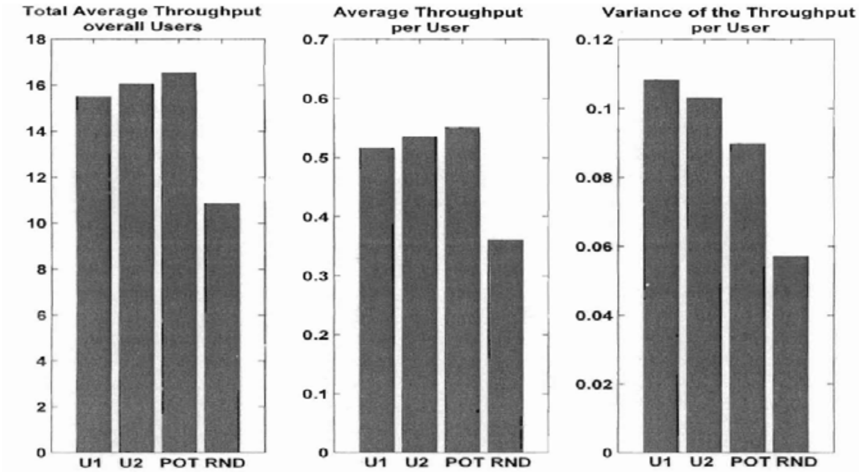

Figure 18: Total Average Throughput, Average Throughput per user and Variance Throughput per user (U1 = selfish users with minimum regret learning algorithm implementation; U2 = cooperative users with minimum regret learning algorithm implementation; POT = cooperative users with potential game implementation; RND = equal probability random channel allocation). From Figure 28.6 in [Comanciu_07].

Likewise [Zheng_05] studies several forms of cooperation in a device-centric spectrum management scheme for cognitive radios where users observe the interference usage of their neighbors and act independently according to preset spectrum access rules. The specified spectrum access rules tradeoff implementation complexity, communication costs (network overhead), fairness of resource allocation and spectrum utilization to varying degrees. Extensive network simulations and theoretical analysis are used to quantify the benefit of the proposed scheme and compare the different allocation rules. It is shown that the rule-based approach considerably reduces communication costs when compared to collaborative approaches (which offer near-optimal allocation efficiency) while still providing good performance.

Specifically, [Zheng_05] considers three rules (all shown to converge): bargaining which is a collaborative scheme with a large communication cost in the network, Rule-E which is a simple CSMA-based approach, and Rule-C which exchanges channel usage information with neighbors at a slightly higher communication cost than Rule-E. Results of simulations averaged over numerous instances are shown in Figure 19 where total system throughput is calculated as $\sum_n \beta_n$ and fairness as $\sum_n \log \beta_n$ where β_n is the throughput for a single user. Note that like with [Comanciu_07], the best performance and most fairness comes with explicit cooperation.

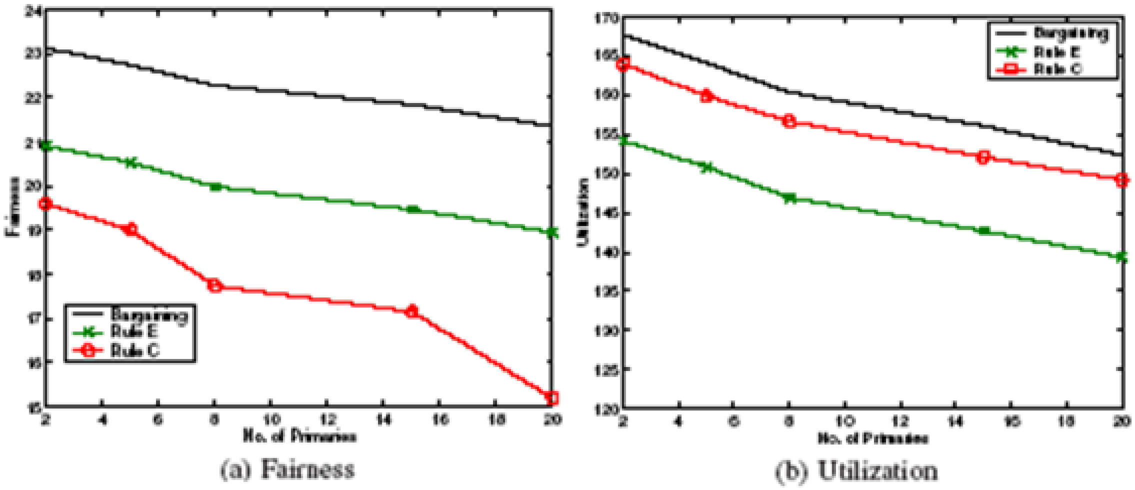

Figure 19: Utilization and Fairness Comparison of different rules assuming 20 channels, 40 secondary users and 20 primary users. From Fig 11 in [Zheng_05]

Another spectrum sharing scheme is proposed in [Auer_07], which is based on busy burst (BB) signaling – a kind of CSMA – whose basic principle is that upon data reception a CR transmits a busy signal in an adjacent time-multiplexed slot. Through exploitation of channel reciprocity, other potential transmitters are prevented from interfering by first listening to the busy signal. Due to its decentralized nature, the considered BB-DSA (Busy-burst DSA) protocol was reported to be ideally suited for dynamic spectrum sharing in license-exempt spectrum. As compared to a fixed timeslot allocation scheme (FSA), the BB-DSA scheme supports throughputs 3 to 4 times higher and approaches a theoretical limit of an ideal scheduler modeled as an M/G/1 queue.

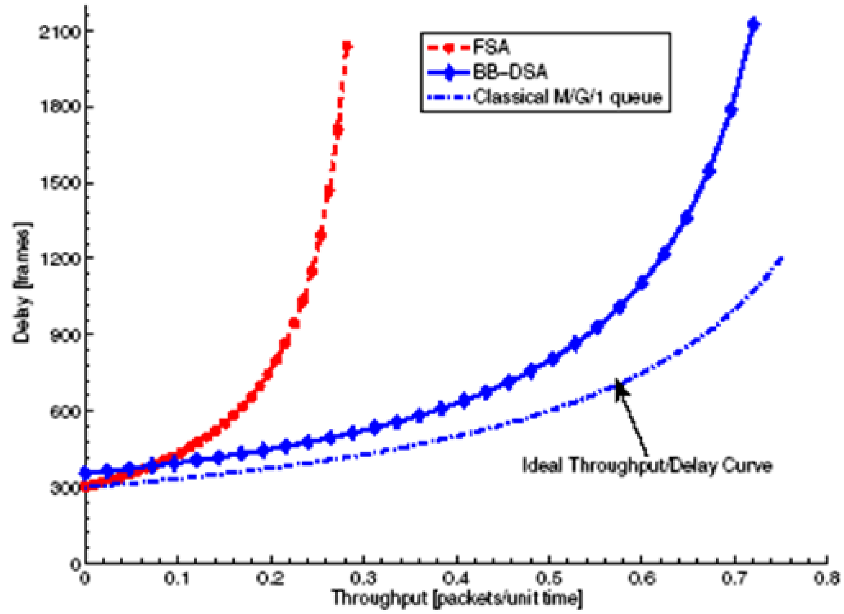

Figure 20: Delay-throughput results comparing a fixed (FSA) and a dynamic scheduling algorithm (BB-DSA) against a theoretical limit (M/G/1 queue). From Fig. 4 in [Auer_07].

When available spectrum is channelized, spectrum sharing algorithms have more structure to work with that allows for simpler, more robust, algorithms, even when across heterogeneous networks. As an example, [Luo_05] presents concepts for flexible spectrum management by employing spectrum pooling and dynamic channel assignment and compares it to fixed channel assignment. [Luo_05] finds that there is spectrum efficiency gain achieved by pooling spectrum between different radio access technologies and cites that a dynamic channel assignment scheme, spectrum pooling, channel borrowing and dynamic channel assignments had respectively improved the number of served users 144%, 66% and 66% compared to fixed channel assignment.

2.3.2.2 Interference Avoidance and Channel Selection

[Ma_07] presents the Single-Radio Adaptive Channel (SRAC) algorithm which enables dynamic spectrum access in multi-hop wireless ad hoc networks where each node has only one half-duplex radio (transceiver). It provides a feasible dynamic channelization mechanism to make the best of the available spectrum, relaxes the radio communication conditions to enhance network connectivity, and exploits the broadcast nature of the wireless medium to provide efficient multicast support. Designed as a relatively independent module, SRAC can upgrade various existing single-radio legacy Medium Access Control (MAC) protocols to be dynamic spectrum access capable, achieving efficient use of the spectrum, relaxing their operating conditions, and naturally supporting multicast applications. The SRAC algorithm is characterized by three features: (a) dynamic channelization in response to jamming, primary spectrum users and channel load, (b) “cross channel communications”, and (c) as-needed use of spectrum.

In this paper, SRAC performance is analyzed and evaluated using a CSMA/CA MAC protocol in QualNet 3.8, which captures the major features of IEEE 802.11 Distributed Coordination Function (DCF). The paper shows significant improvement in performance when a jammer is transmitting (beginning at around 11 seconds in the figures below).

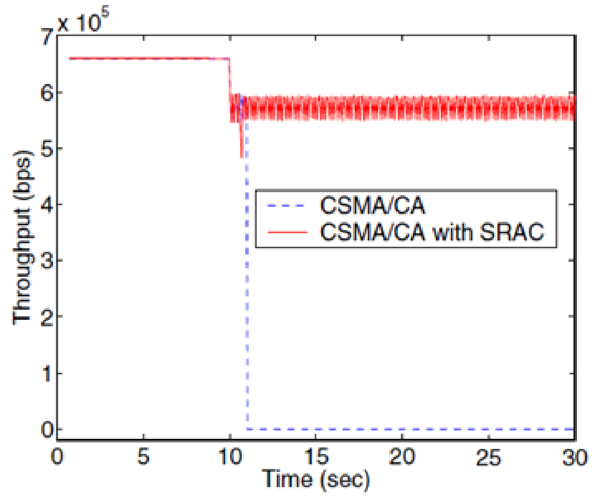

Figure 21: Throughput for the CSMA/CA protocol with and without the proposed SRAC algorithm with a jammer enabled at 11 seconds. From Fig. 11 in [Ma_07]

2.3.2.3 Network Selection

With the increasing deployment of femtocells, growing number of WiFi hot spots, including being integrated into smart phones and cellular service plans, and the general proliferation of wireless networks, devices will frequently need to choose which network to associate with. By gaining information about the available networks, CRs can make decisions that improve their own performance and the performance of the wireless ecosystem.

For instance, [Zekavat_05] proposes and analyzes what the paper calls a user-centric wireless architecture for dynamic channel allocation (DCA) with cognitive radios (CRs). In their system, a user can choose an optimum vendor at any instant of time and geographical location. The CRs choose the optimum vendor via a cost function based on the following parameters: channel availability, congestion rate, the vendor quality of service in terms of bit-error rate (BER) performance, cost per second, and signal power.

After describing the system architecture, the paper shows that allowing radios to make these kinds of association decisions, as opposed to more traditional vendor or network-lock-in schemes, yielded improvements in terms of call blocking rate, spectrum efficiency, and vendor revenues, which are improved by 23%, 8% and 10% respectively in the simulated scenarios.

2.3.2.4 Power Control

Power control is a traditional RRM function and authors have also considered how it can be improved with cognitive radio. For instance, [Neel_06] considers a distributed power control scheme in an ad-hoc network wherein each node attempts to maintain a target SINR on the links' receivers in the context of illustrating techniques whereby distributed, non-cooperative CR radio resource management could be assured of stability (thereby generally reducing network overhead by minimizing the number of adaptations). In the attached figures below, the paper demonstrates that when each link chooses its transmit power to maximize the power allocation equation can produce a stable power allocation for the network even in the presence of noise. It is seen that convergence is rapid, occurring within a practical number of iterations, and in this example in approximately eight iterations.

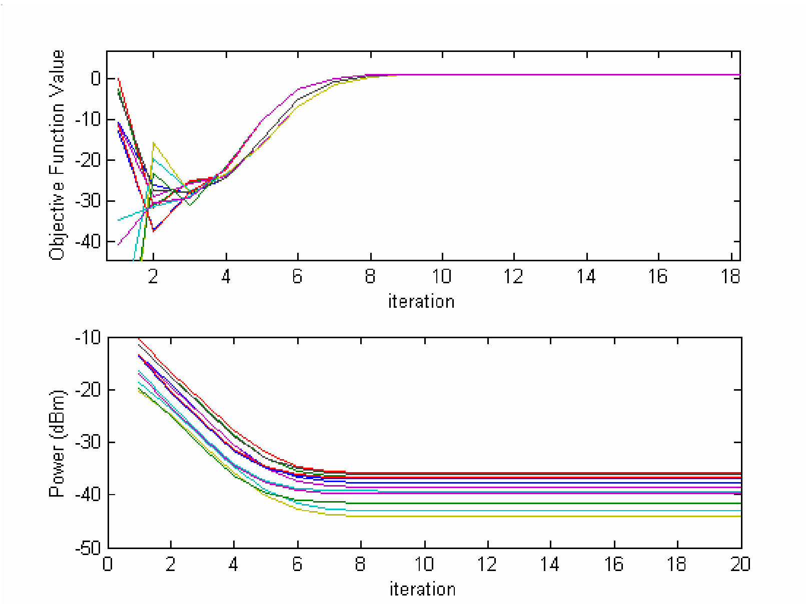

Figure 22: Deterministic simulation of an ad-hoc network of cognitive radios with synchronous adaptations and utility functions given by eqn. 15-30. The top graph plots the value of each radio's utility function versus the iteration; the lower plot shows the power levels for each radio versus iteration. From Figure 15-25 in [Neel_06]

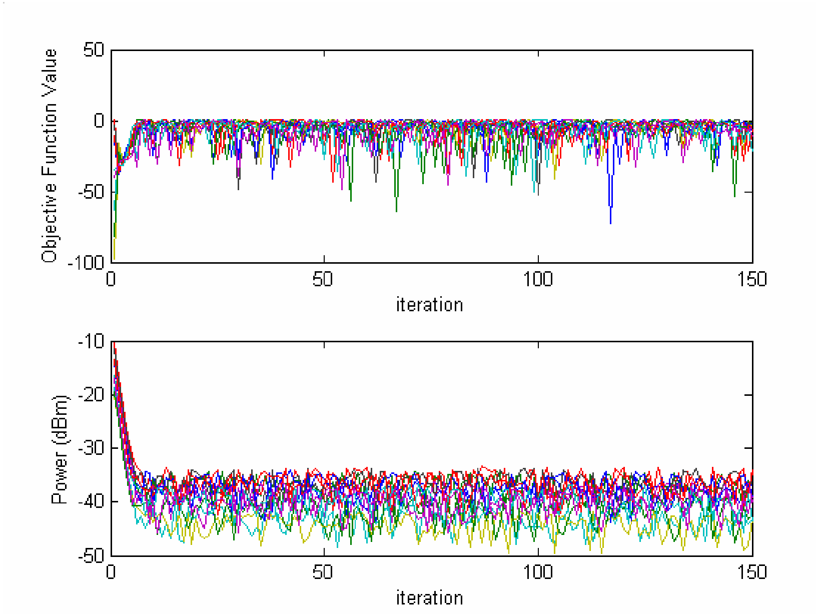

Figure 23: Simulation of an ad hoc network of cognitive radios with synchronous adaptations. The top graph plots the value of each radio's utility function versus the iteration; the lower plot shows the power levels for each radio versus iteration. From Figure 15-26 in [Neel_06]

[Abou-Jaoude_04] instead considers a centralized system wherein power allocation for a HSDPA network is controlled by the network's management subsystem in response to the load changing in time and in space.

The adaptive power allocation at each base station involves a shift of resources between dedicated services such as voice with variable power and shared services such as background traffic with constant power. Moreover, it involves a reconfiguration of the base station's DSP and ASIC boards to allow for a faster decoding of the information depending on its type. In the case of HSDPA, the base station has additional functionalities such as fast scheduling (assigning resources to users on a 3-slot frequency), modulation and coding scheme selection, and H-ARQ as a fast retransmission mechanism. The power assignment is done at the network management level on a less frequent basis, though not standardized by 3GPP. In the paper, the network manager sends frequent signals during the day to base stations as to which fraction of their available total power to allocate to HSDPA, and if necessary to reconfigure HW and SW to work under the dedicated or the shared mode. Figure 2 shows the deployed network considered in the analysis.

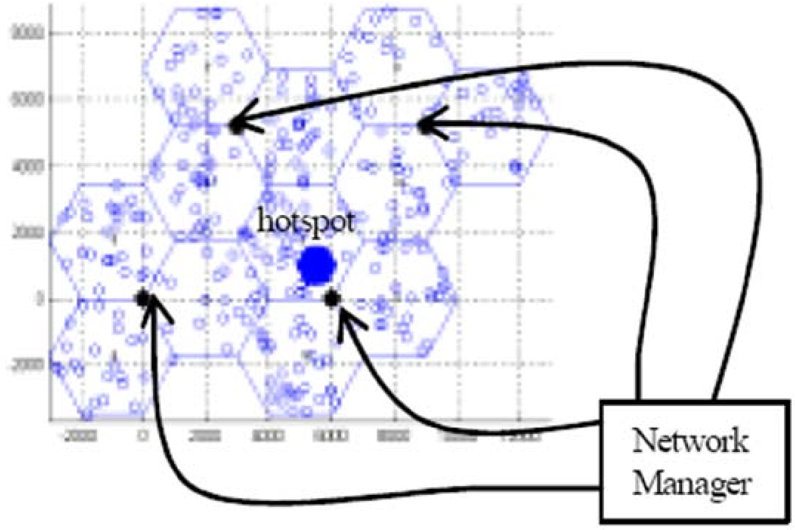

Figure 24: Network layout for power commands. From [Abou-Jaoude_04]

By accounting for the changes, the network manager was able to prioritize the hotspot cell thereby improving its response time and throughput, though at some expense to the other cells in the network.

Table 6: Gains in terms of response time (seconds). From [Abou-Jaoude_04]

Response Time	Hotspot cell	Other cells
70th percentile	0.34 sec less	0.13 sec more
80th percentile	0.75 sec less	0.24 sec more
90th percentile	2.18 sec less	0.58 sec more

Table 7: Gains in terms of throughput. From [Abou-Jaoude_04]

Throughput	Hotspot cell	Other cells
40th percentile	0.72 Mbps more	0.0010 Mbps less
70th percentile	0.37 Mbps more	0.0013 Mbps less
90th percentile	0.36 Mbps more	0.0030 Mbps less

2.3.2.5 General Radio Resource Management

Some authors have proposed the use of cognitive radio to address many different aspects of radio resource management. For instance, [Zhao_07] proposes using shared databases to inform cognitive radios about their environment so that the deployed CRs can minimize harmful interference to incumbent primary users and to maximize the utility of spectrum-sharing networks and considers the impact of global and local information databases. By exploiting the

REM information, the CRs make situation-aware adaptations in transmit power, transmit timing, routing protocol, and topology, thereby reducing interference to primary users. More importantly, the painful hidden node or hidden receiver problem can be mitigated with the help of the Global database.

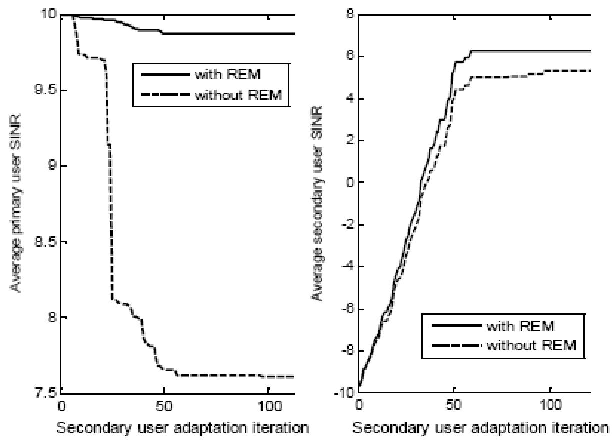

Figure 25: By incorporating shared information databases with a form of case-based reasoning, significant performance. From [Zhao_06]

In contrast to the preceding approach that explicitly shares information to ensure a consistent global view of the network is shared among all devices, [Neel_07] considers radio resource management assuming that information sharing is limited (if at all) and all decisions must be made locally with incomplete information about the network state. Building on techniques from game theory, [Neel_07] introduces a condition the paper calls bilateral symmetric interference (BSI) which ensures that relatively unsophisticated distributed selfish adaptations always converge to stable and locally optimal resource allocations. The paper proceeds to show how this condition can be achieved for distributed channel allocation along with power control and link prioritizations. Performance comparisons are then made to fixed allocations and shows both dramatic improvements and network stability for coexisting WLAN access points and clients in infrastructure mode (average interference reduced up to 30 dB) and ad-hoc networks controlling resources on a link-by-link basis (probability of collisions reduced by a factor of 16).

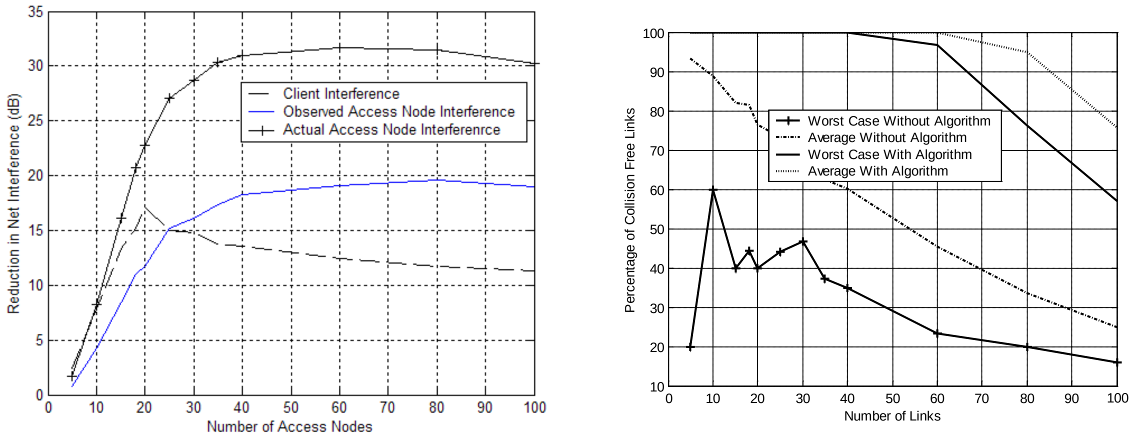

Figure 26: By ensuring all observations in the network satisfy the BSI condition, significant reductions in interference were achieved for coexisting WLANs in infrastructure mode (left) and in collision probabilities in ad hoc mode (right). From Figures 6 and 8 in [Neel_07].

2.3.3 Radio Resource Management References

[Abou-Jaoude_04] R. Abou-Jaoude, W. Koenig, J. Luo, M. Dillinger, “Dynamic Network Management in Reconfigurable Systems- HSDPA Power and Code Allocation,” SDR Forum Technical Conference 2004, November 15-17, Phoenix, paper # 1.3-2.

[Auer_07] G. Auer, H. Haas, P. Omiyi, “Interference Aware Medium Access for Dynamic Spectrum Sharing,” DySPAN 07.

[Comanciu_07] *C.* Comaniciu, “Cooperation of Cognitive Networks,” Cognitive Wireless Networks, Chapter 28, pp 539 - 546, Edited by Fitzek & Katz, Springer, 2007

[Grandblaise_07] D. Grandblaise, C. Kloeck, T. Renk, P. Bag, P. Levine, K. Moessner, J. Yang, M. Pan and K. Zhang, “Microeconomics Inspired Mechanisms to Manage Dynamic Spectrum Allocation,” DySPAN 07

[Luo_05] J. Luo, C. Kloeck, K, Moessner, D. Grandblaise, P. Demestichas, G. Dimitrakopoulos, E. Mohyeldin, O. Sallent, P. Cordier. “Inter-operator Flexible Spectrum Management vs. Roaming,” SDR Technical Conference 2005, November 14-18, Orange County, paper # 4.3-04.

[Ma_07] L. Ma, C. Shen, and B. Ryu, “Single-Radio Adaptive Channel Algorithm for Spectrum Agile Wireless Ad Hoc Networks,” DySPAN07

[Neel_06] Neel, J Reed, A. MacKenzie., “Cognitive Radio Performance Analysis,” Cognitive Radio Technology, Chapter 15, pp 563-567, Editor Fette, B., Newnes, 1st Edition, June 2006

[Neel_07] J. Neel, "Synthetic Symmetry in Cognitive Radio Networks," SDR Technical Conference 2007, Denver CO, Nov 5-9, paper # 3.6-02.

[Zekavat_05] Zekavat, S.A. and Li, X, "User-central wireless system: ultimate dynamic channel allocation," DySPAN 2005, Nov. 8-11, 2005. Paper # TT1-2.

[Zhao_06] Y. Zhao, J. Gaeddert, K. Bae, J. Reed, "Radio Environment Map Enabled Situation-Aware Cognitive Radio Learning Algorithms," SDR Forum Technical Conference 2006.

[Zhao_07] Y. Zhao, D. Raymond, C. da Silva, J. Reed, S. Midkiff, "Performance Evaluation of Radio Environment Map-Enabled Cognitive Radios Coexisting with Incumbent Users," Milcom 2007.

[Zheng_05] Zheng, H. and Lili Cao, "Device-centric spectrum management," DySPAN 2005, Nov. 8-11, 2005. Paper # GS2-2.

2.4 Spectrum Markets and Auctions

2.4.1 Overview and Relationship to Cognitive Radio

Even with cognitive radio, spectrum will continue to be a scarce commodity that will necessitate an allocation mechanism to allot spectrum among the potentially infinite number of competing uses. One traditional way of allocating spectrum access is via spectrum auctions held by national regulatory bodies where the winning bidder(s) gain transmission rights in specified bands, locations, and times for the duration of the lease. For instance, the recent 700 MHz US auction saw Verizon and AT&T pay $9.36 billion and $6.64 billion dollars respectively for transmission rights across enough regions to define a nationwide service area.

However, demand for spectrum by one user/ service tends to vary with time so that these relatively long-term allocations can lead to underutilization – though this underutilization varies greatly from band to band, service to service and location to location. One way that has been proposed to increase utilization is to allow primary users to dynamically resell spectrum to secondary users. This allows for spectrum allocations to be shifted with changing demands and allows primary users to extract further value out of their spectrum when it is not fully utilized.

In theory, this buying and selling of spectrum can be done across varying time-frames, from years or decades as the original auctions held by regulators dictate, or weeks or months as emerging spectrum trading houses currently facilitate (e.g., Cantor-Fitzgerald and Spectrum Bridge) or down to the order of minutes or seconds. While working with spectrum trades that operate on monthly or weekly periods can readily be performed by humans, trading spectrum on a minute-by-minute, or even hour-by-hour basis, will be both tedious and require too much information processing for it to be comfortably accomplished by people.

With the task too tedious and rapid-paced for humans, the opportunistic leasing of spectrum by the minute or by the hour will require automation to be effectively processed. Likewise as the number of potential buyers and sellers increase, automation will again be needed to allow for timely matching of buyers and sellers out of the sea of potential bidders / sellers. To realize this process, an automated buyer or seller agent (presumably responsible for ensuring spectrum availability for some device, network, location, or system) will need to be aware of the operating environment, current and future needs for its system and its capabilities and resources. It will also need to be able to reason over the impact of its decisions, identify and evaluate potential trades, and be empowered to execute its decisions. All of these requirements are consistent with the cognitive radio paradigm, thus implying that these automated spectrum traders will need to be *cognitive radios*.

To facilitate the interactions of these cognitive radios, some system, institution, and / or set of procedures that allow the cognitive radios to buy, sell and trade spectrum have to be established. The system / institution, and /or set of procedures used to facilitate these trades are collectively called *spectrum markets*, and one possible procedure for determining which cognitive radio gets to purchase spectrum from a seller is a *spectrum auction*. Typically, an auction refers to a specific process of soliciting bids for an item (or items) and allocating the item to the winning bidder wherein the final price and determination of the "winner" can vary greatly. More generally, a spectrum auction can refer to any process used to facilitate the exchange of spectrum. Thus a spectrum auction mechanism can be part of a spectrum market.

In the National Broadband Plan released in March 2010, the FCC noted that secondary spectrum markets have been allowed for several years with some success [FCC_10].

> Preliminary analyses establish that there have been thousands of secondary-market transactions involving mobile broadband licenses over the last several years. These have included license transfers, including partitioning and disaggregation, and spectrum leases,[59] thus providing some evidence that the FCC's policies have enabled "spectrum to flow more freely among users and uses," as envisioned in the Commission's Secondary Markets Policy Statement.

The FCC did this with the goal of eliminating regulatory barriers that might hinder making more efficient use of spectrum. Towards that end, the papers surveyed in this study showed that spectrum markets and auctions can be used to significantly increase revenues for spectrum owners, improve the performance of secondary users, and increase overall spectrum utilization and efficiency as discussed in the following section.

2.4.2 Reported Benefits

The following summarizes the benefits reported by employing cognitive radios to create spectrum markets and spectrum auctions.

General trends:

- Significant revenues could be gained by spectrum owners by implementing spectrum auctions [Sengupta_07] [Gandhi_07]

- The greatest gains come from most dynamic auctions based on real-time information of local demand and available resources [Gandhi_07] => this critical awareness could be enabled by cognitive radio and cognitive radio environment maps.
- Increasing revenues with increasing number of bidders => maximize revenues by most open spectrum usage rules [Gandhi_07], [Sengupta_07]
- [Sengupta_07] "However, the effect of collusion decreases with the increase in the number of bidders and the revenue generated even in the presence of collusion reaches almost the same value as that of without collusion."

2.4.2.1 Increased Revenue for Incumbents and Spectrum Owners

One way to make dynamic spectrum access more palatable to incumbents and current spectrum owners is to demonstrate that cognitive radio and dynamic spectrum access in particular will increase the value of their spectrum. Accordingly several researchers have considered how to design cognitive radio processes that will maximize the revenues of incumbents when dynamically leasing their spectrum to secondary users.

For example [Gandhi_07], explores the impact of bidding behaviors, pricing models and node clustering on real-time, "conflict-free" spectrum auctions and shows that revenue could be increased by a factor of 65 as the number of nodes increased in a simulated scenario where nodes are used to simulate the wireless access points (hotspots) which are not uniformly distributed in a geographical area, with hotspot capabilities simulated by deploying a clustered network with varying number of nodes k associated with each access point.

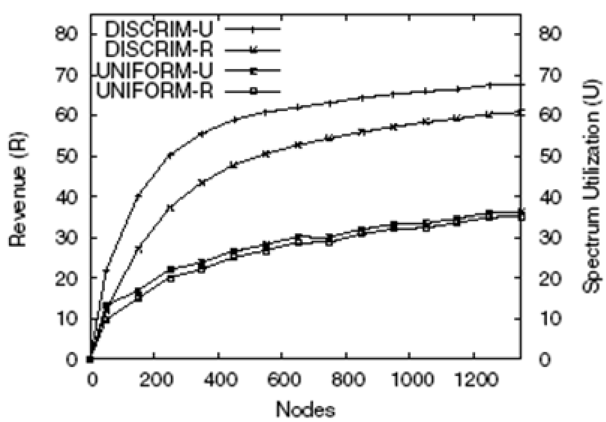

Figure 27: Revenue and Spectrum Utilization under uniform and discriminatory pricing. From Fig. 5 in [Gandhi_07]

While [Gandhi_07] considered a variety of behaviors and scenarios, a critical conclusion was that pricing must be determined based on local demand and availability of resources in order to maximize revenue and spectrum availability. Since awareness of demand and resources is a fundamental feature of cognitive radio, it is clear that cognitive radio is a key technology for maximizing spectrum owner revenues if implementing a real-time spectrum auction.

Likewise [Snegupta_07] considers the impact of pricing in a dynamic spectrum auction where they show that that the proposed auction entices the Wireless Service Providers (WSP) to participate in the auction, makes optimal use of the common spectrum pool, and avoids collusion among WSPs. Moreover, numerical results demonstrate how pricing can be used as an effective tool for providing incentives to the WSPs to upgrade their network resources and offer better services.

[Ji_07] proposes a collusion-resistant dynamic pricing approach to optimize overall spectrum efficiency in the scenarios of user collusion, which traditionally degrade efficiency. Based on simulations of a network with varying number of primary and secondary users, it is shown that the approach leads to significant revenue improvements even in the face of user collusion (Figure 28).

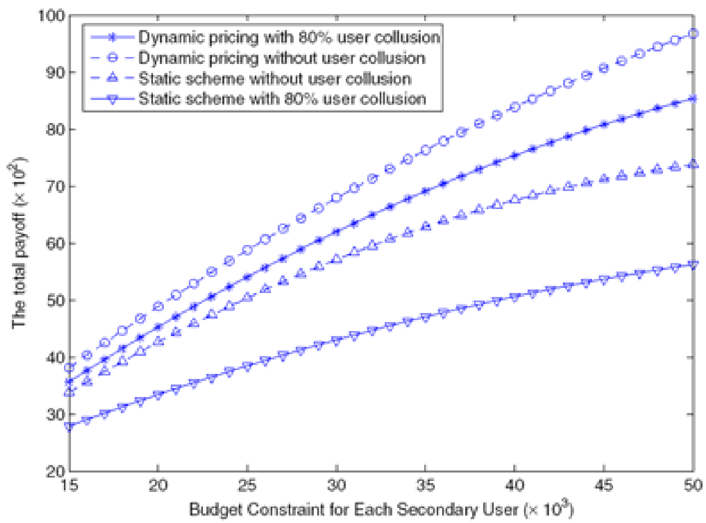

Figure 28: Adopting a dynamic pricing algorithm leads to significant revenue improvements even in the face of user collusion. From Fig. 2 in [Ji_07]

2.4.2.2 Increase Spectrum Utilization

One of the shortcomings cognitive radio and DSA are intended to address is increasing the utilization of spectrum so that, in theory, society maximizes its value from spectral resources. If structured properly, spectrum markets and auctions can significantly enhance the utilization of spectrum. For instance, [Gandhi_07] showed how the design of the spectrum market pricing scheme could have a significant impact on utilization (shown in Figure 27).

2.4.2.3 Improved and Differentiated Performance

By forcing networks and radios to consider how much they actively need (and value) spectral resources via a pricing mechanism, resource utilization can be implicitly directed to those networks and radios that place the highest value on the resources. This can lead to significant improvements in perceived network performance. For instance, [Hultell_07] discuss automating the financial transactions to access spectrum. In this model, the service source holds a periodic auction (period is set to be reasonable period length but to allow changes in rate for time of day, for example for one hour), in which clients bid for access. The access price is in Price per MByte. The service provider first sets a minimum acceptable price. The service provider then allocates the available bandwidth in a ratio to the acceptable bid prices received, known as a proportional fair divisible auction. Thus, clients who pay a higher price experience lower transmission time resulting in shorter delay and reduced battery usage.

Similarly, [Ercan_08] proposed an algorithm for conducting opportunistic spectrum leasing from primary users to secondary users based on a three player Stackelberg game between the spectrum primary owner (PO), the primary users (PUs) and the secondary users (SUs). In the algorithm, the PO adjusts the monthly subscription fees for PUs and SUs and the probability of interference while the PUs and SUs attempt to maximize their value. SUs are allowed to sense the channel and opportunistically utilize it when it is not being used by any PU, while keeping the interference to the PUs below a maximum

Via simulation, [Ercan_08] showed that by allowing opportunistic spectrum access with a non-zero tolerated interference probability to the primary users, the spectrum owner can enhance revenue. In exchange for the degraded QoS of the PUs due to the interference from SUs, the PO offers the PUs a lower subscription fee. The enhancement of the revenue comes from the subscription fee of the SUs and the fact that the spectrum is utilized better. Specifically in their simulated environment, they showed that opportunistic spectrum access increases primary user per-channel revenue by 14% even though primary user subscription fees were reduced by about $2 per user as shown in Table 8.

Table 8: Reported benefits of the spectrum market algorithm . From Table II in [Ercan_08]

Optimal	w/OSA	w/o OSA
p_{tol}	5.31%	–
m_p (monthly)	$29.84	$31.5
m_s (monthly)	$5.89	–
PO revenue (monthly, per channel)	$1,786.4	$1,575.4
SU utilization	47.6%	–
PU acceptance prob. (p_p)	1	1

2.4.3 Spectrum Markets References

[Ercan_08] A. Ercan, J. Lee, S. Pollin, and J. Rabaey, "A Revenue Enhancing Stackelberg Game for Owners in Opportunistic Spectrum Access," DySPAN 2008, Oct. 14-17, 2008.

[FCC_10] Federal Communications Commission, "Connecting America: The National Broadband Plan," Available online: http://www.broadband.gov/download-plan/

[Gandhi_07] S. Gandhi, C. Buragohain, L. Cao, H. Zheng, and S. Suri, "A General Framework for Wireless Spectrum Auctions," DySPAN07.

[Hultell_07] J. Hultell, J. Zander, J. Markendahl, Cognitive Wireless Networks, Chapter 6, pp 115 - 117 , Edited by Fitzek & Katz, Springer, 2007.

[Ji_07] Z. Ji and K. Liu, "Collusion-Resistant Dynamic Spectrum Allocation for Wireless Networks via Pricing," DySPAN07.

[Snegupta_07] S. Sengupta, M. Chatterjee, and S. Ganguly, "An economic framework for spectrum allocation and service pricing with competitive wireless service providers," DySPAN07.

2.5 Single Link Adaptations

2.5.1 Overview and Relationship to Cognitive Radio

One of the oldest intelligent adaptations employed by a wireless system is modifications of a single link, e.g., adjusting the power, modulation, FEC or mode. This is traditionally done to preserve the overall quality of the air waves. These adaptations are sometimes referred to as Adaptive Modulation and Control (AMC) or Transmit Power Control (TPC) and are frequently integrated into broader radio resource management schemes.

This section specifically considers the impact of CR techniques on Quality of Service (QoS) that can be applied to a single link. QoS techniques found in the surveyed documents and papers include:

- using an OFDM Variable QoS Source Channel Design
- using a set of intelligent algorithms called a cognitive engine (CE) to create a cognitive radio (CR) that provides a user with a required quality of service (QoS)
- a proposed unified cognitive cross-layer architecture next-generation IP-based mobile tactical network, where each node in the network can sense and learn from its situational and contextual information and respond to changes of environment by adapting system parameters and network services based on the learned results.

2.5.2 Reported Benefits

In the paper [Kleider_02], a channel adaptive technique combined with an intelligent quality-of-service (QoS) manager, to maximize reception quality while minimizing the required transmitted signal energy is suggested. Three transmission methods: $VQoS^M$, $VQoS^1$, and FQoS/QAM are investigated. $VQoS^M$ and $VQoS^1$ both use adaptive modulation, with the $VQoS^1$ system having a single QoS region (i.e., q = 1). By performing the proposed algorithm over many channels, the paper found the $VQoS^M$ optimization process to result in a performance improvement of at least 2 dB. The $VQoS^M$ method was found to perform better than $VQoS^1$ in all channels. The difference in Peak SNR between the two schemes increases as the channel degrades.

In the paper [Ci_07], a unified cognitive cross-layer architecture for a next-generation IP-based mobile tactical network is proposed. The core of the proposed architecture is a unified cross-layer controller that provides vertical system control and horizontal network control. The authors suggest their proposed architecture will support autonomy, self-configuration, self-organization scalability, adaptability and simplicity for the next-generation mobile, tactical network.

In the paper [Scaperoth_06], the authors present a general method to reconfigure a software defined radio (SDR) using a set of intelligent algorithms called a cognitive engine (CE) to create a cognitive radio (CR) that provides a user with a required quality of service (QoS). The proposed architecture relies on the CE to generate an XML document that describes the SDR behavior. An Application Programming Interface (API) translates the XML document to the platform-specific commands to adjust the SDR. The API structure will find initial applications in public safety and military communications to provide low-cost, multi-band, multi-mode operation for interoperability with SDR technology.

2.5.3 Single Link Adaptations References

[Ci_07] S. Ci, J. Sonnenberg, "A Cognitive Cross-Layer Architecture for Next-Generation Tactical Networks," Milcom 2007.

[Kleider_02] J. Kleider and G. Abousleman, "Joint Source-Channel Matching for Jamming and Fading using and OFDM Variable QoS source channel design,", SDR Conference 2002.

[Scaperoth_06] D. Scaperoth, et al, "Cognitive Radio Platform Development for Interoperability," Milcom 2006.

2.6 Commercial Viability of Cognitive Radio and New Business Models

Cognitive Radio (CR) will initially have a significant impact on military and public safety applications that require adaptable and flexible communications. In order for wide spread commercial deployment of these devices to occur, new business models need to be generated that allow a good business case for CR to be developed. The initial market rationale may be driven primarily by hardware sales for uses such as home and business networking, might be from service providers maximizing existing infrastructure utilization, or enabling access to new spectrum. In all likelihood, the financial justification in the future is for communications standards and applications that are yet to be identified.

In order to get a glimpse of the initial business applications, numerous articles were reviewed and summarized. These articles describe potential improvements to commercial services utilizing CR techniques and depict conditions under which service improvements result from a general analysis of trade spaces. The emphasis is on the technology of making better use of available spectrum by dynamic rather than static (licensed dedicated) spectrum allocations. The economic assumption is made that an overall improvement in service will result in increased revenue under conditions of spectrum scarcity. The technical aspects of many CR technologies are covered in more detail in subsequent sections, but the following are technologies that directly impact the business models used to provision wireless services: cooperative CR techniques, reducing OPEX with CR, and enabling DSA.

2.6.1 Improving Service of Existing Systems via Cooperative CR techniques

Three of the surveyed papers considered how performance could be improved by implementing cooperative CR techniques.

In [Albiero_07], the authors develop a network consisting of 50 nodes, where each node can transmit using cellular or using ad-hoc networking based on 802.11a/g. The network is named NetLogo, and is used to explore potential power savings. Clearly, the nodes can form a cluster, and can then communicate with other clusters through cellular radio, thus creating a network hierarchy. In the selfish mode nodes minimize their own power expense. Using a cognitive radio technique the authors call "wise cooperation", they attempt to minimize the power experienced by all cluster members, thus aiding some disadvantaged members at a slight power expense to other members. Under wise cooperation the nodes tend to form larger clusters, while in the greedy mode, they tend to form smaller clusters. As a result, there are fewer isolated nodes in the "wise cooperation" network protocol. A moderate complexity cost–benefit game theory equation is used for this optimization. As illustrated in Figure 29, this led to a 50% reduction in isolated nodes.

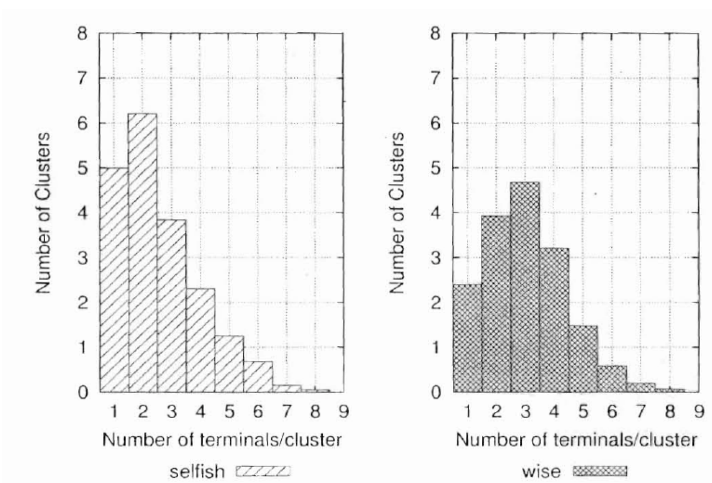

Figure 29: Cluster distribution vs. number of cooperating units for the two strategies. From [Albiero_07]

[Hultell_07] gives a report about research done by the authors at the Royal Institute of Technology where the authors arrange cooperation amongst WLAN 802.11 access points and show that users experience a 65% increase in throughput when access points cooperate due to diversity and load share balancing.

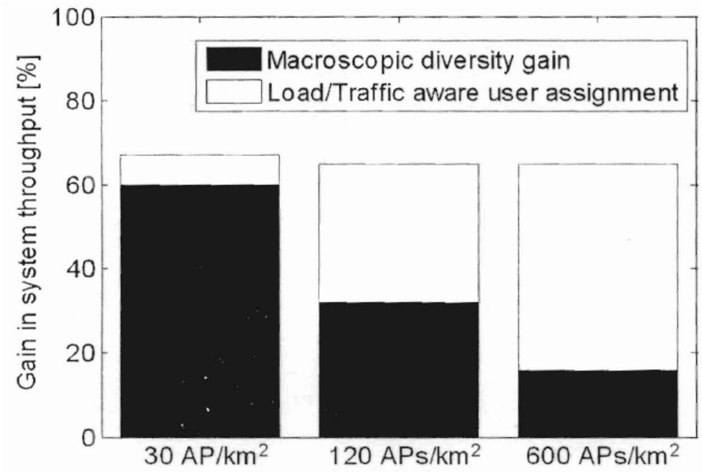

Figure 30: Gain in asymptotic system throughput for a geographically limited traffic Hotspot where two WLAN (IEEE 802.11a) networks cooperate. As the combined system is noise limited, additional gains can be realized by load aware user assignment. From [Hultell_07].

In a related vein, [Hultell_07] gives a report about research also done by the authors at Royal Institute of Technology. Though it does not include the full configuration specification or derivation of analytic equations explaining the result, by arranging cooperation amongst cellular radio data service providers, they show that 90% of users experience from 70% to 180% increase in throughput when three cellular service providers cooperate by dynamically assigning user data traffic among the networks. In practice, this will likely necessitate fast-switching SDR to allow the users to switch between different frequencies and different technologies while maintaining connectivity. This approach may also require a common carrier approach or more liberal roaming agreements than are used today.

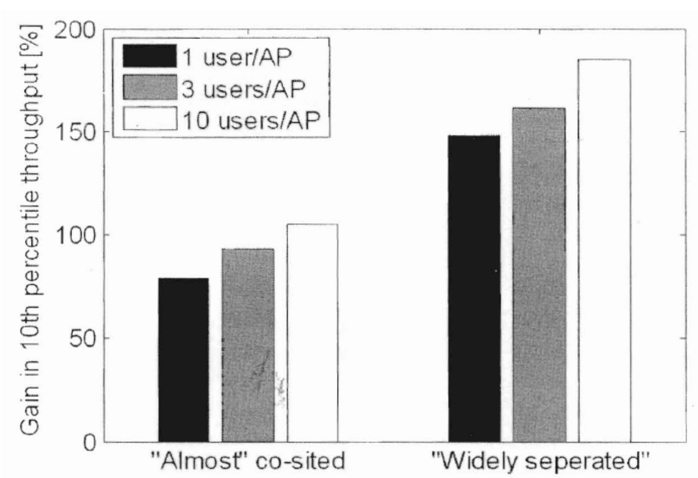

Figure 31: Gain in asymptotic user throughput for the 10th percentile (“coverage”) for uplink transmission in a case where three operators cooperate. From [Hutell_07]

Thus by using CR to enable cooperation between diverse networks, service provision can be greatly enhanced. However, realizing this capability will require changes in business models to better facilitate inter-operator cooperation.

2.6.2 Reducing OPEX Costs with Self Organizing Networks

CR provides the possibility to reduce the lifecycle cost of equipment by reducing the amount of manual configuration of equipment both at the time of deployment and during operation. In effect, this moves the smarts from the technician into the radio, thereby reducing the salary costs and thus operational expenses of a wireless network. As noted in [Brown_08],

> The belief among operators is that 3G represents a missed opportunity to automate network processes, and that much of the ongoing cost to configure and manage Node Bs, radio network controllers, and core network elements is accounted for by the need to allocate expensive technicians to mundane, yet cumbersome, tasks.

The 3GPP group and Next Generation Mobile Networks are working to create and standardize this capability as *Self Organizing Networks*. Thus in the near future, CR will change the way networks are deployed and maintained by replacing existing service performed by people with automated processes performed by radios. Self Organizing Networks are discussed further in Section 3.1.2.3.

2.6.3 Enabling Access to New Spectrum with Information Services

A significant feature of DSA (see Section 2.1) is that it will enable devices to operate in bands allocated to other applications when not in use by those applications. A Microsoft funded analysis published in 2009 [Letzing_09] estimated the market for CRs operating in the TV white spaces at over $100 billion for the United States.[12]

However for this market to come to fruition, the wireless ecosystem will have to expand into a new niche – spectrum access database providers – to provide the needed information on what bands are available at specific geographic locations so primary users are protected. The potential value of this new niche has been widely recognized as evidenced by the fact that in January, 2010, nine different groups submitted proposals to the FCC to be a database administrator for the white spaces.

Outside the United States, other communities are considering methods such as Cognitive Pilot Channels to broadcast similar information to secondary devices. Regardless of the implementation method, there is an emerging market niche of third-parties providing timely information to CRs for DSA and likely for other CR applications as they emerge.

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2.6.4 New Wireless Revenue Models

Today, most of the revenue income for wireless carriers comes from end-user service subscriptions, e.g., when a cell phone customer signs a service contract. While service contracts with end-users will no doubt continue, growth in machine-to-machine (M2M) communications is creating new revenue streams. E-Book readers, such as Amazon's Kindle serve as a good example of how this change affects business models. The E-book owner does not enter into a contractual agreement with the wireless provider. Instead, they buy books, or they subscribe to content while the cost of wireless access is hidden in the cost of the book or the content subscription. From a user's perspective, the fact that the device uses a cellular interface is unimportant, and may not even be obvious. The device is simply expected to work -- anytime, anywhere.

The implication of this new revenue model is that the content provider is highly motivated to minimize the cost of delivering the product to the consumer. Obviously, they could do this by negotiating better contracts with a single wireless service provider, but there could be a more innovative solution. If the device is capable of accessing multiple wireless networks, it could minimize cost to the content supplier by selecting the least expensive form of wireless connectivity available, whether it comes from: cellular service providers, WiFi service providers, open WiFi access points, or by linking through other devices with network connectivity. Similar automated WiFi-cellular roaming techniques are already in use for several service providers to reduce loading on cellular infrastructure and reduce airtime minute usage for customers.

Selecting the least expensive form of communication may also include real-time price negotiations. In 2008 Google submitted a patent application ([Baluja_08]) describing a communication device that would initiate a communications session after first requesting bids to carry the communication session from available telecommunication carriers.

In some cases, the cheapest solution may not be the best solution. For example, if a device is in a moving car, and the goal is to download Tolstoy's "War and Peace", it would be more intelligent of the device to select a wide-area cellular interface over WiFi hot-spot connection. In this case the device needs to understand the application, the characteristics of the communications service, the environmental conditions, and the cost of the service. Balancing these tradeoffs is a natural function for CR.

2.6.5 New Business Model References

[Albiero_07] Albiero, F., Fitzek, F., Katz, M., Cognitive Wireless Networks, Chapter 31, pp 605 - 612, Edited by Fitzek & Katz, Springer, 2007

[Baluja_08] S. Baluja, M. Chu, and M. Matsuno, ''Flexible Communication Systems and Methods,'' Sep. 25 2008, Google Patent application 20080232574. Available online: http://appft1.uspto.gov/netacgi/nph-Parser?Sect1=PTO2&Sect2=HITOFF&p=1&u=%2Fnetahtml%2FPTO%2Fsearch-

bool.html&r=1&f=G&l=50&co1=AND&d=PG01&s1=20080232574.PGNR.&OS=DN/20080232574&RS=DN/20080232574

[Brown_08] G. Brown, “Self-Organizing Networks & LTE,” *Light Reading*, July 8, 2008. Available online: http://www.lightreading.com/document.asp?doc_id=158441

[Hultell_07] J. Hultell, J. Zander, J. Markendahl, Cognitive Wireless Networks, Chapter 6, pp 115 - 117 , Edited by Fitzek & Katz, Springer, 2007.

[Letzing_09] J. Letzing, “Microsoft study says white spaces worth over $100 billion,” *MarketWatch*. September 23, 2009. Available online: http://www.marketwatch.com/story/microsoft-study-places-value-on-white-spaces-2009-09-23

3 Application Areas

The following describes the role cognitive radio can play in addressing the challenges of wireless communications systems for public safety, military, and commercial sectors.

3.1 Commercial Applications

Due to CR's conflation with opportunistic DSA and a desire to protect expensive spectrum licenses, the commercial cellular community was initially resistant to cognitive radio even though many of the techniques associated with CR were already being used in cellular systems. But more recently, CR has been touted as the enabling technology to Ubiquisys's femtocells, as part of self-organizing networks, enabling real-time spectrum markets and auctions, alleviating many of the pressing needs for spectrum access, and improving spectrum efficiency. CR also is a critical enabling technology to several wireless standards, including 802.16h, 802.22, 802.11af, CogNeA, and IEEE SCC41.

The following discusses challenges currently facing the commercial wireless community, CR technologies that can help address these challenges, and issues that remain or will need to be considered once these CR technologies are introduced.

3.1.1 Challenges in Current Systems

Commercial systems currently face several challenges that if addressed would be of significant benefit to commercial system users, network operators, and service providers. These include:

- Adding capacity to support an ever increasing demand for bandwidth
- Improving spectrum access to deploy commercial wireless systems
- Increasing revenues to boost return on investment
- Improving coexistence of multiple waveforms on a device, potentially operating at the same time
- Facilitating inter-operator cooperation and interoperability to better support roaming across networks and across technologies
- Managing standard compliance and mitigating development risk
- Reducing cost, size, and battery life to gain competitive advantages and better address user demands
- Simplifying management and deployment of increasingly complicated networks
- Managing regional policy variations to increase market sizes and support global roaming
- Minimizing risk to insertion of new technologies to protect large investments.

3.1.1.1 Capacity

Increasing capacity allows a communications system to provide greater information bandwidth, thereby allowing the system provider to support more users, improve existing applications (e.g., faster downloads, use of non-loss compression) and add new applications that were impractical with less capacity (e.g., real-time automobile traffic data and video to the phone). Even ignoring the introduction of new applications, increasing capacity has a positive feedback on bandwidth demand as faster content delivery decreases the opportunity cost (time, though not necessarily money!) for downloading content. For instance, [Wortham_09] noted that with the introduction of the 3G iPhone:

> Owners of the iPhone 3GS, the newest model, "have probably increased their usage by about 100 percent," said Chetan Sharma, an independent wireless analyst. "It's faster so they are using it more on a daily basis.

While growing pains from the unexpectedly sharp increase in bandwidth demand have been noted [Wortham_09], communications systems try to stay ahead of this growing demand by continually increasing capacity. One attempt to describe this phenomenon is Gilder's law [Gilder_01] which states that:

> Bandwidth grows at least three times faster than computer power. While computer power doubles every eighteen months (Moore's law), communications power doubles every six months.

While not quite as fast as claimed in 2001, the growth in 3GPP downlink data rates from Q1 2000 with the release of WCDMA (384 kbps) to the release of LTE in Q4 2008 with a data rate of 326 Mbps is equivalent to 9.7 doublings in 9 years[13]. This is faster than Moore's Law which predicts only 6 doublings (9/1.5). Intermediate systems in this progression are illustrated in Table 9 where successive improvements in technologies led to different protocols and increased capacity.

[13] 7.3 doublings if one uses the impractical 2.048 Mbps rate for WCDMA as the baseline .

	Downlink		Uplink	
	Peak Network Speed	Peak Achievable User Rate	Peak Network Speed	Peak Achievable User Rate
EDGE (type 2 MS)	473.6 kbps		473.6 kbps	
EDGE (type 1 MS)	236.8 kbps	200 kbps	236.8 kbps	200 kbps
Evolved EDGE (type 1 MS)[36]	1184 kbps[37]		473.6 kbps[38]	
Evolved EDGE (type 2 MS)[39]	1894.4[40] kbps		947.2 kbps[41]	
UMTS WCDMA Rel'99	2.048 Mbps		768 kbps	
UMTS WCDMA Rel'99 (Practical Terminal)	384 kbps	350 kbps	384 kbps	350 kbps
HSDPA Initial Devices (2006)	1.8 Mbps	> 1 Mbps	384 kbps	350 kbps
HSDPA Current Devices[42]	3.6 Mbps	> 2 Mbps[43]	384 kbps	350 kbps
HSDPA Emerging Devices	7.2 Mbps	> 3 Mbps	384 kbps	350 kbps
HSDPA	14.4 Mbps		384 kbps	
HSPA[44] Initial Implementation	7.2 Mbps	> 4 Mbps	1.46 Mbps	1 Mbps
HSPA Future Implementation	7.2 Mbps		5.76 Mbps	
HSPA	14.4 Mbps		5.76 Mbps	
HSPA+ (2X2 MIMO, DL 16 QAM, UL 16 QAM)	28 Mbps		11.5 Mbps	

	Downlink		Uplink	
	Peak Network Speed	Peak Achievable User Rate	Peak Network Speed	Peak Achievable User Rate
HSPA+ (2X2 MIMO, DL 64 QAM, UL 16 QAM)	42 Mbps		11.5 Mbps	
LTE (2X2 MIMO)	173 Mbps		58 Mbps	
LTE (4X4 MIMO)	326 Mbps		86 Mbps	
CDMA2000 1XRTT	153 kbps	130 kbps	153 kbps	130 kbps
CDMA2000 1XRTT	307 kbps		307 kbps	
CDMA2000 EV-DO Rev 0	2.4 Mbps	> 1 Mbps	153 kbps	150 kbps
CDMA2000 EV-DO Rev A	3.1 Mbps	> 1.5 Mbps	1.8 Mbps	> 1 Mbps
CDMA2000 EV-DO Rev B (3 radio channels MHz)	9.3 Mbps		5.4 Mbps	
CDMA2000 EV-DO Rev B Theoretical (15 radio channels)	73.5 Mbps		27 Mbps	
Ultra Mobile Broadband (2X2 MIMO)	140 Mbps		34 Mbps	
Ultra Mobile Broadband (4X4 MIMO)	280 Mbps		68 Mbps	
802.16e WiMAX expected Wave 1 (10 MHz TDD DL/UL=3, 1X2 SIMO)	23 Mbps		4 Mbps	
802.16e WiMAX expected Wave 2 (10 MHz TDD, DL/UL=3, 2x2 MIMO)	46 Mbps		4 Mbps	
802.16m	TBD		TBD	

Table 9: Data rates for various cellular standards. The growth in data rate requirements is reflected in the shift from 473 kbps for EDGE to 326 Mbps for LTE (with 4x4 MIMO) From http://www.rysavy.com/Articles/2007_09_Rysavy_3GAmericas.pdf

4G (IMT-Advanced) anticipates further improvements with a range of data rate / mobility requirements as illustrated in Figure 32. The 4G requirements provides targets of 1 Gbps for [Neel_09] fixed devices with the latter listed as "research target" indicative that new technology will need to be developed to realize this goal.

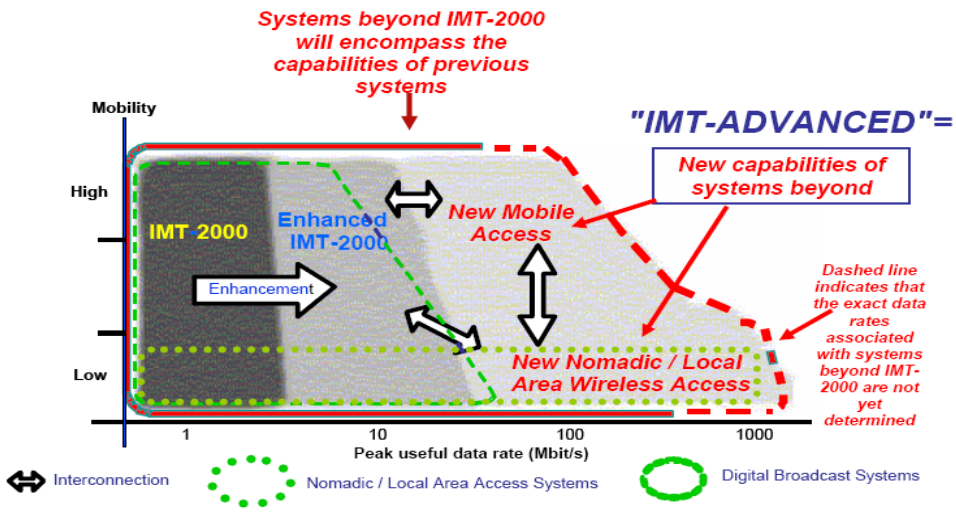


Figure 32: Representation of data rate and mobility requirements for 4G (IMT-Advanced) systems. From 3G Americas, "Defining 4G: Understanding the ITU Process for the Next Generation of Wireless Technology," July 2007 Available online: http://3gamericas.com/PDFs/3G_Americas_Defining_4G_WP_July2007.pdf

With new spectrum generally difficult to come by, achieving these ever-increasing data rates will have to be accomplished by increasing spectral efficiencies. For instance, LTE Advanced (a 4G candidate) has specified spectral efficiency targets of 30 bps/Hz on the downlink and 15 bps/Hz on the uplink and 802.16m (another 4G candidate) has similar specifications. Beyond cellular systems, similar requirements are coming out in WLAN and WPAN systems with the 802.11ac PAR specifying rates of up to 1 Gbps in 40 MHz of bandwidth at frequencies less than 6 GHz and the 802.11ad PAR giving similar requirements but in the 60 GHz range. [Neel_09] The growth in supported data rates provided is illustrated in Table 10 where anticipated 60 GHz systems will provide 25 Gbps of bandwidth.

	Channel Bandwidth	Effective Transmit Power	Max possible data rate
UWB	520 MHz	0.4 mW	80 Mbps
802.11n	40 MHz	160 mW	1,100 Mbps
60 GHz	2,500 MHz	8,000 mW	25,000 Mbps

Table 10: Various bandwidths and data rates for different WLAN / WPAN technologies. From http://www.gigabeam.com/technology.cfm

Continuing to add capacity at a rate that exceeds Moore's Law will be goal for commercial systems for the foreseeable future. While a handful of short-range systems will be able to rely on the larger bandwidths available at higher frequencies (e.g., 802.11ad), most commercial systems will need further improvements in spectral efficiencies from new communications technologies to achieve this goal.

3.1.1.2 Spectrum Access

As discussed in the preceding, wireless service providers are constantly striving to support more users and higher and more reliable data rates. But before they can provide their services, they must first obtain access to the spectrum. According to [Buddhikot_07], spectrum access models can be classified as follows:

1) Command and Control: The regulatory body explicitly lays down spectrum access rules and assigns them to an entity for use. Ownership of the spectrum usually does not use any market mechanisms. Examples of such spectrum use are government, military, and public safety allocations.
2) Exclusive-use: Exclusive spectrum access license under certain rules is given to an entity. This is usually done using some kind of market mechanism, e.g., auctions, biddings etc. This group can be further classified in to *long-term exclusive-use* and *dynamic exclusive-use*.
3) Shared-use of Primary Licensed Spectrum: In this model, spectrum owned by a licensee is shared with a secondary, possibly non-licensed user. Two possible secondary access approaches are spectrum *underlay* and *spectrum overlay*.
4) Commons: An operating model in which no one has an exclusive access of the spectrum and spectrum can be equally accessed by all entities.

The most prevalent spectrum access model for commercial use is the exclusive-use model. Exclusive-use licenses for a certain segment of the spectrum usually delineate the specific usage as well as technology that can be employed in that segment. This can lead to an inability to exploit technological advances as well as benefits provided by comparable technologies, leading to inefficiencies in spectrum usage. For example, until recently a big chunk of spectrum was reserved for analog TV broadcasts employing NTSC transmission. Digital packet-based broadcast technologies (e.g. IPTV) that can pack many more TV channels in the same bandwidth were disallowed in the analog TV spectrum.

This policy also makes the usage of the spectrum contingent on the success and industrial backing of the chosen standards. For example, broadband spectrum at 2.5 GHz is allocated in the US to WiMAX which is now being backed only by a small part of the wireless sector.

Also exclusive–use spectrum reserve swathes of spectrum over large regions of space and time. However, spectrum requirements could vary drastically over space and time. For example, rural areas are often sparsely populated. Another example is public safety, where spectrum usage is minimal in the absence of emergencies. These cannot be exploited using the exclusive-usage model of spectrum access.

Another important issue is that for initial allocations to traditional broadcast services (TV, AM, FM), exclusive-use of spectrum has traditionally been granted to the highest bidder willing to provide a specified class of services. Due to the many competing services, demand for spectrum has become quite high and when new spectrum is allocated for commercial use, service providers pay very high prices for the right to exclusively access that spectrum. For instance, the US recently raised $19.12 billion from a spectrum auction in the 700 MHz band [Hansell_08]. Likewise, the WiMAX Forum made a lengthy lobbying effort with the ITU to have WiMAX classified as a "3G" so its vendors could have access to worldwide spectrum allocated for 3G networks.

The "Shared-use of Primary Licensed Spectrum" model enabled by the DSA has the potential to alleviate many of the issues discussed above. However, regulations for this kind of access still need to be carefully defined such as to make the schemes efficient, of minimal impact to the primary user and yet remain commercially viable. An example in this regard is the recent auction of the 700MHz rebanded TV spectrum for public safety and commercial markets. The initiative allows private commercial entities to build a nationwide broadband network that could be preemptively utilized by public safety. The initiative met with limited success due to revenue and other financial concerns.

The "Commons" spectrum access model could also help in solving some of the spectrum utilization issues. It has been limitedly employed currently and has met with considerable success in the commercial arena. For example, the unlicensed usage of spectrum in the 2.4GHz band has fuelled many innovative technologies and has also played a part in the success of WLAN, as opposed to the licensed usage of a comparable WiMAX technology. However, there also are several challenges associated with this type of spectrum access or policy, e.g., unrestricted spectrum access to wide variety of applications has led to an equally wide variety of interference sources and profiles that users have to contend with in the 2.4 GHz band.

3.1.1.3 Revenues

The impact on revenue of cognitive radio approaches depends on whether the facilities are deployed as controlled or opportunistic. The controlled approach, typified by commercial cellular service providers, permits tightly controlled use of spectrum. Channel access is tightly controlled, and can be optimized statically or dynamically. Opportunistic spectrum access, often referred to as “white space” of “dynamic spectrum access”, is less concerned with optimization than taking advantage of spectrum that would otherwise go unused.

In commercial cellular, users are the dominant source of cash flow. Average revenue per user (ARPU) is carefully watched, and often used as an objective function for business model optimization. Commercial system architectures provide tools to optimize billable spectrum utilization, helping to recover funds spent to acquire spectrum licenses and system build-out. Those tools permit realignment of cell loading, cell size and channel allocation to maximize utilization and minimize call drop or rejection during busy hours.

Commercial systems contain functionality that represents implementation of cognitive radio techniques, so they are already using optimization techniques. Because detailed data on system utilization is immediately available, optimization can be performed at short time intervals over large areas. That data can also be studied to facilitate installation of new infrastructure.

Commercial revenue optimization is also accomplished by the structure of business models and pricing plans. Rather than charge on a per-use basis, most cellular price plans involve payment for large blocks of minutes to be used over a month’s time. Cognitive techniques are not directly involved in this approach, but it cleverly avoids revenue loss during periods of high channel utilization. A user call that is rejected does not have a direct opportunity cost - it simply means that the user’s allocated minutes are not reduced at that time. It is incumbent on the user to use them at another time.

In the future, new product offerings will support sophisticated new terminals and provide data access for a number of effective applications. In summary, functionality as implemented in commercial systems embodies the concepts of cognitive radio, and is the basis of a market worth billions of dollars a month.

The model for revenue generation and markets for unlicensed spectrum are less clear. They avoid the enormous cost of participating in auctions for licensed spectrum, but must incur the overhead cost and uncertainty of probabilistic availability of spectrum. The bad news is that they will probably be effective under conditions of low average spectrum utilization. The good news is that they open availability to vast amounts of spectrum. Unknown at this point are what provisions will be needed to keep conflict, interference, and the overhead of resolving competing spectrum demands to reasonable levels.

The demand for communication of data will experience exponential growth in the near future. Many types of terminals will be employed in a variety of applications using air interfaces such as WiFi, WiMax, and LTE. As individual users come to increasingly rely on such applications in their daily work, cost of access will become an accepted business expense. Revenue derived from such use could come from fees charged the user, perhaps in the form of “micro-charges” (fractions of a cent) per unit of data. Alternately, businesses such as restaurants and coffee shops can offer no-fee hot-spots, carried as a promotional cost in their business model. Again, the concepts of cognitive radio are inherent in these protocols, reduced from conceptual proposals to operational functionality.

In summary, the precepts of cognitive radio have seen wide-spread application in implementation of current commercial communication systems, and will guide future innovation in such systems. A variety of models for revenue generation will be tried, and users perception of the value of service received as a function of price paid will determine which approaches succeed and which fail.

3.1.1.4 Platform and convergence issues

Wireless products are increasingly likely to have multiple air interfaces, several of which may be required to operate simultaneously. A device may have a multi-mode, multi-band radio for accessing cellular networks (including WiMax), a WiFi interface and a Bluetooth interface. It may also have broadcast receivers for FM radio and television. Future interfaces may also include 60 GHz interfaces such as those being developed by the WiGig Alliance.

There are multiple challenges in supporting multiple air interfaces in a single device. These include:

- Selecting the best wireless interfaces to support a given application, where the best interface may be the one that offers the best performance, lowest battery drain, or is least expensive to use.
- Handoff between heterogeneous networks (e.g. cellular to WiFi)
- Interference management within the device to prevent unwanted spurious emissions (e.g. IMD), or self interference (blocking another interface).
- Optimizing adjustable components such as tunable antennas, amplifiers, matching networks, and local oscillators.
- Supporting multiple antennas for MIMO and multi-band operation in a limited volume
- Limited volume of devices such as handsets and dongles limiting the amount of RF isolation that can be achieved within a device using a hardware-only approach.
- Resource allocation
  - Power distribution between interfaces.
  - Baseband processing resource allocation (memory, CPU, busses)
  - Multiple applications (multi-process)
  - Timing constrains (e.g. slot timing)
  - Meeting application QoS requirements (throughput and latency)
- Physical layer implementations which vary in bandwidth, packet duration, packet timing, and power control.
- Multiple wireless interfaces to scan and monitor for activity
- Keeping the product affordable

3.1.1.5 Inter-operator

The more air interfaces a device has, the longer it will take to perform conformance and interoperability testing. Type acceptance and certification will also become more complex and costly, especially if device operation is non-deterministic.

A conformance test verifies that a device meets a given standard, whereas an interoperability test verifies that a device will operate with another similar device or on a specific network. Test effort increases linearly with the number of wireless interfaces available, and geometrically with the interaction between interfaces. A simple example would be a cell phone with a Bluetooth interface for communicating with a hands-free headset. Both the cellular and Bluetooth interfaces must be tested for conformance and/or interoperability as defined by their respective standards. They must also be tested together to ensure that the performance of each interface doesn't degrade with the simultaneous use of both interfaces.

Test effort increases with flexibility in a given interface. Wireless interfaces that incorporate learning, or adaptive algorithms have a much larger test space than static implementations. As wireless network operators derive their revenue from services provided over licensed spectrum, they obviously want to protect that spectrum and are unlikely to allow devices on their network which have not been adequately tested. It may also be harder to achieve type acceptance for a device if it's more difficult to prove test coverage.

Deploying wireless infrastructure is both expensive and time consuming. As a result, new wireless standards rarely replace older standards, or even older versions of the same standard. Today, as 4G wireless systems are being developed, various 3G technologies are becoming widely deployed. Even so, they have yet to replace GSM (2G), which remains the most widely deployed cellular technology. For complete flexibility in connection, a wireless device would need to support all major releases of all wireless standards in all bands used in all countries. Software-defined and adaptive radio technology can help solve the connectivity challenges, but these technologies don't fully address the increasingly complex wireless ecosystem and corresponding interoperability and certification testing requirements.

3.1.1.6 Cost, size and power

Balancing the size, weight and performance of wireless devices is a key challenge facing platform architects. As noted by [German_09], "*Along with call quality, a cell phone's battery life is one of the most important considerations when choosing a handset*." But unlike for transistors where gains have come at an exponential pace, improvements in battery performance have been slower and more linear as illustrated in Figure 33 where battery life can be approximated as the volume of the battery times the charge density divided by the current draw. Thus in addition to improved battery technology, increased battery life can come from larger batteries and decreased current draw.

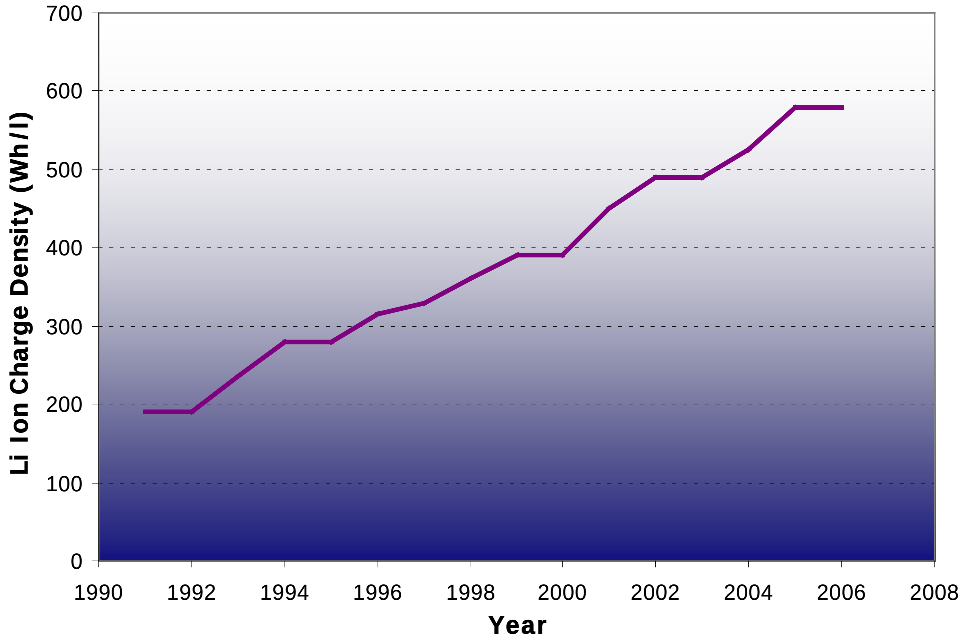


Figure 33: Improvement Trend for Li Ion Battery Technology[14]

However, larger batteries are problematic as the public tends to prefer smaller communications devices, with the practical limit generally determined by the user interface (display, I/O such as a keypad, etc.) as no product can be smaller than the size of the display. Thus gains for battery life need to come from reduced current consumption where exponential improvement in IC gate density derived from Moore's Law and other more physics based, linear, improvements in RF (radio frequency) components have led to numerous strides being made in power conversion and efficiency improvement. The three top current consumers in a wireless product are the RF PA (power amplifier), or transmitter, the digital processor(s), and the display. Reducing power consumption is also a key challenge for base stations as the cost of power can impact an operator's bottom line. For example, [Walko_07] notes that:

> On average, each fully loaded 3G cell site using traditional PAs is estimated to need 3 kW of power, equating to a cost of some $1,600 a year for a US-based operator, or €2,300 (about $3,200) for an operator in Europe buying electricity at about double the cost of their U.S counterpart. Thus, suggests Nujira, for a typical European operator with a network of 20,000 basestations, the total energy consumption on the same basis would be 58MW (equivalent to a large wind farm) resulting in annual electricity costs of €45 million (about $62 million).

Complicating the movement to smaller devices and lower power consumption is the proliferation of standards and increasing number of frequency bands that devices need to support, with some of the standards illustrated in Figure 34. This increase in standards and bands generally requires

[14] Panasonic, 2006.

additional hardware and software for implementation into a given product. In most cases this implementation needs to not only meet the current wireless standard, but also be backward compatible with previous generations of that standard. The fact that these are distinct hardware implementations necessarily requires more space, consequently more weight, and ultimately more power consumption due to static power dissipation considerations.

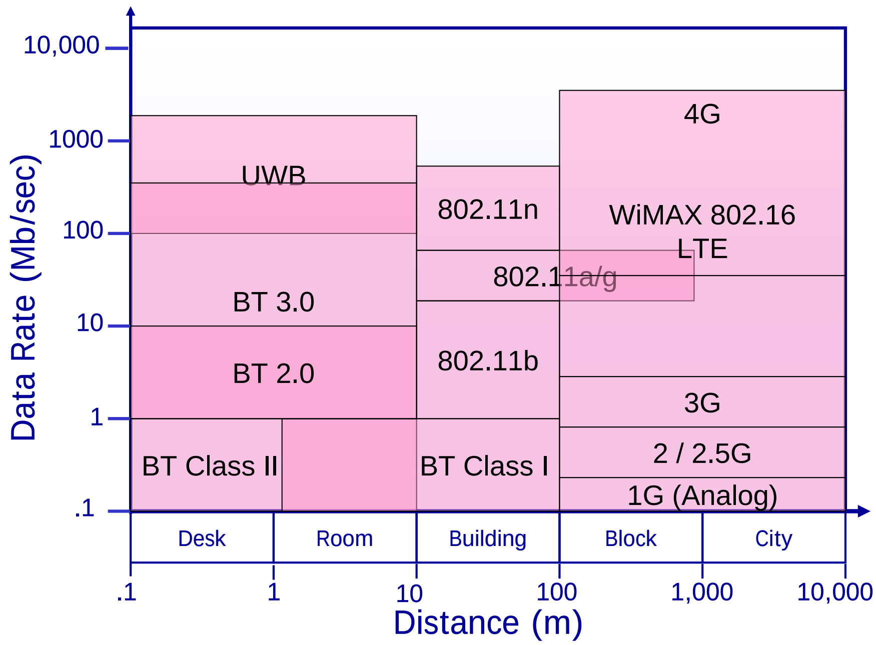


Figure 34: Commercial Wireless Standards. BT = Bluetooth, LTE = Long Term Evolution, UWB = Ultra Wide Band.

While the brute force approach to meet the wireless communication needs for a product has been to have separate transmitters and receivers, SDR technologies can sometimes reduce current consumption, size and weight by reducing the number of RF chains via the use of flexible RF enabled by MEMS and other techniques. Other gains are possible from algorithmic and architectural advances, such as remote radio heads with multiple PAs. But even with these advancements, decreasing size, weight, and power consumption will continue to be critical challenges for commercial devices.

3.1.2 Beneficial or Enabling Technologies

The following CR technologies could help address many of the issues identified in the preceding section:

- Geolocation databases
- Cognitive Pilot Channels
- Self-Organizing Networks
- Dynamic Spectrum Access techniques
- Spectrum Markets

- Green Radio
- Reduced user burden on the network

These technologies and their implications for the identified challenges are discussed in more detail in the following. More detail specifically on these technologies is provided in Section 2.

3.1.2.1 Geolocation (WhiteSpace) Databases (Radio Environment Maps)

Geolocation databases are required by the FCC for to enable TV white space devices. The FCC received nine different proposals to serve as a database administrator that will provide information on a daily basis as to the allowable channels of operation for queried locations. To maximize the viability of markets based on these databases, it will be important to define standard interfaces for accessing the information in the database and processes for synchronizing the information provided by the multiple database offerors. Such an effort is underway in the White Spaces Database Group.

Cognitive radio stakeholders, wishing to further increase their return on investment, may envision the utilization of database applications that go beyond geolocation databases and support or enable the flexibility required to accommodate current and future cognitive applications such as mobility, spectrum economic transactions, dropout, handovers, available networks, services, etc.

Proposed database applications, e.g., Radio Environment Mapping (REM), are envisioned to extend the existing FCC specification by providing guidance for enabling and testing enhanced future cognitive radio databases that can support timely updates of location, id, and operating conditions (e.g., interference levels, waveform, associated network, etc.) by:

- capturing and synthesizing measurements from many radios including DSA radios and mobile radios to allow for more dynamic protection of incumbents (e.g., DTV signals and protected classes of wireless microphones)
- accommodating more advanced spectrum allocation mechanisms such as real time spectrum auctions and real-time coexistence protocols
- utilizing coexistence techniques, e.g., spectrum brokering between secondary systems, simplified policy management, and reduced device costs.

A current REM project within the Wireless Innovation Forum is underway to develop and release a set of use cases that describe key applications that can be supported with more frequent and more expressive interactions between shared spectrum cognitive radios and a shared database in dynamic and mobile conditions.

The results of this project - a document that issues guidelines for data schema, elements and functions that enable the selected use cases - will be submitted to relevant bodies and regulatory agencies such as the FCC, DSO, 802 working groups and relevant standardization groups in other ITU regions, e.g., ETSI and OFCOM.

3.1.2.2 Cognitive Pilot Channel[15]

The Cognitive Radio Working Group in a contribution to the ITU in response to a question on the role of cognitive radio in land mobile radio services [SDRF_ITU_08] discussed some of the benefits of this technology. The following italicized text is an extracted and edited version of a small portion of that submission. The reader is referred to the Wireless Innovation Forum website to view the full and original version of the ITU submission. Quoting from [SDRF_ITU_08]:

> A pilot channel is used to broadcast information to support the operation of cognitive radios. The term cognitive pilot channel (CPC) frequently refers specifically to the proposal being developed under the E^2R and E^3 projects in Europe, but has since more generally referred to any channel (whether logical or physical) that is used to regularly provide overhead and control information to subscriber radios.

Thus a pilot channel may provide registration, location, policy, spectrum assignment and other overhead information not normally required by registered telecommunication devices. An example might be updates to required databases. Continuing from [SDRF_ITU_08]:

> The CPC is generally focused on bootstrapping cognitive radios to have the information required to be aware of local spectrum, policy and networks characteristics. The information broadcast on a cognitive pilot channel can be either continuous broadcast, periodic broadcast, hierarchical broadcast, or on demand to include the broadcasting of policy information (e.g., public safety systems will constrain when a radio can transmit via messages broadcast over control channels), specified transmission characteristics for devices (as is done in 802.16), aid in the bootstrapping of network association (e.g., Flash symbols in Flash-OFDM), or information about relevant operational information.
>
> While the specific CPC proposed by these projects has only been published as paper studies at this point, other CPCs have been successfully fielded for overhead and maintenance in the past, and can readily be adapted to cognitive radio applications.

> Cognitive Networks enable the introduction of the cognition radio concepts and technologies in a multi-RAT environment, such as the CPC (Cognition supporting Pilot Channel). The availability of reconfigurable base stations in the networks in conjunction with cognitive network management functionalities could give the network operators the

[15] Annex 2 and Annex 3 of [SDRF_ITU_08] discusses the use of a CPC and includes suggestions for consideration in developing requirements for Cognitive Radio Networks (CRN) that employ a CPC.

> means for a globally efficient way of managing the radio and hardware resource pool, with the aim to adapt the network itself to the dynamic variations of the traffic offered to the deployed RATs and to the different portions of the area.

As can be seen by the preceding, the CPC is basically viewed as an economically viable enabler of cognitive radio networking and the benefits derived from such networks. The SDR Forum ITU submission also addresses some of the potential vulnerabilities and security related issues which should be considered in the development and deployment of this technology.

3.1.2.3 Self-Organizing Networks

CR provides the possibility to reduce the lifecycle cost of equipment by reducing the amount of manual configuration of equipment both at the time of deployment and during operation. In effect, this moves the smarts from the technician into the radio, thereby reducing the salary costs and thus operational expenses of a wireless network. As noted in [Brown_08],

> The belief among operators is that 3G represents a missed opportunity to automate network processes, and that much of the ongoing cost to configure and manage Node Bs, radio network controllers, and core network elements is accounted for by the need to allocate expensive technicians to mundane, yet cumbersome, tasks.

Telecom service providers have long desired infrastructure that is self-configuring, self-operating, and self-optimizing. Wireless telecom providers want base station (BTS) infrastructure that deploys quickly with no specialized technician expertise, automatically discovers its neighbors, automatically reconfigures around network failures, and automatically optimizes its radio parameters. In addition to this, backhaul and interconnect should be automatically configured, and Quality of Service (QoS) should be self-established and autonomously optimized. Even physical characteristics, such as antenna direction, can be adjusted to eliminate coverage holes.

The 3GPP group and Next Generation Mobile Networks (NGMN) are working to create and standardize these capabilities as *Self Organizing Networks*. A Self Organizing Network (SON) is a network that can automatically extend, change, configure and optimize the network coverage, capacity, cell size, topology, and frequency allocation and bandwidth, based on changes in interference, signal strength, location, traffic pattern, and other environmental criteria. NGMN have defined numerous use cases for SON (see [NGMN_07]) as summarized in Figure 35.

Planning
Planning of eNodeB
Planning of eNodeB Radio parameters
Planning of eNodeB Transport parameters
Planning of eNodeB data alignment

Optimization
Support of centralized optimization entity
Neighbor list optimization
Interference control
Handover parameter optimization
QoS parameter optimization
Load Balancing
Home eNodeB optimization
RACH load optimization

Deployment
Hardware installation
eNodeB/network authentication
O&M Secure tunnel setup
Automatic inventory
Automatic Software download to eNB
Transmission setup
Radio parameter setup
Self Test

Maintenance
Hardware/capacity extension
Automated NEM upgrade
Cell/Service outage detection and compensation
Real-Time Performance management
Information correlation for fault management
Subscriber and equipment trace
Outage compensation for higher level network elements
Fast recovery of unstable NEM system
Mitigation of outage of units

Figure 35: Optimization use cases for SONs. From Table 1 in [3G Americas_09]

The first release of SON (Release 8) supported: automatic inventory, automatic software download, Automatic Neighbor Relation, Automatic Physical Cell ID (PCI) assignment and the next release of SON (in 3GPP Release 9) will address: Coverage & Capacity Optimization, Mobility optimization, RACH optimization, and Load Balancing Optimization.

According to [Motorola_09a], the main purpose of SON is to minimize the operation costs (OPEX) of running a network by using cognitive functionality to eliminate or reduce manual configuration of network operational parameters at the time of network planning, network deployment, network operations, and network optimization. Within the SON solution, network elements are self-aware, self-configuring, auto-optimizing, and self-diagnosing. [Motorola_09b] proposes that 4G Long Term Evolution (LTE) networks have a greater degree of self-management and intelligence for operators to deploy their networks with little or no increase in operation and maintenance staff. Similar developments are reported in [Motorola_09b], [NEC_09], and [Nokia Siemens_09]

Cognitive Network elements can further extend the functionality of the SON solution using intelligent decision making based on:

- Awareness of user, device, context and spectrum information,
- Policy and dynamic geo-location database derivation and
- Learning

The cognition can provide self-healing for not only single-RAT (Radio Access Technology) networks but also for heterogeneous networks leading to:

- Improved utilization of spectrum and radio resources
  - Dynamic Spectrum Management
- Support of heterogeneous standards
  - More efficient Joint Radio Resource Management
  - Reconfigurable Base Stations and Reconfigurable Terminals
- Self-Management and Self-Optimization of
  - Radio Network Infrastructure
  - Cognitive Devices
- Cognition Support Mechanisms
  - Cognitive Pilot Channel, Spectrum Sensing
- Recommendations for service providers, network providers & equipment manufacturers to further enhance the self organizing networks.

3.1.3 DSA Benefits in Commercial Markets

Dynamic Spectrum Access (DSA) is a technology with the potential to reshape spectrum usage in the years to come. The regulatory framework has been established through work from the FCC, OFCOM, and others. On the technology side, it enables opportunities for spectrum sharing that results in better utilization of scarce frequency spectrum with some standards already complete (i.e., IEEE 802.11y) and others under development (IEEE 802.11af, 802.16h, 802.22, etc.).

The business side of this technology is still in its infancy but is gaining traction with the formation of companies like Spectrum Bridge and the opening of the TVWS. DSA brings a new perspective to spectrum and stimulates thoughts of how trading in the spectrum market can be viewed like other natural resources, only one that can be reused. This will inevitably result in cheaper spectrum access. Cheaper spectrum access will make for lower cost of entry resulting in enhanced competition for data communication services. It will also result in further innovation in wireless communications.

A result of lower entry costs is an acceleration of the pace of product introductions and reduced business model lifecycle. Decreased lifecycles makes it more challenging to recover the fixed costs associated with introducing new technologies, services, or business models. It also increases the likelihood that successive generations of technologies will overlap [Chapin_2007] and will allow new services to replace legacy services more gracefully. A new entrant can begin with inexpensive, limited spectrum access rights, and then scale usage rights to match capacity requirements as business grows.

A study commissioned by Microsoft Corp. [Letzing_09] estimates that the unlicensed "white spaces" spectrum could be worth more than $100 billion over the next 15 years. It suggests that by augmenting current unlicensed wireless networks, such as Wi-Fi hot spots, the white spaces could generate between $3.9 billion and $7.3 billion in value annually over 15 years due to the increased use of data hungry consumer electronics and other factors.

It is also mentioned in the report that the use of white space could boost Internet use and improve wireless communications, though these benefits have been difficult to quantify. It also points out the fact that white space spectrum offers a longer transmission range than a typical Wi-Fi connection. A single Wi-Fi access point enhanced by using white space could "fully cover a large building and the neighboring grounds and areas". The use of the white space could also lower the cost of providing Internet access in rural areas.

Wireless operators are slowly embracing femtocells as part of the solution to current bandwidth limitations. Adding DSA capability to these femtocells has been recently proposed [Ubiquisys_2009] as a solution to the interference caused by femtocells to nearby cell sites and neighboring femtocells. Femtocells can use DSA techniques to scan the surrounding radio environment and make necessary frequency and output power adjustments to optimize the link. A very interesting recent proposal to combine DSA capable femtocells with TV white space and wireless operator spectrum sharing [Buddhikot_09] shows the emerging potential of DSA as people begin to apply the concepts to specific problems.

3.1.3.1 Spectrum markets

There is a movement underway to significantly relax the rules of spectrum trading so that spectrum can be reallocated to where it is in greatest demand. To facilitate these trades some system, institution, and / or set of procedures that allow entities to buy, sell and trade spectrum have to be established. The system / institution, and /or set of procedures used to facilitate these trades are collectively called *spectrum markets*. This is not a new phenomenon as evidenced by Spectrum Bridge and Cantor-Fitzgerald's services and as recognized in the National Broadband Plan released in March 2010, where the FCC noted that secondary spectrum markets have been allowed for several years with some success [FCC_10].

> Preliminary analyses establish that there have been thousands of secondary-market transactions involving mobile broadband licenses over the last several years. These have The FCC did this included license transfers, including partitioning and disaggregation, and spectrum leases,[59] thus providing some evidence that the FCC's policies have enabled "spectrum to flow more freely among users and uses," as envisioned in the Commission's Secondary Markets Policy Statement.

Noting these successes regulators are working towards eliminating regulatory barriers that might hinder making more efficient use of spectrum via spectrum markets. For example, Ofcom has announced its intention to significantly simplify the spectrum trading process so that license owners can lease their spectrum to other users without requiring Ofcom's approval for each lease, thereby reducing transaction costs [Ofcom_10].

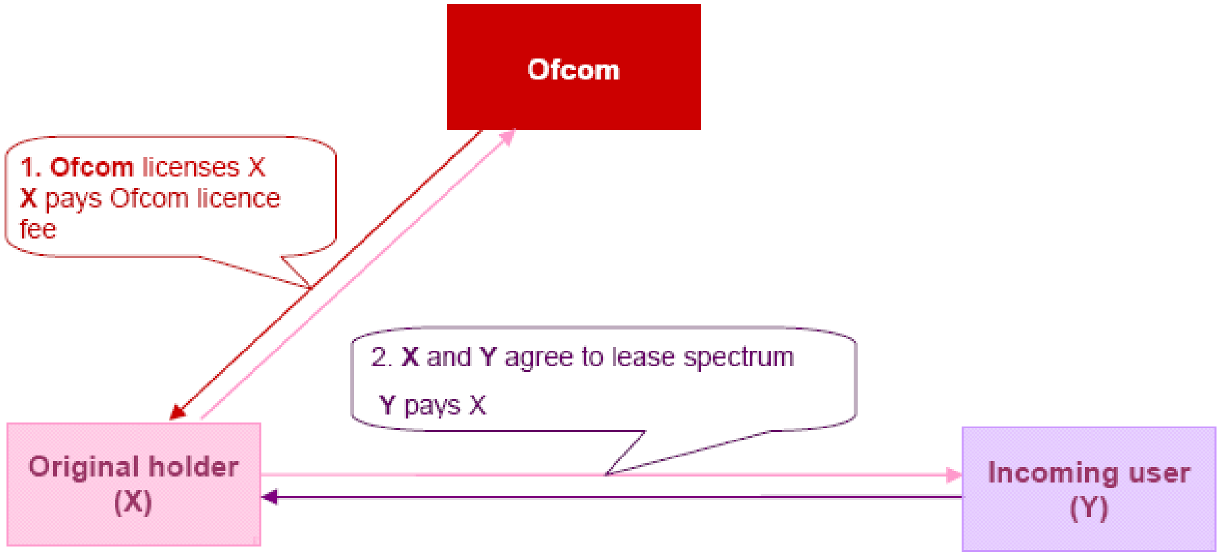


Figure 36: Ofcom's proposed spectrum leasing process whereby spectrum exchanges can be made directly without involving Ofcom in each transaction. From Figure 1b in [Ofcom_10].

However, demand for spectrum by one user/ service tends to vary with time so that the relatively long-term allocations achievable by human trading can lead to underutilization – though this underutilization varies greatly from band to band and service to service. Likewise as the number of potential buyers and sellers increase, automation will again be needed to allow for timely matching of buyers and sellers out of the sea of potential bidders / sellers. While opportunistic leasing of spectrum by the minute or by the hour will be too tedious for humans, it should lend itself well to automation. To realize this process, an automated buyer or seller agent (presumably responsible for ensuring spectrum availability for some device, network or system) will need to be aware of the operating environment, current and future needs for its system and its capabilities and resources. It will also need to be able to reason over the impact of its decisions, identify and evaluate potential trades, and be empowered to execute its decisions. All of these requirements are consistent with the cognitive radio paradigm, thus implying that these automated spectrum traders will need to be *cognitive radios*.

Cognitive radio spectrum trading would allow for spectrum allocations to be shifted with changing demands and allows primary users to extract value out of their spectrum even when the primary user is unable make full use of the spectrum. Reported benefits and approaches to realizing cognitive radio enabled spectrum markets are discussed further in Section 2.4.

3.1.3.2 Green Radio

CR's ability to adapt and reconfigure permits the utilization of these and other commercial and proprietary standards while minimizing the hardware required.

One of the key advantages to a cognitive radio is the inherent ability to sense the surroundings in an RF sense and then adapt, in both a digital and RF sense, to that set of circumstances. Depending upon the use requirements (voice or data, low or high priority, low or high security) the radio can select the most appropriate means of information transfer. While the processor and associated memory required for a CR will likely consume more current than an application specific device, the ability to adapt the RF interface will permit more power efficient transmission of information (reduced watts / bit) under many circumstances.

In addition, CR will receive the same benefit from the advances in associated wireless technologies as other radio technologies. First and foremost is the exponential improvement in IC gate density derived from Moore's Law. Other more physics based, linear, improvements include MEM's for RF agility, and the numerous strides being made in power conversion and efficiency improvement such as energy harvesting, fuel cells, not to mention batteries.

3.1.4 Risks, Issues, and Gaps

Once these CR technologies are introduced, there will remain many issues that will need to be considered. Further, some of these technologies will create new problems, though hopefully less vexing than the ones they solved.

3.1.4.1 Standards for Cognitive Radio

Standardization of wireless protocols traditionally provides significant value to both vendors and customers. Vendors benefit from shorter development time by capitalizing on the efforts of other experts that contributed to the standard and greater potential return on investment by homogenizing the market which allows for greater reuse of equipment and efforts. In addition, there is simpler distribution of development efforts within the vendor's organization and with outside suppliers, simplified management of IP claims, and easier market entry as many technology coordination problems are resolved by the standard. Customers (whether end-users or service operators) gain more flexibility in purchasing decisions since products interoperate, and the purchasing process is simplified as many details of a system do not have to be negotiated. Customers also realize lower costs from increased competition.

Accordingly, whether emerging as de facto standards or through a more formal process, communications standards have a long been popular in both wired and wireless communications. This trend is continuing as evidenced by the explosion of wireless protocol standards that strongly incorporate CR-related technologies including 802.11h, 802.11y, 802.11af, 802.16h, 802.16m, LTE-Advanced, and CogNeA (ECMA TC48-TG1). Additionally, numerous standards for supporting technologies that are explicitly touted as cognitive radio are also underway, e.g., 1900.4 (architectural blocks and interfaces), 1900.5 (policy languages), 1900.6 (sensing interfaces), 802.19.1 (TV Band Device Coexistence), 802.22.1 (beacons for wireless microphones), 802.22.2 (802.22 installation practices), 802.19.1, SON (within 3GPP/NGMN).

Frequently when many wireless standards emerge to address the same solution space, one and sometimes two standards emerge as the clear winner while other standards are abandoned over time or become niche markets serving legacy customers or may never come to field (e.g., Ultra Mobile Broadband). Thus with many emerging CR standards, there is the real possibility that there will be duplication of efforts as seen in the similar MAC operations in 802.16h and 802.22 which have overlapping (though not identical) scope. Similarly if one standard wins out over another, then early adopters of the wrong standard may find themselves with equipment not used by the bulk of the population which may degrade the equipment's usability and value.

The problems created by competing standards cannot (and possibly should not) be avoided as what is the "best" standard or collection of technologies is difficult to assess before it comes to market. Different standards also typically target slightly different (if overlapping) markets and it is frequently difficult to assess a priori what the relative market sizes will be. These problems can be partially mitigated by employing multi-mode devices or software-defined radios that allow vendors and customers to effectively hedge their bets by supporting multiple competing standards, which in turn tends to increase price and to introduce platform convergence issues.

3.1.4.2 User burden on the network

Human interaction with a cognitive or smart radio will extend beyond the traditional user-interface considerations, e.g., learn-ability, training requirements, error prevention/reduction and integration of multi-modal interfaces. While not widely discussed, the issue of human-machine and human-CR interactions has been considered since the beginning of cognitive radio [Mitola_99] as well as in the broader systems engineering community. The users and designers of cognitive and smart radio systems will need to consider the operational approach or cognitive style of these systems as problems are identified and solved. These styles include:

- how nodes - user and systems are nodes - in such a system "consult" with other nodes in the system;
- how such a node "critiques" or self evaluates its own performance;
- how a node "advises" the user regarding tactical considerations or "alerts" the user to operational constraints and "advocates" the system's unique status and perspective to ensure consideration.

In addition, such cognitive systems should streamline the information-processing requirements of users so that they are able to perform critical or crucial tasks in noisy or frenetic environments.

The Measures of Merit for human burden are envisioned to focus on the anticipated "tension" between the user (who, prior to the introduction of a cognitive node, has handled decision "tension" with other humans well) and the new system node - a cognitive engine that the user, up until the point of introduction of a cognitive system, have had no interaction with. Tension can be good (e.g., the cognitive node delivered an agreed to decision or recommend) or bad (e.g., the cognitive node delivered a decision or recommend that is not agreed to by the user). The user and designer must ensure applicable feedback for either tension is accounted for.

3.1.5 Commercial Application References

[3G Americas_09] "The Benefits of SON in LTE: Self-Optimizing and Self-Organizing Networks," *3G Americas*, December 2009. Available online: http://www.3gamericas.org/documents/2009_%203GA_LTE_SON_white_paper_12_15_09_Final.pdf

[Brown_08] G. Brown, "Self-Organizing Networks & LTE," *Light Reading*, July 8, 2008. Available online: http://www.lightreading.com/document.asp?doc_id=158441

[Buddhikot07] "Understanding Dynamic Spectrum Access: Models, Taxanomy and Challenges" In the proceedings of IEEE DySPAN 2007.

[Buddhikot_09] Milind M. Buddhikot [1], Irwin Kennedy [2], Frank Mullany [2], Harish Viswanathan [3], "Ultra-broadband femtocells via opportunistic reuse of multi-operator and multi-service spectrum", Bell Labs Technical Journal, Vol. 13, Issue 4, Winter 2009, pg. 129-143.

[Chapin_2007] J. M. Chapin, and W. H. Lehr, "The Path to Market Success for Dynamic Spectrum Access Technology", *IEEE Communications Magazine*, May 2007.

[FCC_10] Federal Communications Commission, "Connecting America: The National Broadband Plan," Available online: http://www.broadband.gov/download-plan/

[German_09] K. German, "CNET's cell phone battery life charts," *CNET*, Sep. 29, 2009. Available online: http://reviews.cnet.com/cell-phone-battery-life-charts/

[Gilder_01] G. Gilder, "The Twenty Laws of the Telecosm," KurzweilAI.net, February 22, 2001. Available online: http://www.kurzweilai.net/meme/frame.html?main=/articles/art0004.html

[Hansell_08] S. Hansell, "Verizon and AT&T Win Big in Auction of Spectrum," *New York Times*, March 21, 2008

[Microsoft_2009] [Letzing_09] J. Letzing, "Microsoft study says white spaces worth over $100 billion," MarketWatch, Sept 23, 2009, Available online: http://www.marketwatch.com/story/microsoft-study-places-value-on-white-spaces-2009-09-23

[Mitola_99] J. Mitola, III, "Cognitive Radio for Flexible Multimedia Communications", Mobile Multimedia Communications, 1999. (MoMuC '99) 1999 IEEE International Workshop on, pp. 3 –10, 1999.

[Motorola_09a] Motorola LTE Brochure: "Motorola LTE Self Organizing Networks: Motorola's revolutionary SON solution for LTE OPEX reduction," May 2009, Available online: http://www.motorola.com/staticfiles/Business/Products/LTE/Documents/StaticFiles/LTE%20SON%20Brochure.pdf

[Motorola_09b] Motorola Whitepaper – "LTE Operations and Maintenance Strategy: Using Self-Organizing Networks to Reduce OPEX," March 2009. Available online: http://www.motorola.com/staticfiles/Business/Solutions/Industry%20Solutions/Service%20Providers/Network%20Operators/LTE/_Document/Static%20Files/LTE%20Operability%20SON%20White%20Paper.pdf

[NEC_09] Self Organizing Network "NEC's proposals for next-generation radio network management," February 2009, Available online:

http://www.nec.com/global/solutions/nsp/mwc2009/images/SON_whitePaper_V19_clean.pdf

[NGMN_07] "NGMN Use Cases related to Self Organising Network, Overall Description", *Next Generation Mobile Networks*, May 31, 2007. Available online: http://www.ngmn.org/uploads/media/NGMN_Use_Cases_related_to_Self_Organising_Network__Overall_Description.pdf

[Neel_09] J. Neel, "LTE and Other Emerging Wireless Standards," 19th Virginia Tech Syposium on Wireless Personal Communications, June 3-5, 2009, Blacksburg, VA.

[Nokia Siemens_09] Self-Organizing Network (SON) Available online: http://dogpile.com/dogpile/ws/results/Web/!22self%20organizing%20network!22/1/417/TopNavigation/Relevance/iq=true/zoom=off/_iceUrlFlag=7?_IceUrl=true

[Ofcom_10] Ofcom, "Simplifying spectrum trading: Reforming the spectrum trading process and introducing spectrum leasing," April 15, 2010. Available online: http://www.ofcom.org.uk/consult/condocs/simplify/statement/statement.pdf

[SDRF_ITU_08] SDRF-08-R-0010-V0.5.0, "Input to ITU-R WP5A on Cognitive Radio Systems," September 2, 2008.

[Ubiquisys_2009] http://www.ubiquisys.com/ub3b/pressreleases.php?id=115

[Walko_07] J. Walko, "Green Issues Challenge Basestation Power," EE Times Europe, September 19, 2007. Available online: http://eetimes.eu/showArticle.jhtml?articleID=201807401

[Wortham_09] J. Wortham, "Customers Angered as iPhones Overload AT&T" New York Times, September 2, 2009.

[Zhao_07] Y. Zhao, D. Raymond, C. da Silva, J. Reed, S. Midkiff, "Performance Evaluation of Radio Environment Map-Enabled Cognitive Radios Coexisting with Incumbent Users," Milcom 2007.

3.2 Cognitive Radio for Public Safety

The maturing of software defined radio (SDR) technology and evolving concepts of cognitive radio (CR) hold great promise for public safety communications. This section discusses CR technologies and techniques that could possibly be used to address challenges encountered by the public safety first responder. CR technologies/techniques are discussed for the following areas.

- Coverage Enhancements
- Spectrum Availability Enhancements
- Dynamic Prioritization
- Interface to Non First Responders
- Security
- Role-Based Interoperability Reconfiguration
- Resource management
- Reconfigurable RF Gateway
- Cognitive Sensor Network

Much of this material is extracted from documents created by the WINNF Public Safety Special Interest Group (PSSIG) Use Cases on the London Bombing Scenario [PSSIG_07] and Chemical Plant Scenario [PSSIG_09]. Please refer to those documents for additional detail and context.

3.2.1 Challenges

3.2.1.1 Coverage

The ultimate RF solution for a Public Safety (PS) radio system would provide communications at 100% of the locations where a first responder may be needed for 100% of the time, with perfectly understandable and reliable voice and data quality. Unfortunately, cost-benefit tradeoffs in designing a public safety radio system, not to mention laws of physics, have constrained public safety systems coverage from reaching this holy grail.

In practice a public safety system must meet stringent requirements for coverage reliability (usually 95% or greater) in a prescribed service area (e.g., a city, county, or state-wide jurisdictional boundary). In all but the most rural systems, requirements often include portable coverage within any general building that has up to 30 dB loss (or sometimes even higher). Furthermore, urban and/or suburban public safety system will usually require special provisions for coverage in several specified buildings (e.g., shopping malls, government office buildings, jails, and hospitals), often including stairwells and basement areas, regardless of the signal penetration loss. These specified locations could pose a greater coverage challenge in the deployment of a PS communication system because of a significant loss in signal power in such areas.

3.2.1.2 Spectrum Availability

Public Safety communications, being life-critical, typically require a maximum 1% Grade of Service (GOS)[16]. This imposes a much greater requirement on the number of talk-paths (proportional to the amount of spectrum used) required than if higher GOS could be tolerated. Furthermore, Public Safety spectrum requirements are sized for worst case conditions corresponding to the time of the day with the most radio calls as well as for worst case assumptions of how many radio users might have to communicate at the location of an incident.

As such, even though one might be led to believe from spectral usage measurements in some of the literature [McHenry_05] that public safety spectrum is under-utilized, the fact is that public safety systems often do not have enough available spectrum to meet the above requirements, especially in urban areas and during periods of heavy loading such as for a disaster or even during a local incident.

3.2.1.3 Dynamic Priorities

When demand for communication system resources exceed capacity, prioritization by user and content is desirable, and current trunking systems use statically defined priorities. Anyone with a “man down” message should have the highest priority, and messages from command authority should be high priority. It is a technical and intra-personal challenge to establish a dynamic priority protocol. There should be methods to realize user priority and traffic content priority that ensure delivery of the most important information first.

3.2.1.4 Interface to Non-First Responders

In a mass-casualty emergency there is a possibility that there are civilians that have the ability to provide added benefit to the response by the Public Safety community. In some cases the civilian response may be the only response available for an extended period of time. Thus it would be advantageous to leverage this capability and to provide direction to the efforts being put forth. In today’s communication environment the average person carries as a minimum a basic cell phone with the possibility of text messaging, photo and video capture and transmission. Communications capabilities could be adapted to most effectively take advantage of situations in which non-first responder personnel are positioned to play a role in the response.

3.2.1.5 Security

Security is an important issue for Public Safety systems. In the interests of brevity, the reader is directed to the security subsection in the Risks Section of this document (Section 4.3).

[16] Grade of service is the ratio of lost calls to offered calls.

3.2.1.6 Interoperability Role Based Reconfiguration

Often first responders supporting an incident response are not from the jurisdiction within which the incident is occurring, and are outside the area for which there are standing mutual aid agreements and pre-planned communications interoperability capabilities. This means that upon arrival to the incident their radios are not interoperable with communications systems in use for incident response.

However, responders generally have identical capabilities in their radios. In the event of a major incident in which some responders outside the jurisdiction of the incident report, these responders need to have their radios reprogrammed to support the incident response. Because of the general static nature of the radio program templates and the "one-size-fits-all" approach, responders' radios are programmed generically. The challenge is that either a very limited number of functions and channels are provided, which may limit the responders' capabilities, or the maximum capability is provided, which opens the door for the chaos of "everyone talking to everyone."

Current systems have limited and static capability to configure radios based on the roles and responsibilities of the radio user. Some agencies have "supervisor" radios which have different capabilities than radios given to other personnel, but these capabilities are built into the radio and cannot be changed. Radios can also be reprogrammed to include both different channel/frequency assignments and functions, but this is a manual process.

The concept of Role Based Reconfiguration is that radios can be reconfigured specifically to provide the capabilities that the responder requires based on the responders role within the incident response structure. The capabilities that the radio should have is a function of the role that the responder is performing — for example, supervisors in the incident command structure may need more capabilities than other users. This approach provides greater control over communications resources and ensures that interoperability does not result in "everyone talking to everyone." Once a radio is reconfigured, test messages should be sent to ensure that the reconfiguration was successfully executed.

3.2.1.7 Resource Management

Specific situations can arise in a public safety communications system in which the communications requirements exceed the system capacity, creating a need for greater network resource management tools than are available today.

Current public safety systems have some capability to be reconfigured to accommodate network resource management, but to utilize the capabilities effectively in real time is limited, due to:

- Lack of data (such as locations of radios and the RF environment) that can be used to better configure network resources;
    - Present day public safety geolocation capabilities utilize custom alert messages that the radio can send with pre-determined events (such as Unit Emergency Alert) or

more typically, an Internet Protocol (IP) Service where radios can be polled and respond with location (either onetime response or periodic response until time expires and/ or # responses is sent). The PSSIG is not aware of any Land Mobile Radio (LMR) Air Interface that sends Global Positioning System (GPS) location data embedded with a voice call (i.e., embedded in the header data and therefore capable of being sent regularly all the time, with any voice stream).
    - RF information is not available for analysis or for network resource management decisions, and there are currently not capabilities to adjust spectrum demands to arbitrate among competing communications requirements.
- Limitations in reconfiguring radios automatically to take advantage of changes in the network structure.
- Limitations in network reconfiguration capabilities.
- Lack of tools to monitor, anticipate, and identify situations in which network resources should be reconfigured.
- Limitations in automating the network reconfiguration process.

3.2.1.8 Reconfigurable RF Gateway Capability

Situations can arise in which it becomes necessary to establish a voice communications link between first responders and personnel that do not have access to first responder equipment.

Using current technology, the approach to providing the necessary communications capability is typically to deploy a programmable gateway device that patches a communications frequency used by the tow trucks with a communications frequency used by the first responders. There are several different products and approaches that are currently available, including:

- Mobile or fixed-site repeaters that simply retransmit incoming calls on a different outgoing channel.
- Dispatch console patches or audio linking devices (including IP-internetworking devices) that link channels of different radio systems. Such patches are generally permanent capabilities of the network infrastructure rather than capabilities that can be deployed at an incident.
- Intelligent gateway devices that allow a user to define which channels are to be linked together, and can support multiple simultaneous “conversations” through the device.

All of these approaches are characterized by the fact that a radio transmission on one channel must be rebroadcast on each other channel that is linked through the repeater/patch/gateway device.[17]

[17] We also recognize that with current technology it is also possible that an emergency management coordinator could contact individual tow trucks via commercial cell phone. While that is a feasible approach, it is difficult to broadcast information to all tow truck operators simultaneously, or for individual operators to be aware of what other trucks are doing, etc.

While such devices are employed extensively today and provide needed communications interoperability, field experience has indicated a number of challenges with the current technology:

- Such devices require personnel with extensive training to operate effectively.
- While setup can occur quickly, there are typically a number of parameters that must be adjusted to ensure effective operation. Determining the optimum parameters and adjusting them can be time-consuming, labor intensive, and potentially tie up valuable communications channels.
- Improperly deployed devices can have a severe detrimental effect on overall communications.
- All programming is manual; thus if changes need to be made to the device due to changing communications requirements or changes in RF environment, the device parameters must be manually adjusted.

3.2.1.9 Cognitive Sensor Network

There are three significant areas of shortfall in processing sensor information that can be alleviated by improved system design and application of enhanced information technology. The first is inadequate availability of sensor information. Legacy operations depend largely on facilities that responders bring to the scene, and do not take full advantage of supplementary information sources.

The second shortfall is congestion in the communication systems, caused by delivery of information by individual sensors operating independently, and without a coordinated priority structure. This problem can be alleviated by coordination between on-scene CRs, cooperating at the source to avoid data transmission that is irrelevant or redundant.

The third shortfall is on-site information overload on the part of the response team. Both the processing and presentation of available sensor data should provide all the needed information in a form that is easy to understand. For example, an on-screen map of the factory, with color-coded symbols to display the hazard level in different areas, is more readily assimilated than a printed list of coordinated and raw sensor data.

3.2.2 Beneficial Technologies

The following describes how CR has been proposed to address the issues identified in the preceding section.

3.2.2.1 Coverage Enhancements

Table 11 [Taylor09] shows some simple coverage enhancements for PS communication systems that CR could employ. More detail regarding these is discussed in [Taylor_09].

Table 11: Public Safety CR Coverage Techniques[18]

CAPABILITY	DESCRIPTION
Change systems or sites if signal is degraded below minimum criteria	Smart roaming algorithm changes sites/systems if RX signal quality is degraded below minimum criteria. *Note: This is already implemented in high-end land mobile radios*
Receiver front-end gain control	Given blockage interference and an adequately strong desired signal, an attenuator is switched in to reduce signal level into the radio's front-end. *Note: This is already used in some radios*
Power control in terminals (especially Mobiles) to reduce interference to others (e.g., mitigate the "near-far" problem)	Turn down transmit power to "just enough" to maintain the requisite quality to reduce potential for interference to others. *Note: Some radios are already capable of this.*
Change frequencies in the same band if interference is excessive	Change frequencies in the same band and same site/system if excessive interference is detected on a frequency. *Note: Typical PS base stations already do this on the control channel for a trunked system*
Receive delay spread equalizer	Adaptively sense and equalize delay spread in real time. *Note: Some radios have this already.*
Smart RX antennas for the base stations	Steer RX main lobe in desired direction and set a notch in the interference direction. *Note: Not recommended for base stations' TX antenna due to group calls*
Change frequency bands	Change frequency bands to improve noise limited performance or to avoid frequenc(ies) with strong interferences. *Caveat: Requires overlapping coverage of the different frequency bands.*
Smart receiver band-limiting filter	The balance between adjacent channel rejection and sensitivity is dynamically adjusted, depending on whether coverage is noise- or interference-limited, by changing the bandwidth of the receiver band-limiting filter
Smart terminals RX/ TX antenna	Steer main-lobe in desired direction and set a notch in the interference direction.
Smart modulation, data rate, and/or coding control	Balance amount of FEC vs. the modulation's *Eb/No* req'ts vs. data rate to maintain requisite data throughput and/or voice quality, yet reduce interference to others. *Note: Although this technique can offer some improvement by being terminal- or base station-centric, including network intelligence will substantially improve coverage performance*
Network Extension (e.g., Ad hoc or mesh networks.)	Transmissions are passed back and forth from the incident site along a network of individual responder radios operating in peer-to-peer mode. A radio would be positioned where it could maintain connectivity with the infrastructure (such as at an opening to a tunnel) and function as a repeater to bridge between the otherwise disconnected radios and the infrastructure.

3.2.2.2 Spectrum Availability Enhancements

Dynamic Spectrum Access (DSA) is often discussed as one method that might possibly be used to add spectrum to the public safety system on an as needed basis when worst case conditions actually occur. Three possible approaches for DSA are as follows:

Pre-defined agreement among organizations: One approach is to establish agreements among organizations that would allow a non-licensed authorized user to utilize additional spectrum under defined circumstances and by mutual agreement. Implementation of this cognitive capability may be limited to the ability to identify the channel loading limits that would require

[18] Not all of these capabilities/functions would make a system a CR system on its own but are consistent with the CR paradigm. See Appendix A.

accessing additional spectrum. The cognitive capability may also be used to manage network and subscriber reconfiguration to enhance the utilization of the allocated spectrum. There is a broad range of potential types of agreements under which spectrum could be dynamically accessed such as the following.

1. DSA that is triggered by a pre-defined event, such as reaching a capacity limit;
2. DSA that occurs when one organization requests access and the licensed organization grants it (e.g., spectrum mutual aid).
3. DSA granted to another user (spectrum leasing) or to a secondary user on a non-interfering basis.

Government Directive for Emergencies: Another approach to DSA is to establish rules by which some spectrum (licensed for other services) is accessed for emergency response under a governmental declaration. Here again the cognitive capability may be limited to identifying the load circumstances under which access of additional spectrum is appropriate, or may be used to manage network and subscriber reconfiguration to enhance spectrum utilization.

Identify unused or underutilized spectrum not licensed to the network: Another possible approach to DSA is to monitor spectrum utilization in frequencies not licensed to the network, identify spectrum which is unused or underutilized, and reconfigure the network and subscriber equipment to utilize that spectrum. Clearly this type of DSA would be limited to predefined situations that could include emergency situations. Cognitive capabilities would be required to identify available spectrum and to reconfigure the network and subscribers accordingly.

3.2.2.3 Dynamic Priorities

The role envisioned for cognitive capabilities is adjustment of traffic priority in real time as a function of events, resource demand, capacity, and users' roles. Manual intervention by a user or network operator is insufficient in large scale incidents. A simple cognitive capability can associate priority with responder assignment (police assigned to crowd control vs. EMT treating a trauma victim), physical location (at the incident or away from the incident), and / or agency (fire vs. medical vs. police). A more sophisticated capability could consider more variables or become predictive and anticipate the needs of the responders. A role-based approach that leverages a pre-planned priority scheme is promising, and a cognitive capability can assign a user to one of the pre-planned roles thus setting the user's priority.

3.2.2.4 Interface to Non-First Responders

There are various approaches to implementing this capability. If the implementation involves reconfiguring non-first responder radios to provide them with a capability to communicate with the incident command/first responders, then the functional capabilities include the ability to download a waveform and the ability for the non-first responders' radios to be reconfigured accordingly. If the implementation is based on infrastructure linking in a non-responder radio, then there must be a means for the non-first responder radio to upload information about the radio type or the infrastructure must have some other means of autonomously gathering the required information (e.g., see the Cognitive Gateway discussion of Section 3.2.2.7).

A key element of this use, although not considered part of the cognitive capabilities, is ensuring that any user who is linked to the first responders has a legitimate need for such communications, and has a device that will not adversely impact first responder communications. In addition, the role of such responders would need to be incorporated into the incident management (e.g., NIMS[19]) as appropriate. Note that it is common for existing dispatch centers to have a capability to patch a phone line to a radio channel. This cognitive use case extends that concept to include establishing links between first responder communications channels and non-first responder wireless devices/radios.

3.2.2.5 Interoperability Role Based Reconfiguration

The impact of Role Based Reconfiguration can be greatly enhanced by the use of over-the-air reconfiguration, perhaps by reconfiguring while responders are either en route to the incident or in the field as needed when responders are reassigned. However, role-based reprogramming can also be applied even without over-the-air reconfiguration; in this case the cognitive capabilities can still provide reconfiguration information even thought the radios must be physically connected to a computer (i.e., “tethered”) to be reconfigured.

Note that this capability assumes that interoperability is achieved by reconfiguring the responders’ radios to operate within the network(s) supporting incident response communications, as opposed to configuring the network (by activating a patch or gateway capability).

3.2.2.6 Resource Management

There are a number of techniques/technologies that support resource management, as listed below.

- RF Environment Sensing
- Geolocation
- Algorithms for monitoring, anticipating, and identifying network resource allocation issues

The resources must be managed appropriately. Policy engines are commonly touted as an elegant method to enforce appropriate use of resources.

For more details on these, please refer to the London Bombing and Chemical Plant Scenario use-cases ([PSSIG_07] and [PSSIG_09]) and Section 2.3.

[19] National Incident Management System. See http://www.fema.gov/emergency/nims/

3.2.2.7 Reconfigurable RF Gateway Capability

The CR concept is a gateway device that functions much like current gateway devices, with three notable exceptions: (1) rather than plug existing radios into the device (as required by most current devices), the device has front end reconfigurable transceivers (radios) that can configure to the required frequencies, protocols, and other operating parameters; (2) cognitive capabilities determine how the radios need to be configured, and (3) the device can monitor ongoing communications to adjust operating parameters to maintain optimum quality of the communications links.

3.2.2.8 Cognitive Sensor Network

Much benefit could be derived from deploying additional sensors as supplementary sources of data and intelligently managing the resulting information. The following are additional sources of sensor data that have potential to be processed to enhance overall situational awareness.

A. Personal Protective Equipment Supplemental Sensors
B. Building Mechanical and Emergency Systems
C. Environmental Measurement Facilities
D. Video Cameras
E. Commercial Television, including feeds from aircraft at the incident
F. Cellular System Traffic Information.
G. Intelligent Traffic Systems.

Sensors are typically capable of providing data at a very high rate. In general, *changes* in situational parameters are more important than the absolute values. Data filters, operating under control of CR functionality, can be set to provide data as a function of its rate of change. Data from a number of sources can be analyzed for significance, and presented to on-scene personnel in a form most appropriate for their decision making. Analysis can also determine when the situation merits special alarms to supplement presentation of information.

3.2.3 Public Safety Application References

[McHenry_05] M. McHenry, D. McCloskey, "Spectrum Occupancy Measurements: Chicago, Illinois, November 16-18, 2005," Shared Spectrum Company Report, 2005.

[PSSIG_07] Public Safety Special Interest Group, "Use Cases for Cognitive Applications in Public Safety Communications Systems: 7 July Bombing of the London Underground Scenario," *SDRF-07-P-0019-V1.0.0*, 2007.

[PSSIG_09] Public Safety Special Interest Group, "Use Cases for Cognitive Applications in Public Safety Communications Systems: Chemical Plant Explosion Scenario," *WINNF-09-P-0015-V1.0.0*, February 12, 2010.

[Taylor_09] R. Taylor, “Public Safety Coverage Enhancements Using Simple Cognitive Radio Concepts,” SDR Conference and Technical Exposition, 2009.

3.3 Military Applications

The functions that wireless communication offers - the removal of wire tethers thus enabling net-centricity across broad geographic areas - have had a positive impact on military/tactical capabilities and in particular on situational awareness, distributed communications and the integration of Joint Forces, and Command, Control, Communications, Computers, Combat Systems, Intelligence, Surveillance, and Reconnaissance (C5ISR). Cognitive Radio (CR) functions, including Dynamic Spectrum Access (DSA), geo-location awareness, automated configuration and policy interpretation, spawned via the development of new technologies, promise to increase the efficiency and functionality of wireless communications considerably and, thus, improve and further expand the War Fighter’s capability portfolio.

As highlighted in Figure 37, military communications have a number of issues associated with the complexity of setting up networks, tactical planning, spectrum inflexibility, spectrum scarcity, and sub-optimal use of resources. Many of the desired functions identified by the Communications-Electronics Research, Development, and Engineering Center (CERDEC) to address these issues – near-zero setup time, adaptive tactical planning, dynamic spectrum management and optimized spectrum utilization – are capabilities commonly proposed for realization through cognitive radio and were surveyed in this document [Hoppe_09].

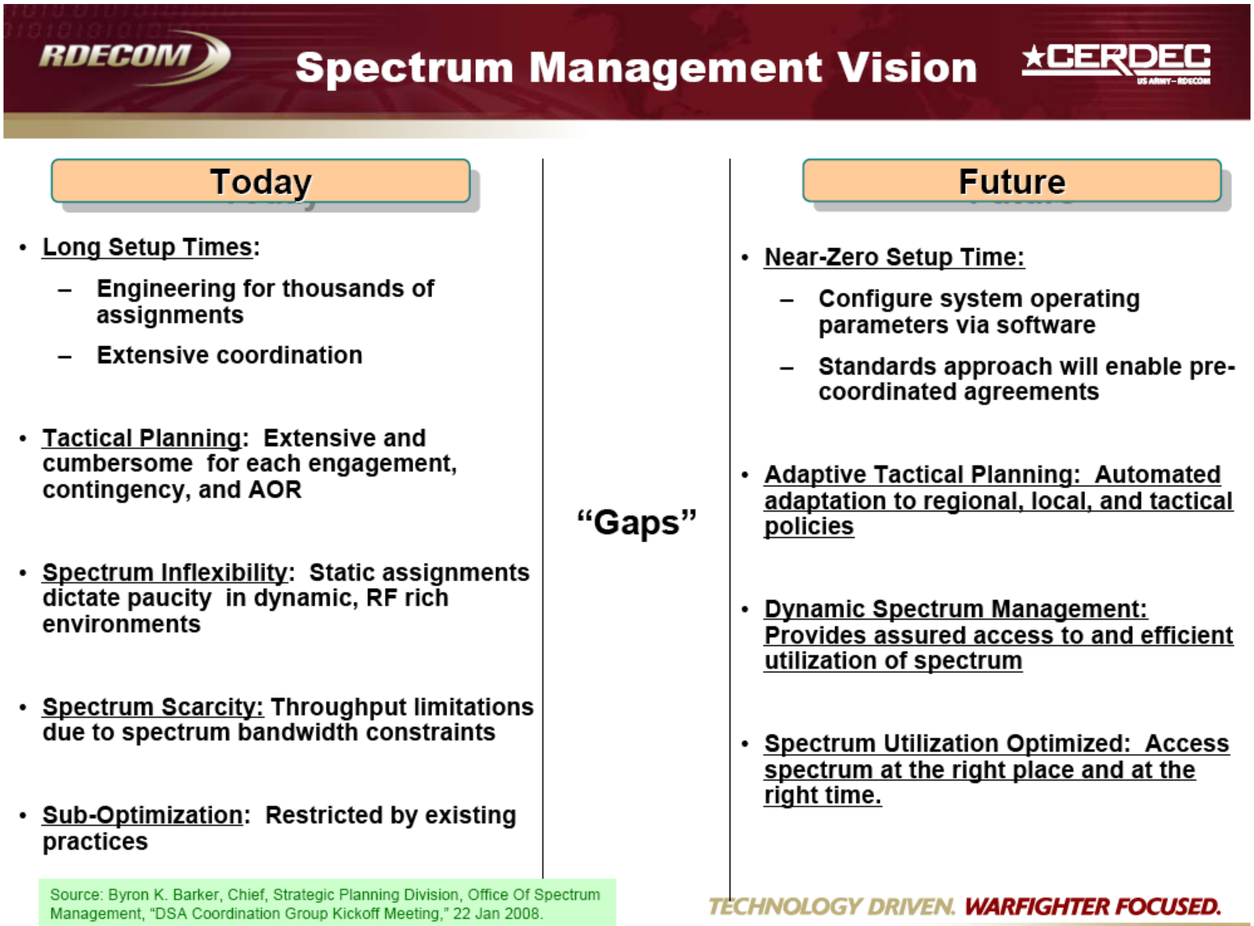


Figure 37: Issues in current military radio systems and desired functions identified by CERDEC [Hoppe_09].

These unique challenges, the associated beneficial CR technologies to meet these challenges and the gaps in technology and new issues posed by CR are addressed in the following sections. Needs of the uniformed services vary greatly by domain and application; thus, the challenges identified in the following sections may not be relevant to all military users, and cognitive radio functions may not be germane in all circumstances. Also many of the challenges and benefits discussed in the preceding sections are also applicable to defense, but are not discussed here for brevity.

3.3.1 Unique Challenges for Defense Applications

Communications officers must deal with the complexities of planning for tactical operations. When deployed, the units must bring with them everything they need to form ad hoc networks, and to access the world-wide grid, including portable and mobile terminals, command center servers, and satellite links.

This task is exacerbated given the typically brief period between the point in time after the operational battle plans have been created and the military units selected to carry out the mission are assigned to support the plan, to the point in time at which the operations must commence. Not only is the process complex, it is further complicated by having to deal with the characteristics of the specific communications assets allocated to the assigned combat and support units; restricted spectrum access (potentially shared with coalition forces during operations); increasing spectrum demand;, and a limited time to configure the actual communications assets themselves. These complexities are then compounded by technical difficulties and challenges that arise during the planning process.

*3.3.1.1 **Planning and setup time constraints***

Even in today's computer assisted world, the planning, management and configuration process associated with military communication systems and networks involves large amounts of time and energy from the communications team. The process involves selecting frequencies, waveforms, and power levels consistent with the radio and antenna characteristics of the assigned units' equipment, identifying and planning for all tactical communication networks, and requesting the necessary TRANSEC and COMSEC key material, while simultaneously managing de-confliction/coordination with all systems in the operational area, including those of coalition forces. This is a burdensome task to which is added the complexity of distributing the contents of the plan and the necessary resources (e.g., key material) to the operational units. The scope of the operation (e.g., number of individual units and missions) only compounds the situation because all tactical communications must be tailored to meet the operational needs of the overall operation and individual unit missions. Furthermore the overall plan must include backups and contingency provisions. An overview of some of these issues and problems, and the anticipated application of Cognitive Radio and networking technologies was provided in a presentation given at a recent meeting of the JTRS Science and Technology Forum (JSTeF) [Lo_09].

*3.3.1.2 **Technical Planning Challenges***

The varying technical performance characteristics of the communication assets which are to be deployed and varying operating conditions also impact planning considerations. If the predicted path loss in a particular band is too great to support the mission or the multipath environment is too severe, either the radio configuration information must be changed to meet requirements or additional communication assets (or perhaps other units) may be needed to be added in support of a specific mission.

*3.3.1.3 **Spectrum Management***

Spectrum management is a particular challenge considering the worldwide deployments in support of peacekeeping, anti-terrorism and humanitarian operations. In the US and elsewhere commercial interests are chipping away at spectrum allocations provided to military forces. In this environment joint operations must also deal with local authorities and coordinate with coalition partners to share the limited spectrum resources. In dealing with local authorities the planners must recognize that rules change from one country to another and compliance with the local rules of friendly nations is a political imperative. This further complicates the spectrum planning process while simultaneously managing de-confliction/coordination with all systems in the operational area, including those of coalition forces.

Several of the issues involving spectrum management and relevant CR technologies applicable to tactical communications were addressed in a presentation given at the same meeting of the JTRS Science and Technology Forum (JSTeF) mentioned above [Hoppe_09].

3.3.1.4 Spectrum Demand / Capacity

In the face of decreasing spectrum availability, military operations have exhibited an exponentially increasing demand for bandwidth and new spectrum to accommodate increasing amounts of sensor, video, and data streams as the military transforms to a net-centric paradigm. Illustrating this growth, [Joe_04] reviewed the US military's bandwidth demand in recent conflicts and found that "*Operation Iraqi Freedom required roughly 10 times the bandwidth demanded by the Gulf War*," while noting that this estimate might be a significant underestimate as "*at the peak of the conflict, the Defense Information Systems Agency claimed that 3 Gbps of satellite bandwidth was being provided to the theater … 30 times the bandwidth made available during desert storm*." With an increasing number of unmanned vehicles, increasing number of sensors, and the deployment of higher data-rate waveforms, the conflict between increasing spectrum demand and decreasing spectrum availability will become increasingly acute with spectrum demand far outstripping available spectrum supply.

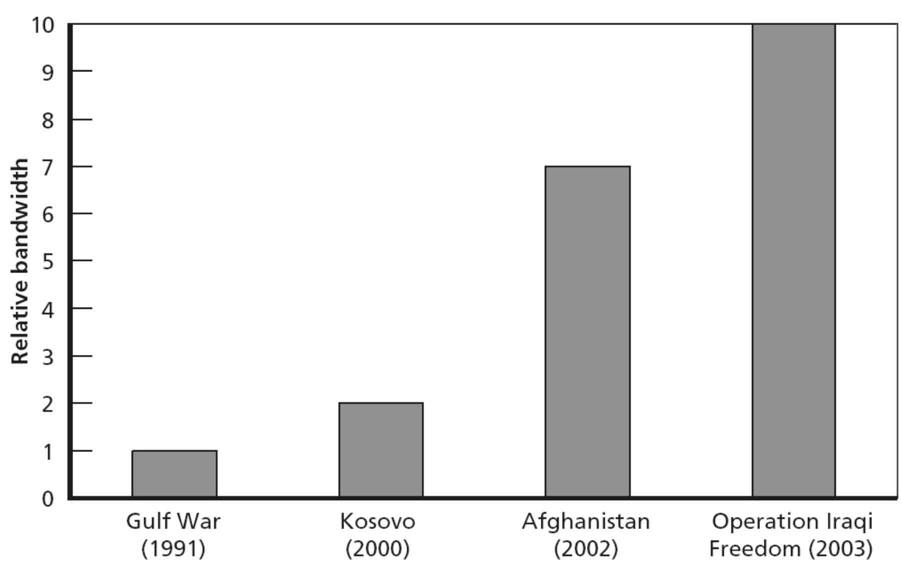


Figure 38: Increase in Bandwidth Demand by US Military Bandwidth Relative to Gulf War [Joe_04]

In the following sections, cognitive radio functions are described with illustrations of how these functions can ameliorate some of the challenges faced by today's military communicators.

3.3.1.5 Jamming

One of the unique challenges for defense applications is the requirement for jamming - denying spectrum and communications to the adversary - while also countering their attacks to achieve spectrum superiority. Quoting from a recent DARPA RFI [SN09-60]:

> Our war fighters are often engaged in operations where they must maintain spectrum superiority over hostile and dangerous adversaries. Important missions include intelligence gathering, reconnaissance, and surveillance which are precursors to the effective execution of a battle plan to control all communications for force protection and ultimately to save lives. These actions occur in large cities, small villages and complex multidimensional (mountains, dense foliage, etc) terrain.
>
> Another reality is that spectrum superiority is not a certainty in this age of rapidly changing technologies driven by commercial standards, readily available internationally and, in some cases, downloadable at no cost over the internet. This is especially true with the advent of radios that are cognitive and software defined because they listen, learn and transmit optimally by having adaptive modes with programmed policies allowing communication in any available white or grey spectrum spaces. They are multi-modal and rapidly adaptable, allowing one radio to switch to and transmit many different waveforms after receiving over-the-air software commands. Additionally, radios operate within networks which are designed to ensure a robust, high quality of service and therefore it is not good enough to deny just one radio from operating – our military must control the behavior of the total network.

Jamming systems must employ techniques that are effective against the adversary while minimizing the effects on coalition radios and jammers, and third parties; this requires the jamming system be able to distinguish among these systems. The jamming system should also seek to maximize its impact while minimizing consumption of its own resources. Further, if the adversary changes its method of communication (or jamming), the optimal methods used in response will also change. In non-cognitive jamming system deployments, accomplishing these goals imposes a significant burden on the human users.

3.3.2 Beneficial Cognitive Radio Technologies for Defense Applications

Applications utilize radios to provide real time video, data, and voice channels to support mission communication needs. Application awareness of mission and operational priorities enables the CR to adapt the communications to match the mission requirements more effectively.

3.3.2.1 Reduced Setup Time via Cognitive Radio

Cognitive Radio promises to address many of the logistical challenges including regulatory compliance, frequency allocation, equipment capability concerns, and potentially, even key distribution. Aided by advances in SDR technology such as over-the-air-programming and configuration management / control, a self-configuring CR system can achieve near-zero setup time using high assurance secure over-the-air (OTA) distribution and configuration capabilities. Emerging standards for interoperability, automatic configuration, and OTA distribution will facilitate rapid deployment.

3.3.2.2 Enhanced Link Performance

Advanced waveform adaptation under the control of the CR has the potential to improve link performance. For example, when the SINR is large, the radio could automatically select a higher order modulation constellation and increase the throughput. Improving link performance without the intervention of communications officers is a significant advantage. As the electromagnetic environment changes, the CR senses the changes and adapts the waveform to achieve the best performance possible. Sometimes this will mean a degraded link when in the past the EME would have meant no link. Sometimes it will mean a rock solid link when historically there was a marginal or intermittent link.

3.3.2.3 Built-In Policy Interpretation

As CR systems are deployed around the world, the ability to internally interpret varying policies will help achieve the goal of dynamic regulatory compliance, e.g., for tactical, strategic or political reasons. This will help simplify planning, help drive improved spectral flexibility and, by providing mechanisms to control the impact on existing systems, help promote the introduction of DSA radios which will improve spectral availability and capacity. Further installation of policy from authenticated and authorized sources could be automated, mostly eliminating the painstaking task of licensing every communication channel. However, temporally and spatially varying policies will require development and configuration management to ensure correct policy application.

The creation of policy engines and policy reasoning capability for cognitive radio was a focus of DARPA Next Generation (xG) Program, and has been demonstrated at a number of locations. [Marshall_06] was described in several publications, e.g., [Seeling_06] and [Perich_08]. Further development of policy reasoning capability is ongoing within IEEE 1900.5 and the Wireless Innovation Forum Modeling Language for Mobility (MLM), both of which would be valuable for the US DoD to monitor and / or contribute to. Configuration management of temporal and spatially varying policies were integrated as part of any of the proposed cognitive radio information distribution / sharing mechanisms such as shared radio environment maps in [Zhao_09], as a centralized database in [Whitt_09], and as a cognitive pilot channel in [Perez-Romero_07].

3.3.2.4 ***Dynamic Spectrum Access***

Military CR systems will realize the commander's intent for communications using policy constrained Dynamic Spectrum Access functionality, with the idea that DSA applications can access spectrum on a non-interfering basis as constrained by policy. The utilization of machine readable policy allows the commander to capture his intent off-line and execute that vision in real time.

By increasing access to spectrum, DSA will improve utilization of spectrum and thereby enhance system performance. Spectral measurements indicate significant spectral capacity is underutilized ([McHenry_05]), and providing non-interfering access to it through the use of CR technology increases effective capacity to enable better military communications. In the form of secondary spectrum access, a DSA enabled system would be expected to avoid interference with legacy users, find open spectrum, comply with regulatory guidance defined in machine-readable policies, and maintain connectivity through dynamic reconfiguration.

DSA is the application most closely associated with CR. xG, a proprietary implementation developed under a DARPA program, is perhaps the best-known realization of DSA. Field test results from xG have been published in [Marshall_06] with key results and program evaluation thresholds summarized from the tests in Table 12.

Table 12: xG Test Results and Evaluation Thresholds

Metric	Threshold	Results
Channel Abandon Time	500 ms	100% in 465 ms
Interference Limit	3 dB	Mean 0.16 dB, Max 0.49 dB
Net Formation	30 s with 6 nodes	90% 3.5 s, 100% 8.68 s
Net Join	5 s	90% 2.07s, 100% 4.36s
Net Re-establish	500 ms	100% 165 ms
Spectrum occupancy	60% with 6 nodes	85% Occupancy @ 83% Confidence

While xG refers to a proprietary technology, the API for xG is available within the defense community so other systems could build to it. This should enable the work of other researchers to be incorporated and to extend this work. For instance, [Nolan_05] describes OFDM-based dynamic spectrum access where narrowband legacy (FM) users are avoided. Gains are shown with respect to a static allocation where all the subcarriers are used for OFDM irrespective of legacy transmission location. Likewise, [Seidel_05] used mesh secondary networks in which secondary nodes use hetero-morphic waveforms that allow multiple discontiguous narrow bandwidth spectrum holes to be integrated into a single wideband logical channel. The nodes continually monitor local spectrum usage and adapt their spectrum according to perceived usage as well as according to regulatory policies. Around 70% of the spectrum is used as compared to 2-10% without DSA.

Finally, [Mody_07] presents machine-learning based DSA. It is shown that the use of non-competitive policy sets results in zero interference with the legacy system and a modest increase in spectrum utilization. Also, use of a competitive policy set that utilizes machine learning to predict future opportunities results in >90% spectrum utilization at the expense of some interference due to errors in prediction.

[Zekavat_05] proposes a user-centric DSA scheme for an ad hoc system with multiple vendors where users can choose their vendors depending upon congestion rate, vendor quality of service etc. Compared to a vendor-centric system, a user-centric system improves blocking rate and spectrum-efficiency by 23% and 8%, respectively.

*3.3.2.5 **Geolocation Awareness and Adaptive Use***

Positional information is key to incorporating spatially varying policies and will be important for many new applications. For example, waveform learned, location-dependent configuration changes such as increasing power or changing forward error correction (FEC) schemes in anticipation of "dead spots" has been proposed for improving link reliability [Reed_05] and depends on timely and accurate geolocation information. Other example benefits of geolocation information include incorporating geolocation information in ad-hoc networks to increase connectivity (e.g., directional forwarding or improved and predictive topology management), minimize energy usage, and support cooperative sensing. [Polson_09] presents a variety of cognitive-radio focused techniques for gaining absolute and relative geolocation awareness beyond satellite assisted services (e.g., GPS, Galileo, GLONASS) including time-of-arrival and received signal strength estimates for trilateration, round-trip-time estimates, distance measuring equipment, and angle-of-arrival for triangulation.

*3.3.2.6 **Cognitive Antennas***

The antenna subsystem is sometimes the most difficult part of the communications system to optimize given the need to support narrowband and wideband channels over a very broad range of spectrum. By making antennas adaptive (potentially via an array of antennas), capacity can be increased, frequency re-use (spatially) can be improved, energy can be conserved and communication range can be increased. Marshall [Marshall_09] reported that radio resources can be configured using MIMO technology to increase the spectral efficiency (bits per Hz) by a factor of 5 when using an 8x8 system. Similarly, [Shin_08] reported 3 dB improvement in SNR (referenced to 10^{-3} BER) for a cognitive radio using MIMO beam forming technology that can resolve multipath components from a transmitted signal and coherently combine the components.

*3.3.2.7 **Collaborative Functions***

Independent radios acting cooperatively can achieve more than the individual radios. Improved capabilities include beam forming, distributed computing, mobile ad-hoc networks (MANETs), cooperative relaying, synthetic multiple-in-multiple-out (MIMO) for increased range / throughput, and disruption tolerance. As reported by [Lu_07], a cooperative cognitive radio acting as a relay increases the link availability by 50% under certain conditions. As reported by [Zhang_07], WLAN nodes participating in cooperative re-transmission, save between 40% and 48% in energy in a packet loss rate condition of 5%.

3.3.2.8 Automatic Configuration for Cognitive NETOPS

As presented in [Hoppe_09], achieving near-zero setup time is a goal of the US DoD. With CR capabilities deployed across the networking stack, network operations can utilize adaptation, anticipation, reasoning, learning, collaboration, and awareness to achieve improved network communications. This will drive the Global Information Grid (GIG) closer to the tactical edge of the network, while ideally not sacrificing security or demanding additional manpower for support. While all necessary technologies and capabilities are not in place to realize this functionality, some key technologies include automated spectrum management [Neel_06], which reported 30 dB improvements in interference reductions, and artificial intelligence based reasoning on policy ([Perich_08] and [Lechowicz_07]). Similar technologies for automated network setup are being explored in the commercial domain to help realize "Self-Organizing-Networks" (See Section 3.1.2.3).

3.3.2.9 Cognitive Radios and Cognitive Jammers

The concept of cognitive radio (CR) operations can be extended to a cognitive jamming (CJ) role. For example, a CR that has goals aligned with a jamming mission, with perhaps additional hardware capabilities could operate as a cognitive jammer. Since adaptation and optimization of jamming systems is currently manpower intensive, CR could automate many of the processes associated with jamming while optimizing a jammer's resource utilization. Further, incorporating learning capabilities would imply a jammer that became increasingly sophisticated over time and able to recognize and adapt to evolving communications systems.

Many of the same beneficial technologies identified for CR also have a role in CJ. For instance,

- collaborative processing and antenna array techniques (e.g., beam forming) could increase aggregate power on target while reducing individual device power requirements and detectability;
- DSA and DFS / DCA could be used to better facilitate communications among devices in a jamming network in the presence of counter-measures.

However, as noted in [Martin_08], CR and CJ present unique challenges in dealing with each other.

> Yet another use of cognitive radios involves jamming. If an adversary is attempting to jam a communications link, a cognitive radio can evaluate the mode of jamming, and attempt to sidestep it by choosing a method of transmission that is robust to that particular type of jamming. If the adversary changes its method of jamming, the cognitive radio will sense this and change its transmission mode accordingly. The radio operator need not be aware of this, and hence the human burden is reduced. In a similar vein, if one wishes to jam an adversary, a cognitive jammer will sense the adversary's mode of transmission, and will select a jammer that will cause the most disruption.

The challenges and complexities that will come into play when CRs and CJs face off against one another are just beginning to be studied, perhaps most prominently in the proposed DARPA program Machine Learning for Behavioral Control of Cognitive Radio [DARPA_09].

Further, a CJ could turn a CR against itself (i.e., convert to a CJ) as several authors have noted. For example, [Bose_09] notes "Essentially a cognitive network can be converted to a cognitive jamming network by changing the training and the available actions." Vulnerabilities in CR learning and observation processes that could be subverted by a CJ are also identified in [Newman_09] and [Clancy_08]. Similarly designed counter-measures might also be used to turn away a CJ, though in both cases, it may be possible to identify and mitigate these attacks. For example, [Thomas_09] writes:

> One mechanism of limiting the effect of a malicious radio is to know in advance whether a transmission is coming from a trusted radio. This mechanism can be accomplished using authentication and non-repudiation schemes.
>
> Some relief may come from actually demodulating the signal to digital and utilizing cryptographic authentication schemes. Other solutions may leverage the stochastic characteristics of the wireless medium that a replay attack would alter.

This implies that a combination of location information, spectral information, signal structure, and identifiable behaviors should be used when anticipating operation in a mixed CR / CJ environment.

Finally, it should be noted that CR as a design paradigm leads to cognitive networks and systems and not just cognitive devices. Thus a battlefield with both CRs and CJs will need to be concerned with the actions and behaviors of entire networks whose combined effects may be more devastating while simultaneously more difficult to uniquely pin-down. As [DARPA_09] notes:

> Additionally, radios operate within networks which are designed to ensure a robust, high quality of service and therefore it is not good enough to deny just one radio from operating – our military must control the behavior of the total network.

3.3.3 Gaps in Technology and New Issues Posed by CR

Cognitive Radio is not a silver bullet for our communication problems. The laws of physics apply, thus not all problems have a technical solution, and there are still regulatory or doctrinal barriers to complete success. As illustrated in Figure 39, several gaps exist in current military networks, including extensive setup times for communication systems, the cumbersome nature of tactical planning, limited and static spectrum availability, and limited optimization of resources. While the cognitive radio technologies identified in Section 3.3.2 address many of these gaps, some will remain for the foreseeable future. Identification and discussion of some technology gaps follow.

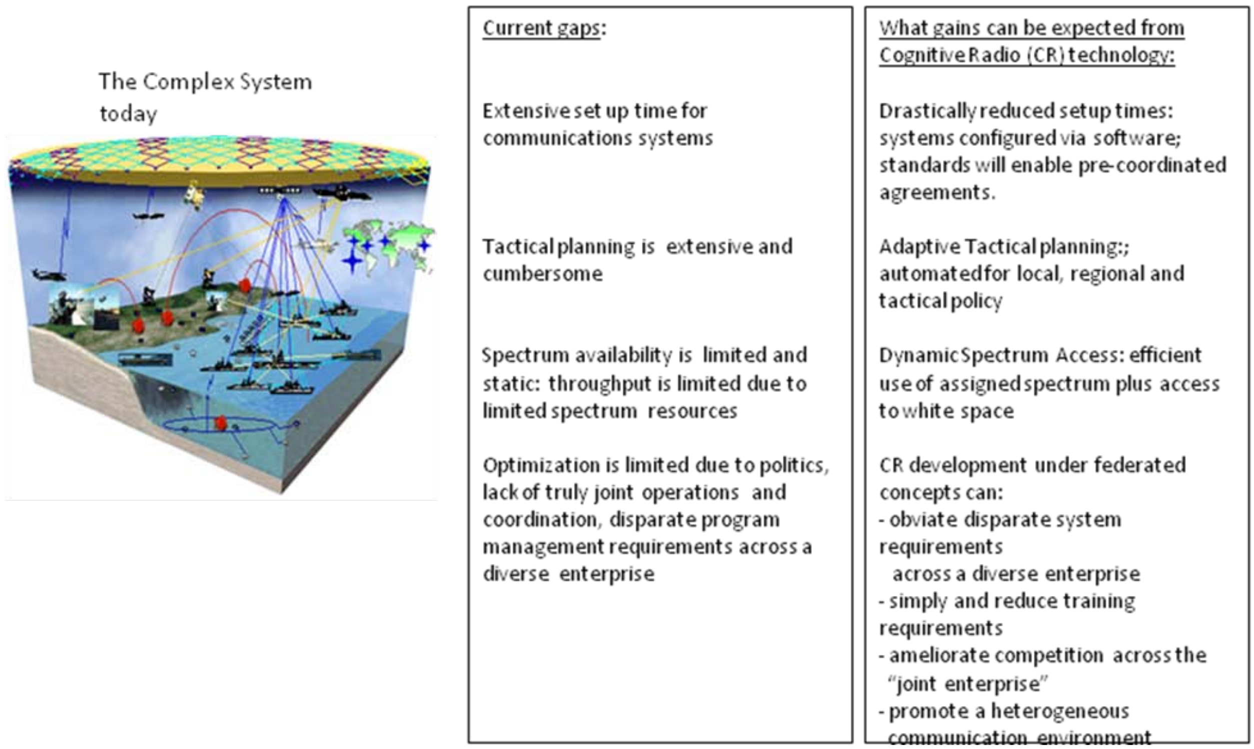


Figure 39: While CR will address many of the current gaps in military communications systems, some will remain for the foreseeable future. Modified from Slide 3 in [Hobart_04].

3.3.3.1 Integration of CR into Complex Systems (Current and Future)

Political, economic, and programmatic considerations can complicate the adoption of CR technologies into complex, legacy systems. The political issues include conflicting agency goals. For example, Federal Law Enforcement has a different mission than first responders and therefore different communication needs that may utilize common resources such as spectrum. Economic considerations dominate stakeholder and user group decision trees. CR developers can mitigate the economic "long pole in the tent" problems by maintaining interoperability with legacy systems while producing modular, extensible, and flexible systems. Programmatic problems include myriad inconsistent requirements across enterprise programs and thus exacerbate the requirements for supporting and interoperating with CR applications. Resolving these issues takes time; this resolution time can be diminished by proactive planning to smooth the integration into existing systems.

Robust, iterative development, capture, and dissemination of interoperability requirements, functional cost models, and transition plans for CRs are the critical weapons to bridging the integration gap above. When stakeholders buy into a plan of action together, many of the concerns and problems are addressed proactively and this reduces the friction of integrating CR into military systems.

3.3.3.2 Organizational and Cultural Issues associated with the application of CR Technologies

This document quantifies CR benefits in terms of functions affording users or organizations gains or efficiencies when accomplishing communication tasks. User communities are complex systems in their own right and solutions for their problems must consider political, societal, and organizational impacts. Technical CR solutions alone cannot guarantee efficacy in wireless communications and operational capabilities. Even with cognitive radio systems that fully realize the benefits identified in this document, doctrinal changes will be required to fully realize these benefits. The user communities that will benefit from this technology are complex systems in their own right and, thus, the total solution set for their problems must take into account the political, societal and organizational impacts. Most assuredly, CR functions alone cannot guarantee those entities an increased efficacy in wireless communications and operational capabilities.

In 1998, Vice Admiral Arthur K. Cebrowski stated, “In spite of a ponderous acquisition process, technology insertion is ahead of and disconnected from joint and service doctrine and organizational development. The problem is cultural and systemic. A process for the co-evolution of technology, organization, and doctrine is required.” [Cebrokski_98] This co-evolution process - applicable to DoD and First Responder entities alike during the introduction of “new technologies such as Cognitive Radios - will have a noticeable impact on or be impacted by myriad user communities. For example, organizations operating in a “joint environment” aren’t necessarily coordinated and in-sync with others when their singular organizations are aligned or set up differently. The diverse politics and societal makeup of intra-local and state agencies and inter-federal entities, when thrust into a joint working environment while completing missions often times, via competition for resources and territorial control, produce tension and overall inefficiencies. Specific areas for consideration include:

- the doctrine under which a CR system and the other systems operate across competing yet jointly structured user groups (organizational and political)
- the organizational construct or hierarchy for the joint/de-centralized domain environment(s) under which this system and others will operate (organizational, political and societal)
- new training requirements for myriad, diverse operators and maintainers with varying skill sets (organizational, technological, and political)
- the acceptance of improved or totally new material components - e.g., the actual Cognitive Radio (physics, technological, societal, and political)
- the competition across myriad agency customers operating in joint and/or de-centralized domains for materiel and logistics dollars (leadership)
- the participation of personnel across myriad and diverse personnel agency homogeneity, which will have to give way to a heterogeneous environment (leadership, organization, political, and societal)

- the need for altered or totally new facilities and life cycle support requirements across multiple agencies and entities (leadership, organizational, political, and technological)

Admiral Cebrowski's observation can be applied correspondingly to many user communities outside of DoD.

The Wireless Innovation Forum wants to emphasize the importance and necessity of co-evolving organizational and doctrinal changes, across communities of interest - communities which currently may not be in concert with each other. Failure to heed this recommendation may lead to inefficiencies in the deployment and utilization of these new technologies and could result in CR not attaining its full potential of usefulness. Such failure may arise, for example, from unresponsive or uncoordinated acquisition processes, organizational and cultural inertia or tension, insufficient scientific advancement or overly eager embracement or overly optimistic assumptions about technical or organizational capabilities.

3.3.4 Military Application References

[Bose_09] T. Bose, "Efficient Jammers Using a Cognitive Radio Network", *Summary of Projects, Institute for Critical Technology and Applied Science at Virginia Tech*, Available online: http://wireless.vt.edu/symposium/2009/2009ProjectAbstracts.pdf

[Cebrokski_98] A. Cebrowski, and Garstka, J. (1998). *Network-centric warfare: Its origin and future*. Proceedings of the U.S. Naval Institute. January, 1998.

[Clancy_08] [T. Clancy, N. Goergen, "Security in Cognitive Radio Networks: Threats and Mitigation," Int'l Conference on Cognitive Radio Oriented Wireless Networks and Communications (CrownCom), May 2008.

[DARPA_09] DARPA-SN-09-60 Machine Learning for Behavioral Control of Cognitive Radios (MLBCCR) Request for Information, August 14, 2009. Available online: https://www.fbo.gov/download/07d/07d080d6b40b30e42b0c630a7e9fdf33/ML_BCCR_RFI_14 Aug09.pdf

[Hobart_04] R. Hobart, 'Marine Corps ForceNet," 2004 Strike, Land Attack and Air Defense Annual Symposium, April 29, 2004.

[Hoppe_09] J. Hoppe, "S&TCD Activities in Cognitive Policy and Antennas," JTRS Science and Technology Forum (JSTeF) 3, January 26-30, 2009.

[Joe_04] L. Joe and I. Porsche III, *Future Army Bandwidth Needs and Capabilities*, RAND, 2004.

[Lechowicz_07] L. Lechowicz and M. Kokar, "Composition, Equivalence and Interoperability: An Example," SDR Technical Conference 2007, Denver, Nov 5-9, 2007.

[Lo_09] R. Lo, “Moving Towards *Cognitive NetOps” JTRS Science and Technology Forum (JSTeF) 3,* January 26-30, 2009.

[Lu_07] C. Lu, C., F. Fitzek, P. Eggers, “A Cooperative Scheme Enabling Spatial Reuse in Wireless Networks,” Chapter 23, pp 466 – 467 in F. Fitzek and M. Katz, *Cognitive Wireless Networks*, Springer, 2007.

[Marshall_06] P. Marshall, T. Martin, M. McHenry, P. Kolodzu, “xG Dynamic Spectrum Experiments, Findings and Plans Panel,” DoD Spectrum Summit 2006.

[Marshall_09] P. Marshall, “Spectrum Awareness and Access Considerations,” in B. Fette, *Cognitive Radio Technology*, ed. 2, Elsevier 2009.

[Martin_08] R. Martin, “The Efficient Use of Radio Resources: How Cognitive Radios Can Help”, *Air Force Research Institute* op ed, August 7, 2008, Available online: http://www.au.af.mil/au/research/op-ed/TheEfficientUseofRadioResources.html

[McHenry_05] M. McHenry, “NSF Spectrum Occupancy Measurements Project Summary”, Aug. 15, 2005. Available online: http://www.sharedspectrum.com/?section=nsf_measurements

[Mody_07] A. Mody, et al.,”Machine Learning Based Cognitive Communications in White as well as The Gray Space,” Milcom 2007.

[Neel_06] J. Neel, J. Reed, “Performane of Distributed Dynamic Frequency Selection Schemes for Interference Reducing Networks,” Milcom 2006, Oct 23-25, 2006, Washington DC.

[Newman_09] T. Newman, T. Clancy, "Security Threats to Cognitive Radio Signal Classifiers," Wireless @ Virginia Tech Symposium, June 2009.

[Nolan_05] Keith Nolan, Linda Doyle, Donal O’Mahony, Philip Mackenzie “Fluid Wireless – Dynamic Spectrum Allocation and Spectrum-Monitoring Application Using Reconfigurable Radio and OFDM,” SDR Technical Conference 2005, November 2005.

[Perez-Romero_07] J. Pérez-Romero, O.Sallent, R. Agustí, L. Giupponi, “A Novel ON-Demand Cognitive Pilot Channel enabling Dynamic Spectrum Access,} DySPAN 2007, April 17-20, 2007.

[Perich_08] F. Perich, R. Foster, P. Tenhula, and M. McHenry, "Experimental Field Test Results on Feasibility of Declarative Spectrum Management", IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, Chicago, October 2008.

[Polson_09] J. Polson, B. Fette, “Cognitive Techniques: Position Awareness,” in B. Fette *Cognitive Radio Technology*, ed. 2 Elsevier 2009.

[Reed_05] J. Reed, C. Bostian, "Understanding the Issues in Software Defined Cognitive Radio," DySPAN 05, Baltimore MD, November 2005.

[Seeling_06], F. Seelig, "A Description of the August 2006 XG Demonstrations at Fort A.P. Hill," DySPAN 2007, April 17-20, 2007.

[Seidel_05] Seidel, S. and Breinig, R "Autonomous dynamic spectrum access system behavior and performance," *DySPAN 2005*, November 2005.

[Shin_08] C. Shin, Y. Yun, S. Choi, "A Beamforming Algorithm for Collaborative MIMO System with Array Antenna," SDR 08 Technical Conference, October 26-30, 2008, Washington DC, paper #2.4-4.

[SN09-60] https://www.fbo.gov/index?s=opportunity&mode=form&id=2775303c458b8e77a160e75bf28ec703&tab=core&_cview=0

[Thomas_09] R. Thomas, B. Borghetti, "IA Implications for Software Defined Radio, Cognitive Radio and Networks", *IA Newsletter*, Volume 12 Number 1, Spring 2009, Available online: http://iac.dtic.mil/iatac/download/Vol12_No1.pdf

[Whitt_09] R. Whitt, "Introducing the White Spaces Database Group," *Google Public Policy Blog*, Feb 4, 2009, http://googlepublicpolicy.blogspot.com/2009/02/introducing-white-spaces-database-group.html

[Zekavat_05] Zekavat, S.A. and Li, X, "User-central wireless system: ultimate dynamic channel allocation," *DySPAN 2005*, November 2005.

[Zhang_07] Q. Zhang, F. Fitzek, "Cooperative Retransmission for Reliable Wireless Multicast Services" Chapter 25, pp 485-497 in F. Fitzek and M. Katz, *Cognitive Wireless Networks*, Springer, 2007.

[Zhao_09] Y. Zhao, B. Le, J. Reed, "Network Support: The Radio Environment Map," in B. Fette, *Cognitive Radio Technology*, ed. 2, Elsevier, 2009.

4 General Cognitive Radio Risks and Issues

While the preceding identified many of the technologies associated with CR that would be beneficial to commercial, defense, and public safety applications, CR will also pose issues and risks that developers, users, and regulators should be aware of. Drawing on publications in the open literature, the following focuses on the following classes of risks and issues with the use of CR.

- implementation issues
- test and measurement issues
- security issues
- regulatory issues

4.1 Implementation Issues

This section provides an overview description of implementation approaches and techniques for cognitive systems. Alternative approaches to implementing cognitive systems can have an impact on the overall performance of the system.

Cognitive radio (CR) can be viewed as the application of techniques from artificial intelligence (AI) to wireless systems. As such CR faces many of the same implementation issues as AI and insights can be drawn from examining the issues that AI has faced. For instance, the AI community is generally working towards achieving "human-like cognition", which has proved to be an elusive goal. To illustrate the illusive nature of the goal, consider that developing a system that could beat grandmasters in chess was once held out as a testable condition which could only be achieved by human-like cognition thereby heralding the success of AI. But when Deep Blue beat Kasparov in 1997, it was not with human-like reasoning but with an ability to perform far more computations per second and with significant, but domain-restricted, knowledge about the rules of chess and the relative values of pieces and positions. Because of the differences in the ways in which chess was played by Deep Blue and Kasparov, Deep Blue was not seen as true artificial intelligence because it did not think like a human and was not a general-purpose intelligence, though it was a tremendous specific-purpose intelligence.

When considered under these two hypotheses, AI has either been a spectacular failure as the date at which AIs would actually think and have a mind has always been at least a decade in the future, or AI has been a resounding success when restricted to performing specific "intelligent" tasks that humans could do but without the requirement of having to perform those tasks in the manner that a human would. Indeed numerous successful achievements for intelligent processes with scope can be cited including Deep Blue, Roomba, automated parallel parking cars, and numerous other capabilities that can be achieved without a general-purpose intelligence. Likewise, this document presents many different highly specialized "intelligent" technologies that act in a way that would be consistent with thinking and having a mind when restricted to a specific domain, e.g., DSA, cognitive MIMO, spectrum markets, self-organizing networks, and various radio resource management schemes. Thus CR applications which can be realized with specific-purpose intelligence that do not have to "think like a human" have a great chance for implementation success, but CR applications that require general-purpose human-like intelligence (e.g., true self-awareness) will have problems for at least the near-future.

4.1.1 Implementation Complexity

The following capabilities are often associated with a general purpose cognitive capability (generally applied to varying goals): symbolic reasoning, making decisions with uncertain information, planning, learning, and communicating in natural language. Some of these are also assumed more limited cognitive capabilities, but can be quite difficult to achieve even when considered alone. For instance, consider the complexity of performing natural language reasoning for CR applications – a popular field of research in the CR community with related efforts being undertaken by IEEE 1900.5 (policy languages) and the Wireless Innovation Forum (Meta-Languages for Mobility). In [Kokar_06], the impact of the choice of different reasoning languages on reasoning capabilities and implementation complexity is explored with results reproduced in Table 13. Note that the processing time for these reasoning engines built on the more advanced languages becomes untenable for all but the most sophisticated platforms as the radios' reasoning and knowledge bases grow (where N is the size of the knowledge base in the complexity column). This highlights the value of restricting the operating domain (to reduce the required knowledge base size.

Table 13: Order of complexity (cycles) as a function of the number of facts, N, and reasoning language. From Table 13.1 in [Kokar_06]

Language	**Features**	**Reasoning**	**Complexity**
XTM	Higher order relationships	None	$O(N)$
RDF	Binary Relationships	None	$O(N)$
RDFS	RDF plus subclass, subproperty, domain, and range	Subsumption	$O(N^m)$
OWL Lite	RDFS plus some class constructors; no crossing of metalevels	Limited form of description logic	$O(e^N)$
OWL-DL	All class constructors; no crossing of metalevels	General description logic	$<\infty$
OWL Full	No restrictions	Limited form of first order predicate logic	**unbounded**

But even when not attempting to employ natural-language-like reasoning, many cognitive radio applications require resources far beyond the capability of many platforms. For instance, at the WAND Proposers' Day, General Dynamics announced that they had estimated the cognitive radio will require 30 GigOps/Sec to implement. While this proposed estimate incorporated many beneficial algorithms such as MIMO based medium-access control, disruption tolerant networking, and automated edge caching, 30 GigOps/Sec is well beyond the capabilities of existing and near-future small form-factor radios – the class of devices which arguably has the greatest need for cognitive radio due to their higher deployment density. More generally, Turner [Turner_06] has written that to maximize the portability of SDR software across platforms designers should "*target the performance and memory footprint requirements of the smallest, and most processing disadvantaged radio form factor*." As evidenced by proposals which require 30 GigaOps/sec or assume support for processes with unbounded complexity, maximizing CR theoretical functionality will lead to significant implementation complexity thereby significantly reducing the portability of CR designs.

4.1.2 Verification and Software Stability

For the purposes of this discussion, consider a cognitive system implementation defined as a set of algorithms that are realized using a high-level programming language that is transformed into a form that is directly executed by a digital processor such as a general purpose processor, digital signal processor, or field programmable gate array. Additionally, this cognitive algorithm can be proven to be deterministic but is not implemented in a procedural fashion – consistent with implementing cognitive radio with a reasoning engine. The following provides a simple example of this concept. Consider the two conditional expressions:

if $x > 5$ **then do** *A*

if $x > 10$ **then do** *B*

Both expressions reference a variable x which is implied or defined as numeric. Each expression performs some action if the Boolean test is true. The action performed is clear if $x \leq 5$, neither *A* nor *B* is performed, and if $10 \geq x > 5$, *A* is performed. However, if x > 10 both conditional expressions evaluate to a true condition. So, whether *A* or *B* is performed is dependent on the implementation.

If the statements are implemented in a procedural language, such as the C programming language, the statements will be evaluated and executed in the order in which it is executed. Thus, if $x > 10$ and the statements are in the above sequence, A would be executed. Depending on the actions performed by *A* it may change the value of *x* to some value less than 10 thereby prohibiting the execution of *B*.

A cognitive algorithm using a rule-based system would identify both *A* and *B* as potential actions and could select one or the other to perform based on other information, priorities, or other additional data. So, while both methods are deterministic, a rule-based inference algorithm does not necessarily perform actions in the order they are defined on input. Likewise other implementations will use a large and possibly growing number of different input sources and internal states which will also influence the actions that a CR takes and complicate testing. Thus ensuring proper behavior in such systems will be a complicated task.

Software stability or instability due to software bugs and design errors has long been recognized as an operational and security vulnerability risk area and will continue to be so for CR. In his paper presented at the 2002 SDR technical conference [Fitton_02], Fitton noted the security issues involved with software radio and indicated the need for "testing, testing and more testing" as a preventative means to address these risks. He also makes the point that software alone is not sufficient; SDR security will require some elements to be enforced by hardware measures.

The Wireless Innovation Forum Security Working Group (SecWG) is also currently completing the preparation of a document entitled "Securing Software Reconfigurable Communications Devices" which addresses these and other import security functions as well as fundamental design aspects that are recommended to be a part of any software reconfigurable radio. Among many other vulnerabilities and potential threats this document addresses issues related to software design processes and the resultant security vulnerabilities and stability of the software. This report advocates the use of formal software development practices with rigorous reviews during the design and development process. Similar development practices will be needed for CR.

4.1.3 Implementation and Measurement

The implementation approach of any system or component of a system will have a quantitative impact on the overall system performance. The performance of the system will have an impact on the ability of the system to meet the objectives and requirements of the system, acceptance by users of the system and the cost to design, build, and produce the system.

Analysis of system performance is typically performed using a set of metrics that define key performance measures. Key performance measures define discrete, measurable data together with the acceptable range in which the measured values must lie in order to meet the requirements. These measures may define data throughput, time to complete a computation, or maximum time to respond to a request or stimuli, to name a few.

Much of the performance analysis in cognitive radio to date has focused on performance aspects of the radio elements and behavior, such as efficient use of available spectrum. In contrast, the performance analysis of algorithms has typically focused on time-oriented measures, such as the time to complete a computation. Coupled with algorithm analysis, additional technical measures may be defined, for example memory size.

Implementation of cognitive radio systems generally follow the Observe → Orient → Decide → Act (OODA) cycle defined by J. Mitola [Mitola_00]. This cycle corresponds to a general reasoning approach: identify state information that matches conditional expressions (Orient), select which of potentially several actions is to be performed (Decide), and then perform the action (Act), with the addition of sensory and external state information (Observe). Many other CR architectures have been proposed [Amanna_10], with each having its relative advantages and disadvantages.

	Name	Type	Description
Cognitive Architecture	OODA	Simple	Feedback loop developed for modeling situations requiring adaptation to changing conditions
	CECA	Simple	Expansion on OODA Loop to model situation in broader context
	SOAR	Complex	General cognitive architecture for modeling systems of complex behavior
	Storm	Complex	Extension on SOAR
	ACT-R	Complex	Similar to SOAR a programming language enables representation of tasks
Implementation	Mitola Architecture	OODA based	First cognitive architecture developed based on OODA feedback loop
	Virginia Tech 802.22	OODA using Case Based Reasoning (CBR)	Incorporates long term learning through the use of historical database
	Virginia Tech Public Safety Radio	OODA with CBR and Genetic Algorithms	Two loop cycle that first makes a decision on radio action then optimizes actions using genetic algorithms
	OSCR	SOAR based	Utilizes the SOAR Cognitive software to model and operate software defined radios
	xG Radio	Ontology based	Utilizes policy rules to govern radio behavior driven by spectrum observations

Figure 40: CR Architectures surveyed in [Amanna_10].

The implementation of a cognitive system must account for the collection of sensory data, for example spectrum sensing, performing the pattern matching and decision process, and then performing any associated actions. Some of these elements, for example collecting sensory data, may be implemented as asynchronous, parallel processes. The pattern matching and decision processes typically result in finite state machines realized through a high-level programming language and executed on a digital processor. Finally, performing the actions associated with the decisions must be included as part of the implementation. As illustrated in [Zhao_09], the choice of algorithms used can lead to radically different outcomes. So, care must be taken in not just determining individual observation, orientation, or decision processes, but in determining the goals the CRs will operate with, the context within which the CRs will be deployed and the interactions between these choices.

	Scenario 1			Scenario 2		
Observation	Parameters	O	*Interference at access point from other access points*	Parameters	O	*Interference seen by clients*
		A	Frequency (channel)		A	Frequency (channel)
		D	Lowest interference channel		D	Lowest interference channel
		G	Minimize interference		G	Minimize interference
		C	Tent city		C	Tent city
	Result	Converges to near-optimal frequency reuse pattern [48]		Result	Enters an infinite loop with probability 1 as network scales [51]	
Actions	Parameters	O	SINR at cluster head	Parameters	O	SINR at cluster head
		A	*Frequency*		A	*Power*
		D	Maximize goal		D	Maximize goal
		G	Maximize SINR		G	Maximize SINR
		C	Isolated cluster		C	Isolated cluster
	Result	Network tends to converge to low interference states		Result	Network tends to converge to self-jamming states	
Decisions	Parameters	O	Collisions	Parameters	O	Collisions
		A	Transmission times		A	Transmission times
		D	*Collaborate on times*		D	*Noncollaboratively choose times*
		G	Maximize collisions		G	Maximize collisions
		C	Isolated cluster		C	Isolated cluster
	Result	Rapid convergence to minimal interference state, adjustable to different user priorities		Result	Slow (if at all) convergence, throughput as low as ALOHA $(1/e)$	
Goals	Parameters	O	SINR at cluster head	Parameters	O	SINR at cluster head
		A	Power		A	Power
		D	Maximize goal		D	Maximize goal
		G	*Target SINR*		G	*Maximize SINR*
		C	Isolated cluster		C	Isolated cluster
	Result	If target SINR is feasible, converges to target SINR [78]		Result	Network tends to converge to self-jamming states	
Context	Parameters	O	SINR at cluster head	Parameters	O	SINR at cluster head
		A	Power		A	Power
		D	Punish (jam) radios deviating from target SINR		D	Punish (jam) radios deviating from target SINR
		G	Target SINR		G	Target SINR
		C	*Isolated cluster*		C	*Isolated cluster with a jammer*
	Result	Network overcomes defection problems for significant improvement in performance [41]		Result	Network self-jams as it "punishes" the jammer	

Figure 41: Even with all other parameters held constant, varying the Observations (O), Actions (A), Decision Processes (D), Goals, (G) or Context (C) can lead to radically different outcomes. From [Zhao_09]

Thus, assessing the effectiveness of a cognitive radio must encompass the processing and overhead associated with each of these aspects. Each of these aspects should be analyzed individually to assess the computational complexity of the cognitive processing element and the impact on the radio size, weight and power (SWaP). However, it is intuitively obvious that incorporating cognitive capabilities will increase the overall SWaP of the system. Therefore, in order to more establish a more effective metric of the impact of insertion of cognitive technology, some type of quantitative analysis of the benefit provided by cognitive capabilities must be established. One possible measure of effectiveness is a comparison of the ratio of the SWaP impacts of incorporating cognitive capabilities in the radio as compared to the ratio of Spectrum Utilization Effectiveness (SUE) with and without the cognitive capabilities. Many other metrics for evaluating specific nodes and network performance of CR have been proposed in the literature [Zhao_09]. It will be up to the network designers and regulators to decide which metrics will be the most relevant with respect to their individual applications.

Domain		Performance Metrics
Cognitive Functions	Situation Awareness	Location accuracy, availability, integrity, and continuity at various (outdoor/indoor) environment [12]
		RF environment awareness: - Receiver Operation Characteristics (ROC): PU detection rate vs. false alarm rate under various SNR and certain time bandwidth product [55], [80] - Required SNR for PU detection at certain detection rate and false alarm rate [19] - (Total) spectrum sensing time for PU detection for a given sensitivity [75] - Signal classification/recognition functionality [15] - Spectrum opportunity tracking and prediction [81] - Radio channel condition (such as multi-path delay spread and Doppler spread) awareness [59]
		Mobility and trajectory awareness [83]
		Power supply and energy efficiency awareness [83]
		Regulation, mission, context, policy, and priority awareness [64], [65], [83]
	Adaptation Capability	Channel evacuation time when PU (re)appears [42] Cross-layer adaptability Operation channels/bands and switch time between operational channels or bands [42] Antenna pattern adaptability [24] Dynamic range at receiver and transmitter Waveform/air interface flexibility and reconfigurability Routing protocols adaptability
	Reasoning, Decision Making, Planning, and Learning	Overall radio IQ level: "infant," "toddler," "preschool," "child," "adolescent," "teenager," "young adult" [65]
		Reasoning capability [86] - Case/knowledge/policy-based reasoning capability - Case retrieval time
		Decision making capability - Distributed or centralized decision making [82] - Decision-making algorithm convergence time [86], [87]
		Learning capability - Flexibility of learning (type of learning methods supported) [17] - Effectiveness of learning: performance vs. training time: Learning period [79]
Overall Node Performance		Spectrum utilization (in terms of sum throughput, network available time)
		Impact to other SU nodes or incumbent radios, in terms of - Transfer (net utility loss of the other nodes caused by one CR node) [13] - SINR or INR [42]
		Power efficiency (in terms of active time, battery life)
		Communication cost for end users
		Link reliability (in terms of BER, FER, or packet drop ratio) [68]
Node Complexity		In terms of signal processing power requirement, memory footprint, implementation costs, etc.
Technical Maturity		Overall CR node technology maturity
		Maturity of key technologies: - Software Defined Radio [61] - Analog-to-Digital Converter [37], [54] - Multi-band RF transceiver and antennas - Policy conformance enforcement [56] - Artificial Intelligence [16], [17], [53]

Figure 42: Node-level Metrics surveyed in [Zhao_09]

Domain		Performance Metrics
Cognitive Functions	Situation Awareness	PU, SU awareness: PU/SU detection rate, false alarm rate [12] Policy awareness [83] Awareness of adaptation capability of each node in the network Awareness of network topology, routing protocol and awareness of network status and current goal
	Adaptation Capability	Routing protocol and topology adaptability Cross-layer adaptation capability
	Reasoning, Decision Making, and Learning	Overall network IQ level Decision-fusion overhead [84] Decision-fusion time
Overall Network Performance		Spectrum utilization in terms of - Sum throughput or goodput [10], [81] - Throughput of secondary system [18], [79] - “Packing factor” (or “idle percentage”) in frequency, space, and time domains - Spectrum utilization efficiency [28], [32], [33]
		Impact to PU networks or other co-existing SU networks [60], [68] - Increased average packet delay experienced by the incumbent PUs [89] - SINR, INR, or BER degradation at the PU receiver [89] - Increase in call drop rate, handover failure, origination failure, termination failure [68]
		End-to-end metrics: average throughput, delay, packet drop rate, jitter [10]
		Networking metrics: - Rendezvous time (network access time) [42] - Network availability [42] - Rate of convergence [48]
		Network reliability, fairness, scalability, and mobility support [58]
		Network security - Robustness to malicious node [7], [56] - Vulnerability to denial-of-service attack [6]
		Application QoS - Voice quality, e.g., mean opinion score (MOS) [29] - Video quality, e.g., media delivery index (MDI) [76], distortion, and peak-signal-to-noise-ratio (PSNR) - Response time for interactive data applications (e.g., Telnet or World Wide Web) - Throughput for bulk data applications (e.g. FTP or distributed database synchronization)
Network Complexity		In terms of signal processing power requirement, implementation costs, etc.
Technical Maturity		Overall CR core network technology maturity Maturity of key technologies for CR networks: - MANET (scalability) [58] - Policy conformance enforcement [56]

Figure 43: Network-level Metrics surveyed in [Zhao_09]

4.1.4 Observation Issues Including Hidden Nodes

CRs frequently need to utilize information that cannot be gathered locally. The classic example for this is the hidden node problem where a CR’s transmission interferes with a device but the device itself cannot be directly detected by the CR. This is a particular concern for DSA applications where wireless microphones, TV receivers, and cable head-ends can be difficult for a CR device to detect on its own. To address this problem, various mechanisms have been proposed, such as sharing sensing information (e.g., 1900.6), geo-location databases, and pilot channels (e.g., the Cognitive Pilot Channel). However, incorporating information from other systems introduces issues with trust (for both malicious and malfunctioning devices) and establishes a need for standardized messages and roles for sharing this information. Resolving these issues necessarily complicates a CR implementation.

4.1.5 Coexistence of Cognitive Radio Algorithms

In the cognitive radio world, the primary goal of coexistence is to provide means by which two or more radios can operate effectively in the same space. Minimizing negative impact usually means reducing interference though other metrics (e.g., dropped calls, latency, voice quality) can also be used.

When primary and secondary cognitive radio systems coexist, it is the responsibility of the secondary system to ensure that it does not significantly impact the primary system. However, the coexistence of multiple cognitive radio systems introduces an element not seen in traditional wireless networks – interactive decision processes. In an interactive cognitive radio decision process, an adaptation by a cognitive radio (or network or system) alters the operating environment changing the observations of other cognitive radios (or networks or systems) and influencing their adaptations. This interaction can easily spawn an infinite sequence of adaptations that never converge, yield an unstable network whose behavior radically changes with small changes in the environment, or produce a network with decidedly suboptimal performance (e.g., a tragedy of the commons). The analysis and design of these networks is further complicated by the expected vendor-specific implementations of the radio platforms as well as the observation, orientation, decision, and learning processes.

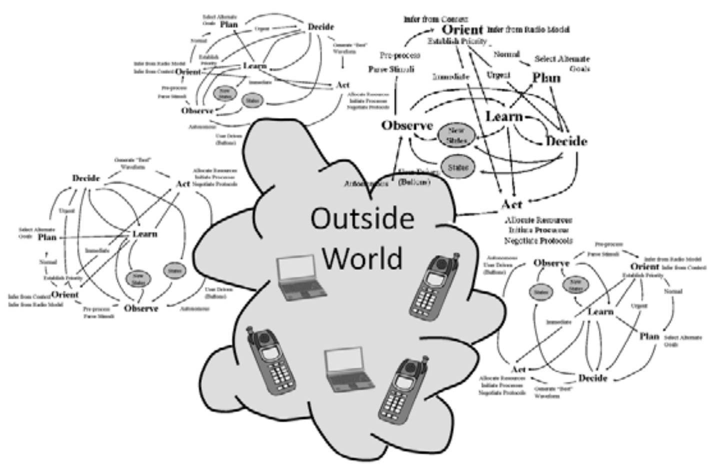


Figure 44: Each adaptation of a CR can potentially influence the adaptations of many more CRs. From Figure 1.18 in [Neel_06].

Game theory has emerged as a popular tool for modeling, analyzing and designing cognitive radio networks. It has been shown in [Neel_06] that by considering the cognitive radios' objectives the behavior of coexisting cognitive radio systems can be analyzed and designed to yield predictable operating states and desirable convergence and stability properties, even with significant implementation variation.

Other approaches that have been proposed to help manage the coexistence of cognitive radio systems include spectral etiquettes and policy, e.g., IEEE 802.19.1 investigates coexistence mechanisms for white space cognitive radios implemented from the 802 family of TVWS standards. Specifically, the standard is defining mechanisms for coexistence management (e.g., specific decision processes and events), inter-network communications (e.g., for neighbor discovery, trust, information sharing), and time-base management (e.g., for coordinating on quiet periods and scheduling transmission times).

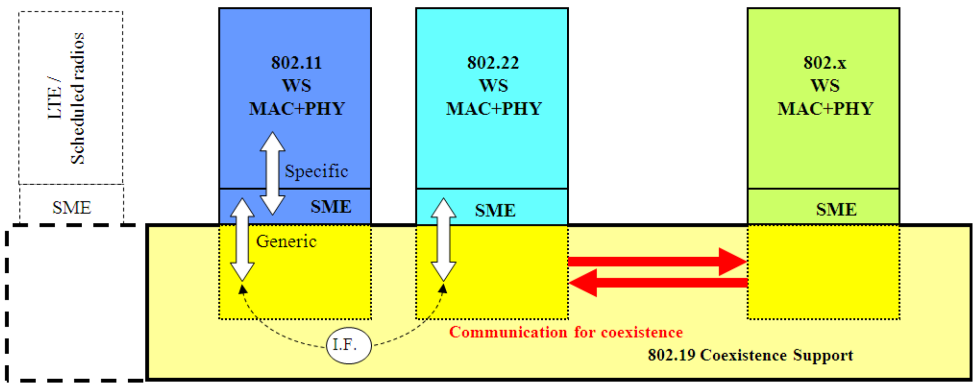


Figure 45: Proposed Coexistence Architecture of 802.19.1 which will support collaborative, but distributed coexistence decisions. From [Kasslin_10]

4.1.6 Implementation References

[Amanna_10] A. Amanna and J. Reed, "*Survey of Cognitive Radio Architectures*," in *IEEE SoutheastCon 2010*, Charlotte, NC, 2010.

[Fitton_02] J. Fitton, "Security Issues for Software Radio," SDR Technical Conference 2002.

[Kasslin_10] M. Kasslin, P. Ruuska, "Coexistence Architecture of 802.19.1," *IEEE 802.19-10/0013r0*, January 2010.

[Kokar_06] M. Kokar, *The Role of Ontologies in Cognitive Radio* in **Cognitive Radio Technology**, ed., B. Fette, 2006.

[Mitola_00] J. Mitola III, "Cognitive Radio: An Integrated Agent Architecture for Software Defined Radio," PhD Dissertation Royal Institute of Technology, Stockholm, Sweden, May 2000.

[Neel_06] J. Neel, "Analysis and Design of Cognitive Radio and Distributed Radio Resource Management Algorithms," PhD Dissertation, Virginia Tech, Sep. 2006.

[Turner_06] M. Turner, "Software Defined Radio Solutions 'Taking JTRS to the Field' with Current and Future Capabilities," *SDR Technical Conference 2006.*

[Zhao_09] Y. Zhao, S. Mao, J. Neel, J. Reed, "Performance Evaluation of Cognitive Radios: Metrics, Utility Functions, and Methodology," Proceedings of the IEEE, vol. 97, Issue 4, pp. 642-659, April 2009.

4.2 Test & Measurement Issues Posed by Cognitive Radio

Development of test and measurement procedures and associated equipment for a Cognitive Radio (CR) is another piece of the process for defining, developing and fielding innovative technologies. Unlike traditional radios, where the fundamental operating parameters (e.g. frequency bands and waveforms) and worst case scenarios (e.g., power out, band edges) are established by known specifications and standards, the ability of a CR to provide a greater range of impromptu reconfigurations of a radio and the wireless network it operates within makes test and certification a challenge

Conventional devices utilize a predictable set of mode configurations and reconfigurations. However, a cognitive device has a broader scope and depth of frequency band and waveform changes that may be called into service as the system requirements and surrounding conditions change. Since the wireless network will frequently be mobile and the environment dynamic with primary users and other networks intermittently occupying the same spectrum, there are a large number of potential coexistence issues that may occur. Thus, methods need to be developed to test a device's performance under various operating and environmental conditions.

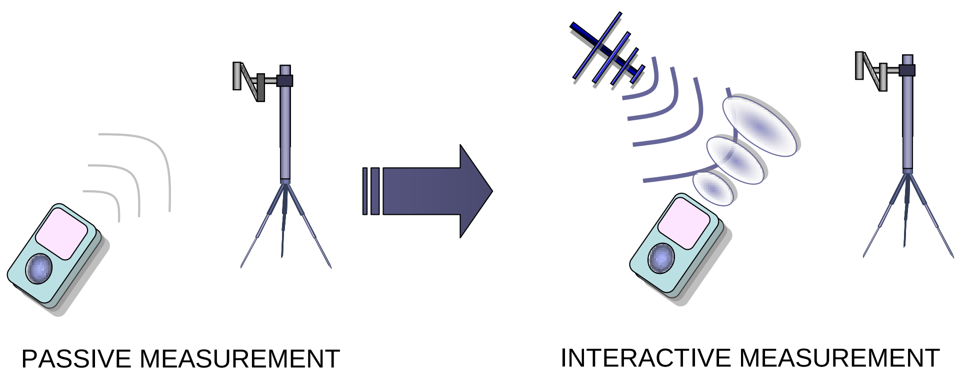


Figure 46: Because CRs are expected to respond to and interact with a more complex ecosystem and exhibit a greater range of responses than traditional radios would, interactive measurements will need to be more extensive to ensure proper operation of cognitive radios.

These new and enhanced capabilities present a test challenge at the regulatory and interoperability levels. Regulatory measurements, today, focus on the emissions from a device under very specific conditions, while interoperability testing is concerned with the interaction of devices verified against specific standards. CRs will be tested for the effect of the device on the environment (e.g., secondary user interference with primary user) and for the effect of the environment on the device (e.g. primary user appearing in band with a secondary user).

Standpoint emissions from traditional devices are typically what are measured. However, additional testing will need to be developed that quantifies a device's ability to react to a changing environment and the impact of that reaction on other devices. Examples of this dynamic interaction include capabilities such as dynamic spectrum access, hidden node determination and bandwidth adjustments. Many of the other issues posed by CR discussed in other sections (e.g., software stability, coexistence, and security) will require more extensive and possibly new tests as well.

To quantify these test requirements, the Wireless Innovation Forum has established a project entitled "*Test Guidelines and Requirements for Television Band Devices (TVBDs) designed to operate on available channels in the Broadcast Television frequency b*ands." This project's goals are to examine the specific requirements for testing TVBD devices and to develop a report that will serve, initially, as the foundation for testing secondary spectrum usage with an eye towards future testing needs as CR technology advances.

4.3 Security Issues from the Open Literature

The introduction of any new technology necessitates that security concerns be considered to determine whether the technology raises any new security issues that may be either unique or more vulnerable than those for current technologies. Much of current academic research regarding learning threats evolves from the recognition that since a Cognitive Radio (CR) learns from its local environment and alters its behavior based on what it learns, that it would be possible for an attacker, who is knowledgeable of the externally accessible parameters and factors which can influence a given CR system's behavior, to influence these factors by altering the external environment in such a way as to direct the behavior of the CR system. The objectives of these attacks may, for example, be a denial of service or directing a cognitive radio into a sub-optimal communications mode. These issues, as raised in the literature, are discussed in the following.

4.3.1 Overview of Issues

[Clancy_08] identifies the following broad ways of attacking a cognitive radio network:

- "sensory input statistics can be altered;
- faulty sensory input statistics can lead to belief manipulation;
- manipulated individual statistics and beliefs may be distributed through a cognitive radio network; and
- behavior algorithms based on manipulated statistics and beliefs can result in suboptimal performance or malicious behavior."

More specifically, [Clancy_08] identifies the following classes of attacks:

- primary user emulation attacks where characteristics of a primary user are spoofed to impact the behavior of secondary cognitive radios

- belief manipulation attacks wherein the learning phases of CRs are subverted to train the systems to operate in undesirable states, e.g., by jamming the "correct" choices and leaving the "wrong" choices unmolested
- a "cognitive radio virus" wherein cooperative learning or shared software allows a single compromised radio to propagate problems across a network,

[Brown_08] considers attacks as they apply to an 802.22 system whose primary components can be modeled as shown in Figure 47 – a model that can be generalized to many CR systems. [Brown_08] then considers attacks on this model for different sources of information about the existence of primary user related to awareness derived from a cognitive beacon, from a geo-location database and from detection and sensing. A summary of these attacks are shown in Figure 48 where the greater the number of squares shown indicates the greater the risk of the threat in terms of impact – horizontal axis - and ease of attack –vertical axis.

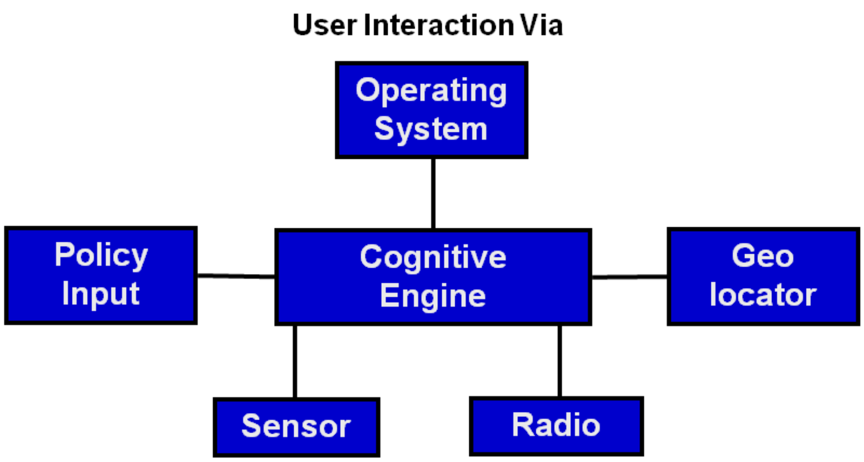


Figure 47: Primary components in 802.22 system modeled in [Brown_08]. From Slide 4 in [Brown_08]

Attacker …	Bea-con	Geo+ DB	Detect Sense
injects policies that prevent CR communication on specific primary channels.			
injects policies that deny CR communication on all primary channels.			
injects policies that allow CR communication on specific primary channels.			
injects policies that induce CR communication on all primary channels.			
emulates primary user on all primary channels.			
emulates primary user on specific primary channels.			
masks primary user on specific occupied primary channels.			
blocks location information			
jams at spectrum handoff.			
blocks access to networked sensor information.			
blocks access to policies.			
induces receiver errors on specific licensed channel			
induces receiver errors on multiple licensed channels.			

Figure 48: Threats identified in [Brown_08] for 802.22. Risks reduce significantly with encryption. From Slide 27 in [Brown_08].

Other attacks identified in the literature include the following:

- Spectrum sensing data falsification in the context of cooperative sensing of primary users [Chen_08a]
- Quiet period jamming [Bian_08] which reduces the ability of a secondary system to sense a primary system
- Replay sensing attacks [Bian_08]
- False coexistence information such as requesting excessive bandwidth or manipulating the beacon in 802.22 [Bian_08]
- Honey pot attacks that lead users to vulnerable states by selectively jamming good states [Newman_09]
- Chaff point attacks that mistrain signal classifiers [Newman_09]

The following discusses some of these issues in more detail, but the reader is encouraged to consult the cited sources for more context and for additional reading.

4.3.2 DSA Related Issues

Zhang, Xu and Geng [Zhang_08] provide the perspective that security threats in CR networks can be accounted for by first identifying the general characteristics of CR and CR networks and then addressing the security threats to the functional components of those characteristics. From their perspective, the general characteristics of CR include Dynamic Spectrum Access (DSA) and Artificial Intelligence (AI). The general characteristics of CR networks are network architecture (centralized or distributed), access behavior (cooperation or non-cooperation) and secondary access technique (e.g., underlay or overlay). Each of these characteristics would then provide an avenue attack as well as their supporting functions, e.g., performing spectrum sensing, identifying the licensed (or primary) users and accessing available spectrum.

Several authors have considered attacks related to spectrum sensing. Chen, Park, Hou and Reed [Chen_08a] have worked towards securing this function and examine the sensing issues related to *incumbent emulation* (sometimes called *Primary User Emulation* or PUE) and *spectrum sensing data falsification*. In PUE attacks, another device transmits a signal so that it appears as a primary user thereby driving secondary systems out of the spectrum for either malicious reasons (to reduce available bandwidth) or for selfish reasons (to claim the spectrum solely for themselves). Various techniques have been proposed to mitigate this including more detailed signal classification, encoding unique spectral identifiers, and database and geo-location based techniques.

In a similar fashion, Newman and Clancy [Newman_09] have described research involving attacks which exploit vulnerabilities in systems which employ signal classification. In particular these authors are concerned with users that intentionally train signal classifiers to make misclassifications by emulating a primary user and then slowly varying their transmission characteristics. They suggest that unsupervised learning schemes should not be used and that cooperative sensing should be used when possible.

However, cooperative or distributed spectrum sensing has its own issues. In these architectures the spectrum data is fused either at the central point or at the individual distributed-cooperative points. This raises the security issue of *Spectrum Sensing Data Falsification* whereby sensing data is intentionally misreported thereby impacting the operations of many CRs. To counter this kind of attack [Chen_08b] proposes a two-level defense. In the first-level, all shared sensing results are authenticated to prevent replay attacks or false data injection from nodes that are outside the CR network. In the second level, the algorithm should employ data fusion scheme that is robust against SSDF attack and they suggest employing a Sequential Probability Ratio Test and / or reputation-based schemes.

4.3.3 Control Channel Issues

While Spectrum Sensing Data Falsification indirectly influences the operation of a CR network (CRN), attacks can also be directly launched on the control channels (whether logical or physical) in a CR network. Most CRNs will be characterized by a centralized network architecture or by a distributed-cooperative network architecture, both of which require a control channel which can be attacked in a variety of fashions. This can thus directly disrupt changes to the network and indirectly create problems by introducing policy threats such as policy creation errors, policy distribution errors, policy distribution denial and also distribution of false policy.

Control channels are subject to jamming and spoofing. In addition, as per any channel rendezvous mechanism based on global clock synchronization, the channels are susceptible to the distortion of the global clock synchronization mechanism. Synchronization based on GPS time is subject to jamming of the GPS. GPS signals are low power and therefore susceptible to jamming or spoofing, which would disrupt services that rely on GPS as was seen when unintentional jamming of GPS in San Diego Harbor in January 2007 disrupted light aircraft, cell phones and pagers. [Ward_08]

Bian, Park and Chen [Bian_09] note that many DSA rendezvousing schemes require GPS, which presents a potential vulnerability. To address this, [Bian_09] proposed an asynchronous Quorum-based Channel Hopping (QCH) system that does not require global clock synchronization.

Other security aspects impacted by the jamming or spoofing of the global synchronization mechanism would include precision time stamping of spectrum sensing data and transmission symbol timing.

As part of its review of the Cognitive Pilot Channel (CPC) – a proposed scheme for distributing information related to a radio's operating environment to reduce end user device complexity and simplify policy management – the Forum noted in [SDRF_ITU_08] several security concerns and suggested the following mitigation techniques which can and should be generalized to other control channel schemes:

- If adopted, the CPC should not be essential for operation and should primarily be used to enhance awareness of information that terminals could learn by other means. This will reduce the impact of a malicious attack or network failure.
- Embedding cognitive pilot signals in strong fixed signals (such as radio or TV broadcast) would reduce the impact of jammers.
- When deployed as private CPC, logical channels should be used to make jamming and spoofing more difficult.
- Introducing redundancy to CPC functionality would reduce the impact of jammers.
- The CPC should include authentication measures, such as digital certificates, digital signatures, EAP, and 802.1x. Cognitive authentication may also help.
- Eliminate the requirement for autonomous initial location determination so the system does not fail if GPS is jammed or the terminal is located where the satellites are not visible. However, having this function as an optional feature may be beneficial.

4.3.4 Other Security Issues

Elsewhere in this section (Section 4.2), the importance of testing to eliminate software defects that could be exploited is discussed. Additionally, addressing jamming becomes a more difficult problem if one assumes the jammer is also a cognitive jammer. In fact, as noted in [Thomas_09], a cognitive radio and a cognitive jammer can in fact be the same device which changes its operation based on changing mission needs. This is discussed further in Section 3.3.2.

Finally, while CR necessarily tends to focus on the radio portion of the system, CR will also face security issues from wire-line connections, though the distinction between security issues for CR and traditional radios may be a matter of degree. With CR (assuming also SDR and flexible RF), the wire-line issue could be worse in that groups of radios could be configured to respond to some trigger which causes them to simultaneously jam some other frequency band (e.g. public safety). They could also be reconfigured to monitor spectrum (i.e., spy from afar). With normal radios, especially non-SDR radios, the amount of potential damage is much less because of less computing power, less post-production flexibility in the RF, in the modulation, and in the protocol stacks. For example, many of these issues are motivating concerns over securing the TV White Space databases that will inform TV Band Devices (TVBD) of which channels are available and were a requirement for proposers to be a TVBD database manager, e.g., [Google_10] and [Telcordia_10]. Generalizing to other CR applications (e.g., markets and spectrum control) information source authentication (perhaps using trusted 3rd party certificates) will be a key to adoption of many CR applications.

4.3.5 Security Working Group in the Wireless Innovation Forum

The Security Working Group in the Forum recently produced a report entitled “Securing Software Reconfigurable Communication Devices” intended to cover the full spectrum of Software Defined Radios, including those which employ cognitive technologies.

This Forum document is intended to provide essential guidance and valuable recommendations for SDR developers regarding the process and key considerations necessary to produce security solutions applicable for a radio platform. It spans a comprehensive range of security topics such as the consideration of stakeholder roles and security needs as well as potential vulnerabilities, threats, attacks/exploits, and their associated risk analysis. It delves into the role of the radio platform security policy in enforcing higher level security policies and the considerations to apply when developing a viable security architecture to ensure that all necessary security services and mechanisms are present and implemented in a manner which is consistent with the defined policy. Considerations are also given to the security, application and use of the emerging technology of machine interpretable downloadable policies. Guidance is provided regarding the application and implementation of services and mechanisms for traditional as well as emerging radio security services, security mechanisms and security critical system processes. The document includes a representative set of requirements which manufacturers can consider for use in their products as well as references to other existing standards.

4.3.6 Security References

[Bian_08] K. Bian, J. Park, “Security Vulnerabilities in IEEE 802.22,” *ACM International Conference on Wireless Internet*, Session: Cognitive Radio Networks, Article 9.

[Bian_09] K. Bian, J. Park, R. Chen, “A quorum-based framework for establishing control channels for dynamic spectrum access networks,” *International Conference on Mobile computing and networking*, Beijing, China, pp. 25-36, 2009.

[Brown_08] T. Brown, "Threat Assessment to Primary and Secondary Users in a Centralized Cognitive Radio Network," *802.22-08/0217r0*, July 2008.

[Chen_08a] R. Chen, J. Park, T. Hou, J. Reed, "Toward Secure Distributed Spectrum Sensing in Cognitive Radio Networks," *IEEE Communications Magazine*, April 2008, vol. 46, issue 4, pp. 50-55.

[Chen_08b] R. Chen, J. Park, & J. Reed, "Defense against primary user emulation attacks in cognitive radio networks," *IEEE Journal on Selected Areas in Communications*, vol. 26, no. 1, Jan. 2008.

[Clancy_08] C. Clancy, N. Goergen, "Security in Cognitive Radio Networks: Threats and Mitigation," *Int'l Conference on Cognitive Radio Oriented Wireless Networks and Communications (CrownCom)*, May 2008.

[Google_10] R. Witt, M. Stull, "Proposal by Google Inc. to Provide a TV Band Device Database Management Solution," January 4, 2010. Available online: http://www.scribd.com/doc/24784912/01-04-10-Google-White-Spaces-Database-Proposal

[Newman_09] T. Newman, T. Clancy, "Security Threats to Cognitive Radio Signal Classifiers," *Wireless @ Virginia Tech Symposium*, June 2009.

[SDRF_ITU_08] SDRF-08-R-0010-V0.5.0, "Input to ITU-R WP5A on Cognitive Radio Systems," September 2, 2008.

[Telcordia_10] J. Malyar, "Comments of Telcordia Technologies: Proposal Seeking to Be Designated as a TV Band Device Database Manager," January 4, 2010. Available online: http://fjallfoss.fcc.gov/ecfs/document/view?id=7020355227

[Thomas_09] R. Thomas and B. Borghetti, "IA Implications for Software Defined Radio, Cognitive Radio and Networks," *IAnewsletter* Vol. 12 No 1 Spring 2009. Available online: http://iac.dtic.mil/iatac

[Ward_08] R. Ward, "Innovation: Interference Heads Up," *GPS World*, June 1, 2008. Available online: http://www.gpsworld.com/gnss-system/receiver-design/innovation-interference-heads-up-4240

[Zhang_08] Y. Zhan, G. Xu, X. Geng, "Security Threats in Cognitive Radio Networks," *High Performance Computing and Communications 2008*, pp. 1036-1041, September 25-27, 2008.

4.4 Regulatory and Legal Issues

Regulations strongly influence the development of technologies from a technical perspective, e.g., which bands are and are not allowed and what applications are and are not allowed, and from a business perspective as changing the "rules of the game" impact the profitability of differing business models. As a new technology which users and regulators are not well acquainted with, it is expected that CR will face several regulatory hiccups as CR matures. This includes:

- matching the right spectrum management / ownership regime with the operational bands, CR applications and possible protected applications
- balancing the impact to existing and new services as CR devices come online
- minimizing regime uncertainty that limits deployment
- developing appropriate liability models

For instance, Figure 49 shows varying spectrum management regimes that have been proposed for cognitive radios. Each of the different approaches has its relative merits and demerits for a given intersection of technical, business, and social considerations. CR complicates this decision by allowing the technical considerations to be more varied and to evolve more quickly and by easily enabling new management regimes that might require much care in deployment.

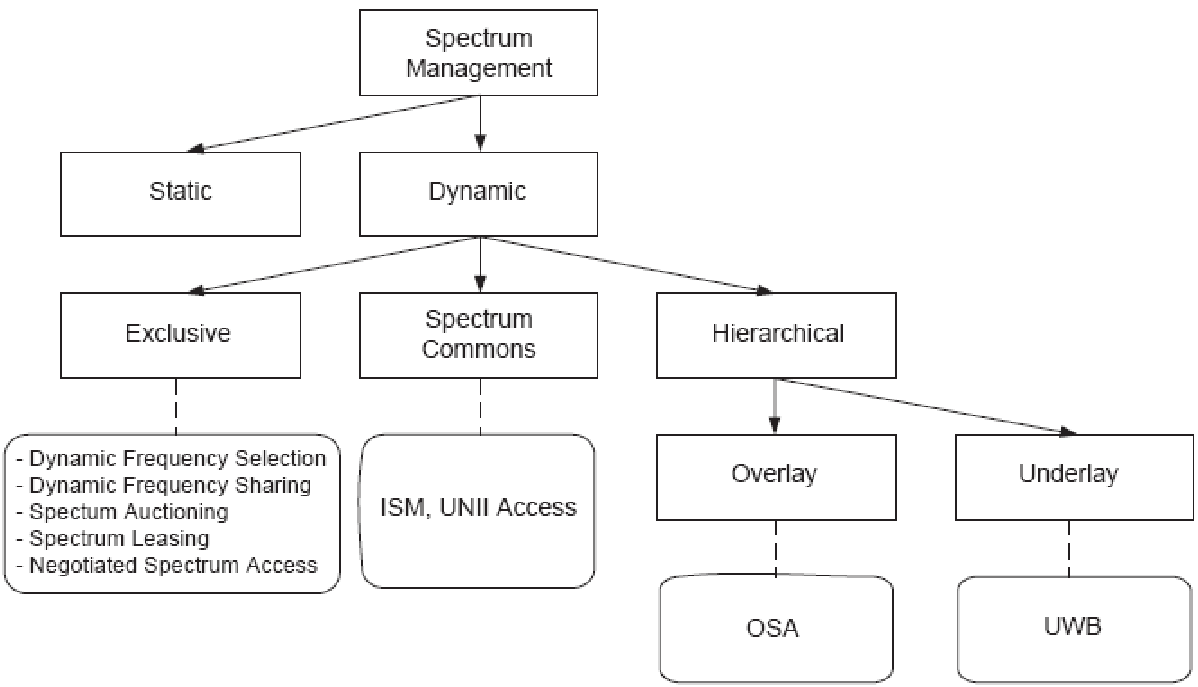


Figure 49: Classification of Spectrum Management Regimes. From Figure 4 in [Lemstra_08]

One reason great care needs to be taken in choosing the regulatory regime is the need to balance the competing interests of potential users of the regulated spectrum. In the case of TV white space, the needs of existing TV and wireless microphone users need to be balanced against the new potential users that could also use the spectrum, with the balance strongly influenced by the technical capabilities of the devices and the choice of regulations. Sometimes this balancing is not done well as seen in the initial proposed rules for Block D in the 700 MHz spectrum where the FCC tried to balance the needs of public safety users with potential commercial services and created proposed rules that were too unattractive to commercial service operators to attract sufficient bids in the initial auction.

Another problem facing regulators is that even not making a decision, or not sticking with a decision, can lead to bad outcomes. The phenomenon known as *regime uncertainty*, a term popularized by Robert Higgs in [Higgs_97], refers to uncertainty created by political action (or inaction) so that the "rules of the game" are unclear to (potential) market participants who then delay taking action. While Higgs was referring to a possible cause for the length of the Great Depression, it applies to CR as well where delays in finalizing the regulations for TV Band Devices (TVBD) have retarded the development of TVBDs rather than allocate significant capital that may turn out to be wasted if the final regulations are not as expected.

One CR-related technology that might help alleviate these issues in the future are CRs whose operation is constrained by policy engines (whether on the device or in the network) and which support software definable policies. Such a technology is being pursued in IEEE 1900.5 and was considered as part of the xG program. With such a capability, policy can be more readily changed post-deployment and with less impact on the technology development process. Then potentially bad regulatory decisions could be mitigated by supporting later policy changes in the field and regime uncertainty could be reduced by allowing devices to come to market with the understanding that their policies might be changed later. Further a policy engine approach would allow some policy experimentation across varying geographic regions.

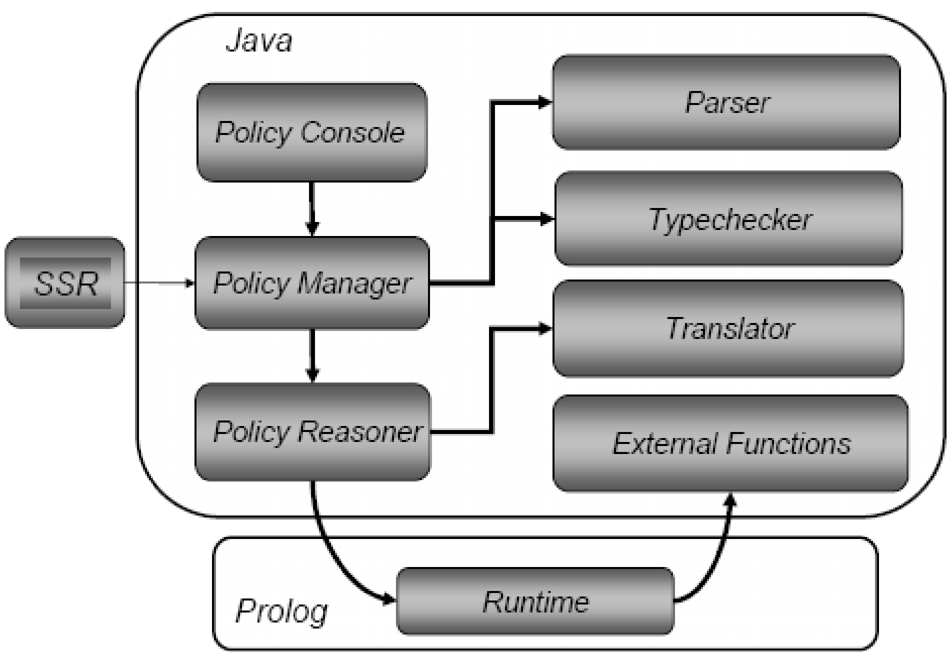


Figure 50: Main Modules of xG Policy Reasoner. [Denkar_07]

How to assign liability is another issue that has been discussed for CR (e.g., the 2008 SDR Forum Technical Conference Regulatory Workshop [SDRF_08]). For the SDR value chain, this is difficult enough as liability for tortuous behavior (e.g., harmful interference to a protected service) could need to be apportioned between user, device manufacturer, software vendor, and service operator. With users and operators assuming greater control of device operation (to better tune the devices' inherent flexibility to suit the users' needs) perhaps by modifying or "jail-breaking" their devices, the traditional assignment of damages to the manufacturer becomes less clear. Then with devices, such as CRs, given greater latitude of operation, detecting and isolating the source of harmful interference will likely be more difficult. How these issues will be resolved over time as case law evolves and specific situations are encountered.

4.4.1 Regulatory References

[Denkar_07] G. Denker, D. Elenius, R. Senanayake, M. Stehr, D. Wilkins. "A Policy Engine for Spectrum Sharing," DySPAN 2007.

[Higgs_97] R. Higgs, "Regime uncertainty: why the Great Depression lasted so long and why prosperity resumed after the war," *Independent Review*, March 22, 1997.

[Lemstra_08] W. Lemstra, "Cognitive radio defying spectrum management." In M. Finger, R.K. Kunneke & D.J. Scholten (Eds.), *Proceedings of the first annual conference on Competition and Regulation in Network Industries* (pp. 1-41). Brussel: CRNI.

[SDRF_08] 2008 SDR Forum Regulatory Workshop. http://www.sdrforum.org/sdr08/program_regulatory_workshop.html

5 Summary and Conclusions

5.1 Document Summary

This report is intended for members of the worldwide telecommunications and spectrum community who need to understand the benefits of using cognitive radio technologies in next generation wireless systems. Unlike most surveys that focus on a specific application or technology, in this report, published literature from renowned journals, conferences, and leading textbooks in this area were reviewed to identify reported quantifiable benefits of a wide range of cognitive radio technologies, including Dynamic Spectrum Access (DSA), spectrum markets, enhanced radio resource management techniques, cognitive networking applications, and cognitive MIMO approaches.

To provide hard numbers to quantify the hype of cognitive radio, the Cognitive Radio Work Group reviewed over 300 papers from a diverse range of conferences, e.g. the SDR Conference, DySPAN, CrownCom, Milcom, patents, and textbooks. Over 100 papers satisfied our selection criteria of papers that touted their technologies as “cognitive radio”, compared performance with a non-cognitive radio implementation, and provided hard numbers. Key CR results from each identified source were extracted and summarized in Section 2 and detailed results were included in the body of the report to facilitate comparisons between various approaches while an appendix provides additional context to describe how the original authors’ generated the cited results for every cited paper / result.
In Section 3, this document reviewed how CR could help address the needs of commercial, public safety, and military users. For commercial users, we saw, among other applications, where revenues could be increased by reducing deployment costs (e.g., self-organizing networks) and finding additional revenue streams for spectrum (e.g., spectrum markets and auctions); capacity could be increased by allowing leveraging femtocells which leverage several CR techniques (DSA, DFS, self-organizing networks) to reuse a provider’s own spectrum , size, weight and power (or SWAP – an issue for all user groups) could be improved by applying CR-related “green radio” techniques.

Drawing from documents created by the WInnF Public Safety Special Interest Group (PSSIG) Use Cases on the London Bombing Scenario [PSSIG_07] and Chemical Plant Scenario [PSSIG_09], we saw where CR could help with coverage issues, enhance spectrum availability, better support dynamic prioritization, support interfaces to civilian responders, improve interoperability and resource management, and help synthesize sensor network information.

After identifying communications-related needs of the military community published in recent proceedings, we saw where DSA and spectrum management applications could help reduce the lengthy times required to plan and set up networks by using and improve spectrum access and capacity, though distribution of key material remains an issue and spectrum demand will continue to increase exponentially. The military user community is also exploring CR applications towards achieving “spectral dominance” wherein CR is applied to electronic warfare applications.

While the document identified many CR technologies that would be beneficial to commercial, defense, and public safety applications, Section 4 reviewed issues and risks posed by CR which developers, users, and regulators should be aware of. First, depending on the implementation, CR implementations can grow quite complex, significantly reducing potential SWAP gains while making verifying software implementations a more complicated task. Likewise, hidden node and spoofing issues should be expected to arise from sensing-based CR schemes, though external sources of information such as Cognitive Pilot Channels and CR databases can help alleviate these. Likewise the coexistence of many CR systems will pose new issues as systems react to one another's decisions; this is currently being studied for the TVWS under 802.19.1. Because of the larger range of stimuli, greater freedom in adaptation, greater system interdependence, and the deployment in new operational scenarios, testing and certifying CRs promises to be challenging; for TVWS CR, this is currently being explored by the WInnF Test and Measurement Group. Because CR is much more sensitive to the outside world, there are many new avenues for attack (e.g., primary user emulation, learning-based attacks, cognitive "viruses", compromised information sources, and interrupted control channels; some of these issues were addressed by the WInnF Security Working Group in a report entitled, "Securing Software Reconfigurable Communication Devices." While many different regulatory regimes have been proposed for CR, regime uncertainty is currently limiting further TVWS development, but this has to be tempered against the large impact that regulations have on subsequent market development.

5.2 Conclusions

CR has emerged as one of the principle technologies researched for wireless networks across all user domains, with real empirical work now being published. By far, DSA remains the CR technology that has received the most interest and study, though CR was applied to numerous different applications with varying degrees of sophistication, and a particular increasing interest in cognitive networks and systems applications.

Further, CR as a technology is beginning to mature as it transitions from the laboratory to practical deployments as evidenced by the large number of standards under development that leverage CR techniques such as 802.11h, 802.11y, 802.11af, 802.16h, 802.16m, 802.22, LTE-Advanced, and CogNeA (ECMA 392). IEEE 1900.4 (architectural blocks and interfaces), IEEE 1900.5 (policy languages), 1900.6 (sensing interfaces), 802.19.1 (TV Band Device Coexistence), 802.22.1 (beacons for wireless microphones), 802.22.2 (802.22 installation practices) and 802.19.1, SON (within 3GPP/NGMN). While it is always risky to try to pick winning technologies and standards, the combination of CR with SDR can help reduce development risk.

As CR has become increasingly popular, the use of the term "cognitive radio" is growing more inconsistent as the associated meaning varies widely across authors and organizations, partly driven by attempts to glom onto the buzz word du jour. However, in a countervailing trend many technologies and systems that would have originally been termed "cognitive" are not called as such, as CR is subject to the same submergence phenomenon experienced by the artificial intelligence community where after each hurdle is passed, the technology is no longer considered "cognitive", but just software. The combination of the submergence and buzzword trends means that for many, what is and is not CR is often in the eye of the beholder. However, it is also justified to view these many differentiated applications, definitions, and publications as focused windows into a much broader movement, much as blind men feeling an elephant will report radically different features as central to what being an elephant is. Broadly, the CRWG views CR as part of a larger movement to incorporate artificial intelligence into systems ranging from intelligent transportation systems to the Smart Grid. This trend is being explored in more depth as part of the Information Process Architecture project undertaken by the WInnF CRWG and Public Safety Special Interest Group, with volume 1 recently published.

Realizing the gains of CR reported in this document will require care to address the implementation, security, and regulatory issues identified in this document and new test and certification regimens will need to be created. Further, maximizing the benefits of CR will require a need for doctrinal, policy, and / or regulatory changes, which will take time much as shifting business practices to best leverage the IT revolution took time.

Finally, while this document identified many promising CR technologies and applications, the reader should be aware that technologies have a way of developing in unexpected ways at unexpected times. For instance, the SDR market has not yet converged on a monolithic infinitely tunable front end; instead multiple front-ends (sometimes nine or more) are still sometimes packaged into a single device, while software (baseband) SDR functions were somewhat submerged as every base station is an SDR, for all intents and purposes. Likewise, it seems reasonable that functions and features that we now view as critical to CR may fall by the wayside with other functions becoming more important. For example, broadband sensing may follow the same path as a monolithic infinitely tunable front-end with many band-specific modules used instead; general purpose reasoning on edge devices may be eschewed in favor of cognition in the network cloud (where TVBDs seem to be converging), though privacy and security issues may necessitate a return of cognitive functions to the network edge; and self-organizing context-aware, user-focused devices may converge to a solution where macro-level decisions and contextual inputs remain performed by the human user while lower level functions are handled by the device or network, e.g., as is now done when enabling a smart phone as a WiFi access point whose operational and security parameters strongly depend on who is accessing the phone, where it is being accessed, and why it is being accessed.

CR has transitioned from a laboratory curiosity to a practical, beneficial, deployable technology as part of a larger trend to incorporating artificial intelligence into information processing systems and will continue to evolve in surprising ways.

A Appendix: Cognitive Radio Definitions

In preparing this document, we struggled with what should and should not be included as it seems as every author has a different definition for cognitive radio. Even internally, the CRWG first defined a cognitive radio in "SDRF Cognitive Radio Definitions," SDRF-06-R-0011-V1.0.0, 2007.) as (also now the IEEE 1900.1 definition):

> 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. -

But later, in recognition that cognitive radio was perhaps more meaningful as a way to design communications systems and that like artificial intelligence, once implemented CR would always be treated as "just software" which would prohibit any device from being generally agreed upon as an example of CR, the CRWG reworded its definition to place an emphasis on CR as a design paradigm, defining CR in ("Cognitive Radio Definitions and Nomenclature," SDRF 06-P-0009-V1.0.0, 2008.) as:

> 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.

which was explained in further detail in the same publication as:

> 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*).

Ultimately, for the purposes of this document we decided to avoid making judgment calls as to whether or not others' use of "cognitive radio" was correct and included in the survey any published technology that the authors explicitly called cognitive radio and tried to we tried to adhere to our CR-as-an-engineering paradigm definition in our more general discussions due to its more inclusive nature. A similar decision was made in the Information Process Architecture project currently underway (a joint effort of the Cognitive Radio Work Group and the Public Safety Special Interest Group) to abandon a formal definition and instead describe the capabilities and functions that have been ascribed to CR.

To give the readers a feel for the wide range of definitions and uses encountered in preparing this document, the following is a listing of definitions of CR and the source where they were found.

J. Mitola, III, "Cognitive Radio for Flexible Multimedia Communications", Mobile Multimedia Communications, 1999. (MoMuC '99) 1999 IEEE International Workshop on, pp. 3 –10, 1999.

> *A radio that employs model based reasoning to achieve a specified level of competence in radio-related domains.*

S. Haykin, "Cognitive Radio: Brain-Empowered Wireless Communications," IEEE Journal on Selected Areas in Communications, vol. 23, No 2, Feb. 2005.

> An intelligent wireless communication system that is aware of its surrounding environment (i.e., outside world), and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters (e.g., transmit-power, carrier-frequency, and modulation strategy) in real-time, with two primary objectives in mind:
>
> - highly reliable communications whenever and wherever needed;
> - efficient utilization of the radio spectrum.

FCC, ET Docket No. 03-108, March 11, 2005.

> A radio that can change its transmitter parameters based on interaction with the environment in which it operates.

Comments of the National Telecommunications and Information Administration on FCC ET Docket No. 03-108: "Facilitating Opportunities for Flexible, Efficient, And Reliable Spectrum Use Employing Cognitive Radio Technologies," February 15, 2005.

> A radio or system that senses its operational electromagnetic environment and can dynamically and autonomously adjust its radio operating parameters to modify system operation, such as maximize throughput, mitigate interference, facilitate interoperability, and access secondary markets.

H. Harada, "Needs, research and development of software defined cognitive radio technology," Seminar on Software Defined Radio and Cognitive Radio Systems, Geneva, Feb 4, 2008.

> A radio or system that senses and is aware of, its operational environment and can dynamically and autonomously adjust its radio operating parameters accordingly by collaborating wireless and wired networks

IEEE USA, "Improving Spectrum Usage through Cognitive Radio Technology," IEEE USA Position, Nov 13, 2003, Available online:

http://www.ieeeusa.org/policy/positions/cognitiveradio.asp

> 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.

I. Cosovic (Nokia), et al., "Editorial: Cognitive Radio and Dynamic Spectrum Sharing Systems," *EURASIP Journal on Wireless Communications and Networking*, vol. 2008, January 2008.

> Cognitive radios (CRs) are self-learning, intelligent SDRs that are able to monitor their environment and to adapt to actual conditions like available base stations (standards) or channel properties. Most important CR properties are, for example, self-location, spectrum awareness, transmission power control, or radio signal analysis. By extending cognitive radio principles to a network layer, a concept of cognitive networks arises. Cognitive networks can adapt their topology and parameters in self-configurable and dynamic manner according to the any sort of relevant changes.

M. Uusitalo, C. Wijting, P. Ojanen (Nokia), "Challenges in Cognitive Radio," Nokia, 2008.

http://akseli.tekes.fi/opencms/opencms/OhjelmaPortaali/ohjelmat/CONE/fi/Dokumenttiarkisto/Viestinta_ja_aktivointi/Muu_viestinta_ja_aktivointi/Aiheryhmat/AR1/2009/20090331/Liite_1_-_Uusitalo_GIGA_ar1_090330.pdf

> A cognitive radio system is defined as a radio system that has the capability to obtain knowledge from, and become aware of its environment (radio, service and user preferences). The radio system dynamically and autonomously adjusts its behavior and operating parameters to serve the specific needs of the user in the best way within the current environment

H. Tirri, "Future Mobility: Building the Path Forward," *The Way We Live Next, 2008*, Nokia House, Finland, September 23-24, 2008. Available online:

http://www.nokia.com/NOKIA_COM_1/Press/Press_Events/The_Way_We_Live_Next_2008/The_Way_We_Live_Next_2008_Palo_Alto/presentations/TWWLN_Henry_Tirri.pdf

> Cognitive connectivity allows all nodes to be aware of neighboring nodes and available resources

S. Shankar (Qualcomm), "Squeezing the Most Out of Cognitive Radio: A Joint MAC/PHY Perspective," ICASSP 2007, Honolulu, Hawaii.

Cognitive radios provide means to improve the spectrum utilization by allowing opportunistic usage of allocated spectrum today if they are not utilized by the primaries There are two types of cognitive radios, namely, static bandwidth cognitive radios and dynamic bandwidth cognitive radios

K. Kalliola (Nokia), "Spectrum Sharing and Flexible Spectrum Use," ***FUTURA Workshop*****, Oulu Finland August 16, 2004. Available online:**

http://www.cwc.oulu.fi/projects/Futura/160804/kimmo_kalliola.pdf

A cognitive radio is a software radio equipped with sensors and software that allow it to perceive the operating environment and learn from that experience.

P. Olanders (Ericsson AB), "Future Cellular Challenges" Micro and Nanoelectronics Design: Future challenges in R&D Framework Programme VII, Brussels, January 8-9, 2008. Available online:

ftp://ftp.cordis.europa.eu/pub/fp7/ict/docs/nanoelectronics/20080108-09-wireless-olanders_en.pdf

Cognitive radio – to use unused parts of spectrum, depending on time and location

J. Haartsen, L. Wieweg, J. Huschke (Ericsson AB), "Spectrum Management and Radio Resource Management Considering Cognitive Radio Systems," Proc. XXVIIIth Int'l Union of Radio Science (URSI) General Assembly, Oct. 2005. Available online:

http://www.ursi.org/Proceedings/ProcGA05/pdf/C09.6(02005).pdf

The characteristic features of CR are: • CR's autonomously or in negotiation with one or several peers adapt their transmit and receive parameters without the need for a higher order controller that coordinates multiple CR devices • CR's adapt their transmit and receive parameters obeying limitations on interference that their emissions could cause to other spectrum users.

"Beyond 3G: Technologies that will shape future wireless networks: An interview with Al Javed," Nortel Technical Journal, Issue 2, Available online:

http://www.nortel.com/corporate/news/collateral/ntj2_javed.pdf

> Cognitive radios "exercise judgment" to determine which slots of spectrum are available; which frequency, power level, transmission format, and protocol are required; and which mechanisms to use to avoid interference.

Dragan Boscovic, (Motorola), "Cognitive Networks," Motorola Technology Position Paper, 2005. Available online:

http://www.motorola.com/mot/doc/6/6005_MotDoc.pdf

> Cognitive, wireless access networks are those that can dynamically alter their topology and/or operational parameters to respond to the needs of particular user while enforcing operating and regulatory policies and optimizing overall network performance. A cognitive infrastructure consists of reconfigurable elements and intelligent management functionality that will progressively evolve the policies based on the past actions. The current wireless ecosystem consists of wide area networks such as 2G/2.5G/3G/3.5G, wireless local/metropolitan area networks (WLANs/WMANs), wireless personal area networks (WPANs) and short range communications, as well as digital video/audio broadcasting DVB/DAB infrastructure.

Dr. Dragan Boscovic (Motorola), "CROWNCOM 2006 Panel: Autonomic Communication and Wireless Cognitive Networks," CROWNCOM 2006, June 8-10, 2006. Available online:

http://www.autonomic-communication.org/publications/doc/AC-CognitiveRadio-PanelReport-v2.pdf

> Adaptive Radio System + Learning Feature = cognitive radio

R. Popescu-Zeletin, (FOKUS-Fraunhofer, Germany), "CROWNCOM 2006 Panel: Autonomic Communication and Wireless Cognitive Networks," CROWNCOM 2006, June 8-10, 2006. Available online:

http://www.autonomic-communication.org/publications/doc/AC-CognitiveRadio-PanelReport-v2.pdf

> Motivation for autonomic computing (presented within the context of CR and cellular)
>
> - New security threats endanger network operations
> - Exploding costs for network management
> - New application fields and services

Another example of the variation in definitions for CR is summarized in the Table shown below where sources for definitions are in the first column and capabilities in each subsequent column where a bullet notes that the associated source (row) ascribes the specified attribute (column) of to CR in its definition.

Table A-1: Cognitive Radio Definition Matrix. From J. Neel, "Analysis and Design of Cognitive Radio and Distributed Radio Resource Management Algorithms," PhD Dissertation, Virginia Tech, September 2006. Available Online: http://scholar.lib.vt.edu/theses/available/etd-12082006-141855/

Definer	Adapts (Intelligently)	Autonomous	Can sense Environment	Transmitter	Receiver	"Aware" Environment	Goal Driven	Learn the Environment	"Aware" Capabilities	Negotiate Waveforms	No interference
FCC	•	•	•	•							
Haykin	•	•	•	•	•	•	•	•			
IEEE 1900.1	•	•	•	•	•						
IEEE USA	•	•	•	•	•	•					•
ITU-R	•	•	•	•	•	•					
Mitola	•	•	•	•	•	•	•	•	•	•	
NTIA	•	•	•	•	•	•	•				
SDRF CRWG	•	•	•	•	•		•				
SDRF SIG	•	•	•	•	•	•	•	•	•		
VT CRWG	•	•	•	•	•	•	•	•	•		

B Appendix: Paper Summaries

In the first step of this literature survey, a large number of publications (journal papers, conference proceedings, textbooks, and patent applications) were surveyed by the CRWG. Summaries of these papers were written to allow for later classification and analysis. These summaries are provided below to give the reader further context.

B.1 Appendix Table of Contents

B.2 Benefits Quantified in CR Textbooks

B.2.1 Shankar, S., "Efficiency and Coexistence Strategies for Cognitive Radio,", in Software Defined Radio, and Adaptive Wireless Systems,Chapter 7 pp 193 - 201, Edited by H. Arslan, Springer, 2007.

Summary:

The author develops both analytic and simulated validation that a cognitive radio with spectrum awareness (known in his chapter as "spectrum agile") operating in the unused spectrum of primary users is able to find amongst N primary users unblocked spectrum opportunities without creating interference. In fact up to M secondary users can operate in the accessible spectrum of M users when M<N. Using knowledge of the XMT On and XMT OFF probability distributions of each of M primary users, the cognitive radio can find unblocked opportunities with high probability. The author recommends using cognitive techniques where the primary user is using less than 50% of the available channel capacity.

Quantified Benefit:

In the simulation results shown in figure 7.7 the authors shows that with M=1 cognitive user, and with N=3 primary users, and on and off distributions of the primary users as exponential, uniform or Rayleigh, and traffic load distribution of the secondary user either constant (homogeneous) or highly variable (heterogeneous), the cognitive radios are able to experience up to 200% improvement in spectrum utilization.

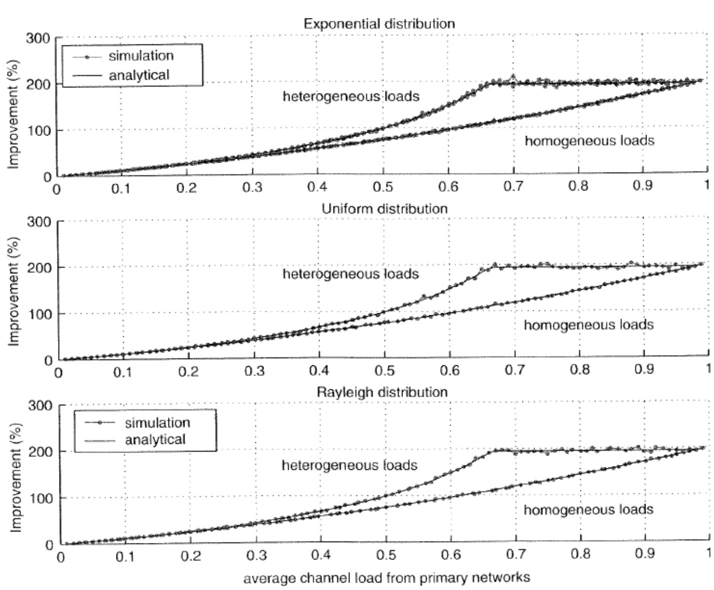


Figure 7.7 Improvement of spectral utilization for spectral-agile networks: different ON/OFF distributions.

It is possible that the horizontal axis is mislabeled, and should have been labeled channel load of secondary networks.

Considered Scenario:

One cognitive radio with spectrum awareness finds available windows of opportunity amongst three channels of primary users operating at 50% On/Off ratio, thus increasing spectrum utilization up to 200%.

Tags:

Spectrum efficiency

B.2.2 P. Marshall, "Spectrum Awareness," Cognitive Radio Technology, Chapter 5, pp 166-167, Editor Fette, B., Newnes, 1st Edition, June 2006

Summary:

In Section 5.4 of Chapter 5, Marshall discusses the issue of spectrum efficiency. By recognizing that we are not interested in bits per Hz, but rather in users per square Km, or equivalently bits/Hz/ Km^2, therefore it is important to understand the impact of increasing the transmit power in order to achieve the high SNR required for higher complexity modulation constellations that are used for higher bits per Hz. Since the higher power results in a larger radius of interference around the transmitter, even though the spectrum is kept narrow the interference radius grows significantly.

Quantified Benefit:

In the attached figures, Figure 5.2 shows the increasing power required to achieve higher bits/Hz. Figure 5.3 shows the resulting effect on bits/Hz/Unit Area. Since most terrestrial propagation is R^3.8, Figure 5.3 shows that optimum spectral efficiency measured in bps/Hz/Km^2 occurs at approximately 2 Bps.

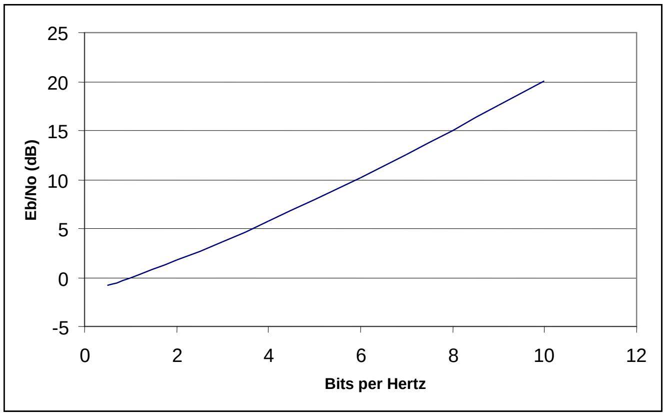


Figure 5.2: Shannon EB [energy per bit] for various spectral efficiency values.

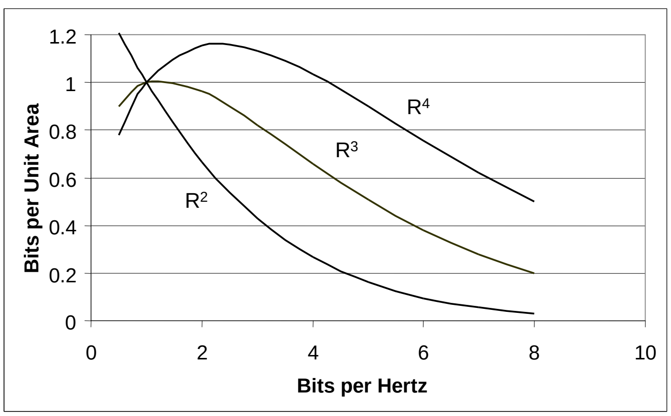


Figure 5.3 Impact of bits per Hz on Spectrum footprint

Considered Scenario:

Though not explicitly stated, the presumed situation is ad hoc terrestrial networking for defense applications. However, the derivation is valid for terrestrial communications in general.

Tags:

Spectrum efficiency

B.2.3 Devroye, N., Tarokh, V., "Fundamental Limits of Cognitive Radio," Cognitive Wireless Networks, Chapter 17, pp 333-337, Edited by Fitzek & Katz, Springer, 2007

Summary:

The authors provide an estimate of the rate capacity region of a communication channel when there is a single primary transmitter, and when a cognitive cooperative secondary user aids the primary in transmission thus creating a MIMO communication channel condition.

Quantified Benefit:

By cooperation, the cognitive radios are able to expand their achievable rate over what would be possible as individual transmitters time-sharing the resource. The achievable rate region is more than doubled.

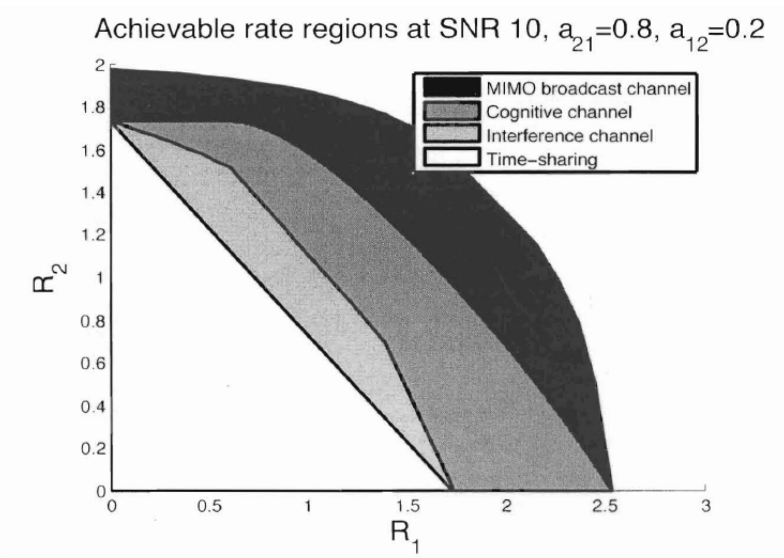


Figure 17.4 Capacity region of the Gaussian 2x1 MIMO two receiver broadcast channel (outer), cognitive channel (middle), achievable region of the interference channel (second smallest) and time-sharing (innermost) region for Gaussian noise powers N1=N2=1, power constraints P1=P2=10 at the two transmitters, and channel parameters a_{12}=0.8, a_{21}=0.2.

Considered Scenario:

A cognitive node participates with another node to help deliver its data traffic, thus expanding the achievable rate.

Tags:

Cooperation, Achievable rate, Cooperative MIMO

B.2.4 Lu, C., Fitzek, F.H.P., Eggers, P.C.F., "A Cooperative Scheme Enabling Spatial Reuse in Wireless Networks," Cognitive Wireless Networks, Chapter 23, pp 466 - 467, Edited by Fitzek & Katz, Springer, 2007

Summary:

This chapter discusses many considerations of cooperative spatial reuse (mostly MISO). In section 23.4.1, the authors discuss availability of a cooperative link, as a function of the SNR from the source to destination on link 1, and SNR from the source to a relay node on link 2. The net result is that as SNR of each link increases, then it becomes more likely that a node will be able to find a cooperative partner for forwarding traffic. There is an assumption that a field of radios that are equipped with cooperative relay waveforms and protocols already exist in the environment.

Quantified Benefit:

From Figure 23.7 we can see that even when the primary link has high SNR (say 30 dB) as the SNR of Link 2 (the relay link) increases, the cooperative spatial reuse availability increases as well, rising from approximately 0.6 to approximately 0.9. This is a 50% increase in link availability.

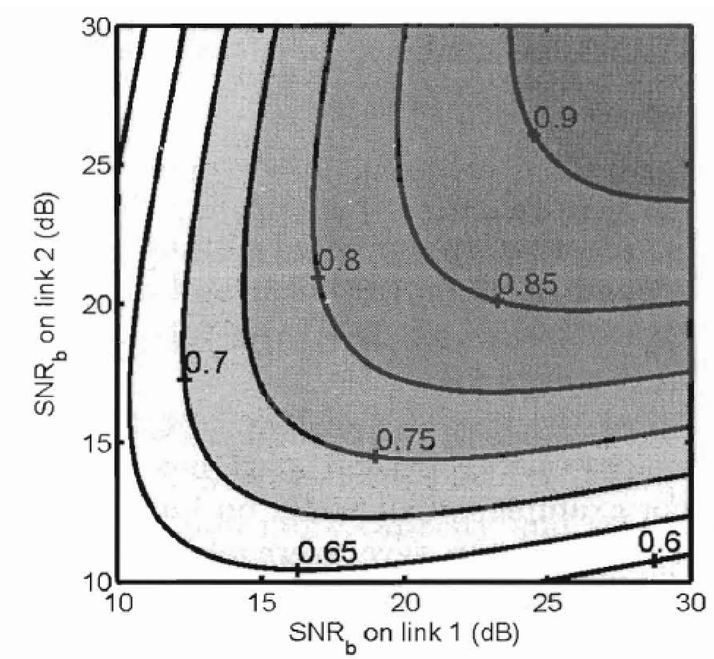


Figure 23.7 CSR availability when both links satisfy Condition I. SNRb denotes the mean SNR per branch.

Considered Scenario:

A region populated with cognitive radios that have cooperative MIMO waveform and protocol cooperate to forward traffic and improve network availability.

Tags:

Cooperative spatial reuse, MIMO

B.2.5 Zhang, Q., Fitzek, F.H.P., "A Cooperative Scheme Enabling Spatial Reuse in Wireless Networks," Cognitive Wireless Networks, Chapter 23, pp 494 - 497, Edited by Fitzek & Katz, Springer, 2007

Summary:

In a WLAN environment with 128 nodes, where the 128 nodes are partitioned into various group sizes and therefore various number of groups, where the nodes participate in cooperative spatial reuse, the nodes experience savings of energy.

Quantified Benefit:

WLAN nodes participating in cooperative re-transmission save between 40% and 48% in energy in a packet loss rate condition of 5%, with groups of smaller number of nodes per cluster experiencing higher energy savings.

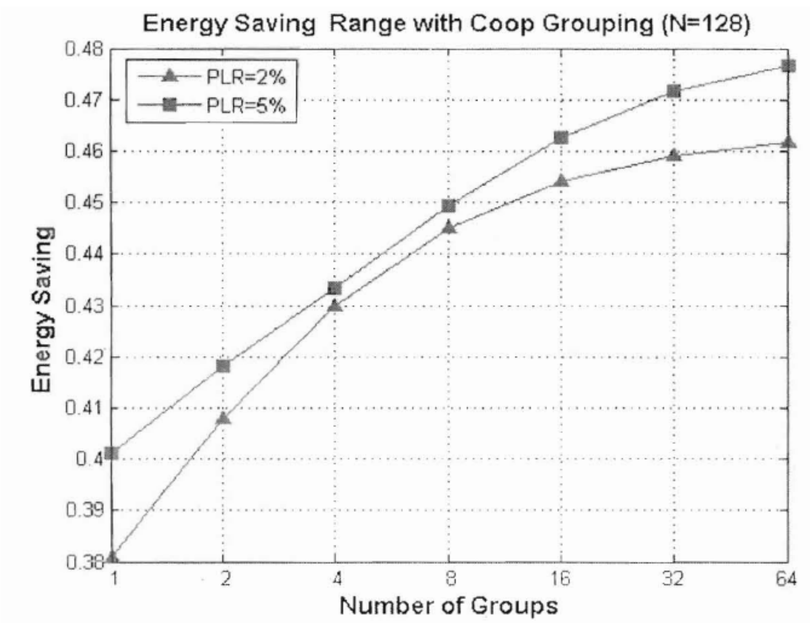


Figure 25.8 Cooperative Energy Saving Gain with Grouping.

Considered Scenario:

WLAN nodes participating in cooperative re-transmission, save between 40% and 48% in energy in a packet loss rate condition of 5%.

Tags:

Cooperative spatial reuse, MIMO

B.2.6 Comaniciu, C., "Cooperation of Cognitive Networks," Cognitive Wireless Networks, Chapter 28, pp 539 - 546, Edited by Fitzek & Katz, Springer, 2007

Summary:

The author explores game theory equations for cost and utility, and compares networks that consist of selfish users seeking their own highest possible throughput, cooperative users, cooperative users using game theory based cost and utility, and traditional equal probability random access. The author finds that highest network throughput, highest per user throughput, and lowest variance of throughput occurs when the nodes use cooperative game theory equations.

Quantified Benefit:

Throughput is increased 7% while throughput variance is reduced 15% when greedy use algorithm is replaced by cooperative game theory based utility and cost functions.

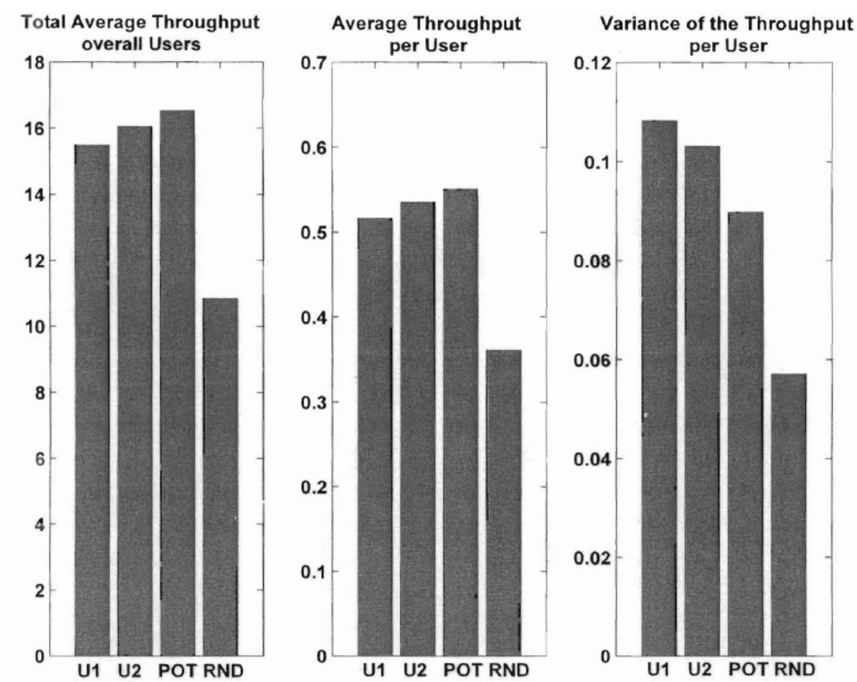


Figure 28.6 Total Average Throughput, Average Throughput per user and Variance Throughput per user (U1 = selfish users with minimum regret learning algorithm implementation; U2 = cooperative users with minimum regret learning algorithm implementation; POT = cooperative users with potential game implementation; RND = equal probability random channel allocation).

Considered Scenario:

Thirty transmitters in a network randomly distributed over 200 m x 200m sharing 4 available channels.

Tags:

MAC protocols, Game theory

B.2.7 Albiero, F., Fitzek, F., Katz, M., "Analysis of Cooperative Power Saving Strategies with NetLogo," Cognitive Wireless Networks, Chapter 31, pp 605 - 612, Edited by Fitzek & Katz, Springer, 2007

Summary:

The authors develop a network consisting of 50 nodes, where each node can transmit using cellular or using ad hoc networking based on 802.11a/g. The network is called NetLogo, and is used to explore power savings. Clearly, the nodes can form a cluster, and can then communicate with other clusters through cellular radio, thus creating a network hierarchy. In the selfish mode, nodes can minimize their own power expense. In the cognitive radio technique, called "wise cooperation" in this chapter, they attempt to minimize the power experienced by all cluster members, thus aiding some disadvantaged members at the slight power expense of other members. Under wise cooperation the nodes tend to form larger clusters, while in the greedy mode, they tend to form smaller clusters. As a result, there are fewer isolated nodes in the "wise cooperation" network protocol. A moderate complexity cost – benefit game theory equation is used for this optimization.

Quantified Benefit:

50% reduction in isolated nodes.

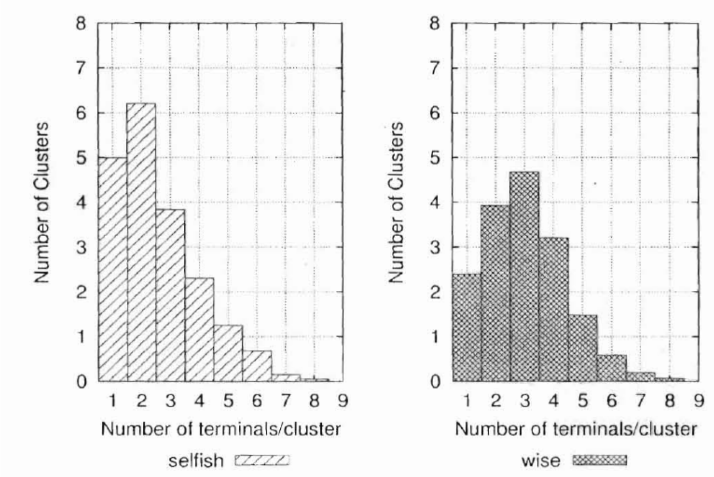


Figure 31.3 Cluster distribution vs. number of cooperating units for the two strategies.

Considered Scenario:

Fifty nodes with a choice of radio 2 links (ad hoc network or cellular), which form clusters.

Tags:

Network Protocols, Game theory

B.2.8 Marshall, P., "Spectrum Awareness," Cognitive Radio Technology, Chapter 5, pp 174-177, Editor Fette, B., Newnes, 1st Edition, June 2006

Summary:

In Section 5.6 of Chapter 5, Marshall discusses the issue of spectrum efficiency that MIMO techniques bring to communication channels. While it is clear that MIMO brings value in high multipath conditions, this section of Chapter 5 recognizes that high spectrum efficiency is achieved when MIMO allows multiple channels of traffic to be delivered in the same spectrum bandwidth. It also shows that the radio must treat this trade as a resource allocation issue, since getting the spectrum efficiency of MIMO is at the cost of allocating additional radio transceiver resources that could be used for other links from the same radio node.

Quantified Benefit:

In the attached figures, Table 5.3 shows various tradeoffs between various MIMO topologies. Figure 5.5 shows these tradeoffs graphically. In these figures, it shows that MIMO can be used for a 5X improvement in spectrum efficiency if the RF resources are available at both ends of the link.

	Channels Used	Resources	Throughput	Throughput/ Resource	Throughput/ Channel
Pure 8x8 MIMO	1	8	5.04	0.63	5.04
6x6 MIMO	1	6	4.49	0.75	4.49
2 sets of 3x3 MIMO	2	6	5.68	0.95	2.84
2 sets of 4x4 MIMO	2	8	7.18	0.90	3.59
4 sets of 2x2 MIMO	4	8	7.80	0.98	1.95
8 Independent Channels	8	8	8.00	1.00	1.00

Table 5.3 Alternative approaches for mixed spectral and MIMO adaptation

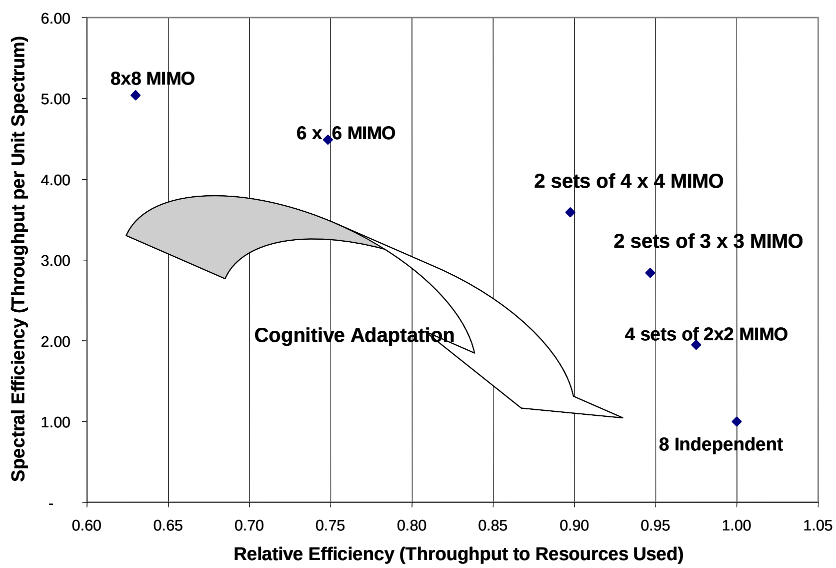


Figure 5.5 Adaptive trades from MIMO and spectrum usage

Considered Scenario:

Though not explicitly stated, the presumed situation is ad hoc terrestrial networking for defense applications. However, the derivation is valid for terrestrial communications in general.

Tags:

Spectrum efficiency, MIMO, RF Resource allocation

B.2.9 J. Neel, J Reed, A. MacKenzie., "Cognitive Radio Performance Analysis," Cognitive Radio Technology, Chapter 15, pp 563-567, Editor Fette, B., Newnes, 1st Edition, June 2006

Summary:

Section 15.6.1 of Chapter 15, Neel discusses the issue of adapting transmit power level of the nodes of a network. The section describes setting up a utility function to achieve a target SINR at the receiver of each network link. The objective was to show that if the utility function is designed correctly to account for interference that each transmitter produces at unintended receivers, which the system can converge to a stable power allocation for each node of the network.

Quantified Benefit:

In the attached figures, Fig. 15.25, and 15.26, Neel demonstrates that the power allocation equation (Eq. 15-30 below) can produce a stable power allocation for the network even in the presence of noise. It is seen that convergence is rapid, occurring within a practical number of iterations, and in this example in approximately eight iterations. [N.B. While the author does not state this, if the system converges to stability, then network overhead for managing power will be minimized - Fette].

Utility – An appropriate utility function for a target SINR (dB) algorithm is given by eq. 15-30 where $\hat{\gamma}_j$ is the SINR target of cognitive radio j.

$$u_j(p) = -\left(\hat{\gamma}_j - 10\log_{10}\left(g_{jj}p_j\right) + 10\log_{10}\left(\sum_{k\in N\setminus j} g_{kj}p_k + N_j\right)\right)^2$$ Eq. (15-1)

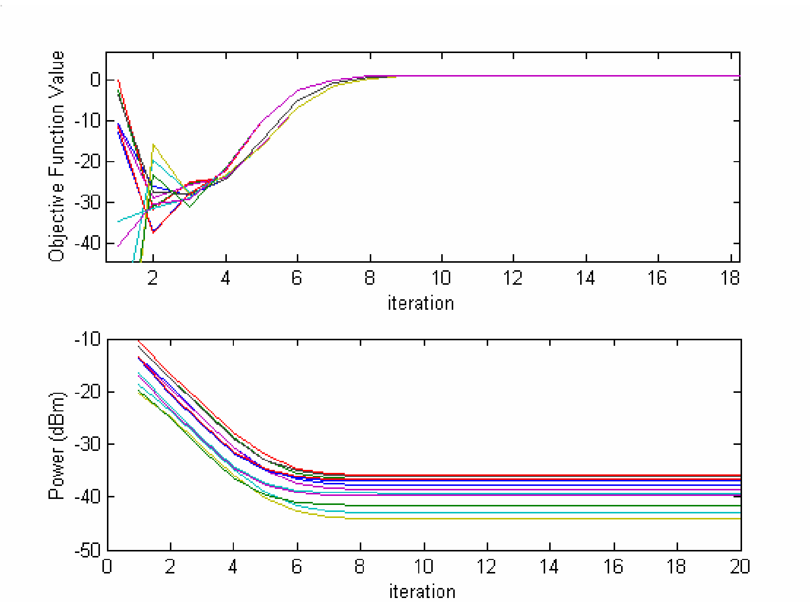


Figure 15-25 Deterministic simulation of an ad-hoc network of cognitive radios with synchronous adaptations and utility functions given by eqn. 15-30. The top graph plots the value of each radio's utility function versus the iteration; the lower plot shows the power levels for each radio versus iteration.

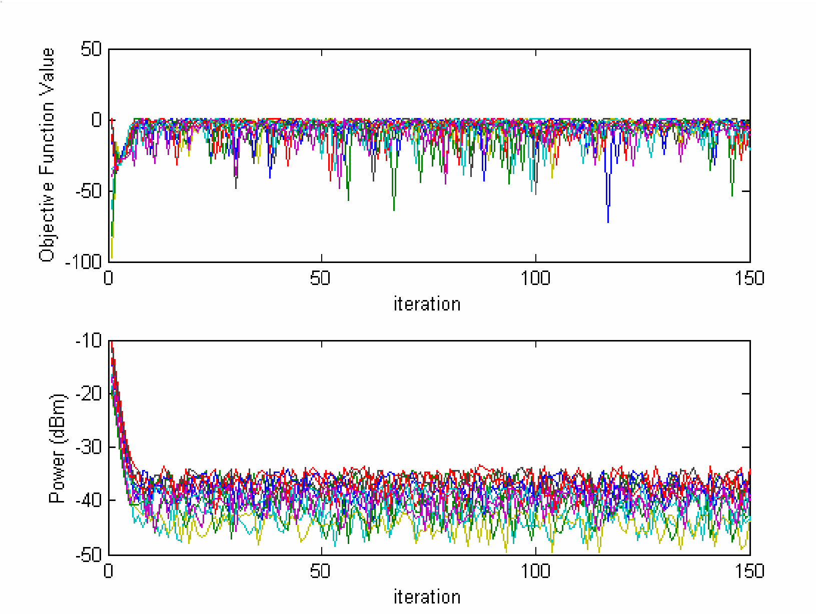


Figure 15-26 Simulation of an ad hoc network of cognitive radios with synchronous adaptations, utility functions given by eqn. 15-30, and stochastic channel models. The top graph plots the value of each radio's utility function versus the iteration; the lower plot shows the power levels for each radio versus iteration.

Considered Scenario:

The simulation is performed for two adjacent networks of six nodes each network communicating to the other through a common gateway node.

Tags:

RF Power allocation, Solution Stability

B.2.10 Niyato, D., Hossain, E., "Microeconomic Models for Dynamic Spectrum Management in Cognitive Radio Networks," Cognitive Wireless Communication Networks, Chapter 14, pp 396-408, Edited by Hossain & Bhargava, Springer, 2007

Summary:

Section 14.5 considers Cournot Game theory for the economic relationship between a spectrum primary user and a secondary user. In this game, multiple secondary users all purchase spectrum allocation for their purposes from a primary user. Each secondary user attempts to maximize his profit from the purchase and use of the secondary spectrum.

Quantified Benefit:

The equations show how to optimize profitability of the secondary users, assuming that all conditions fit the Cournot game model given in equation 14.32:

$$\frac{\partial \pi_i(Q)}{\partial Q_i} = r_i k_i - x - y\left(\sum_j Q_j\right)^{\mathrm{T}} - yQ_i \mathrm{T}\left(\sum_j Q_j\right)^{\mathrm{T}-1} \qquad \text{Eqn 14.32}$$

Where x, y, and T are nonnegative constants, T>1, and Q is the set of strategies for each secondary user. Ri x Ki x Qi is the revenue for secondary user i. It can be seen from Figure 14.11 that resale profit to the primary user of selling spectrum to secondary users is optimized at T=1.9 approximately.

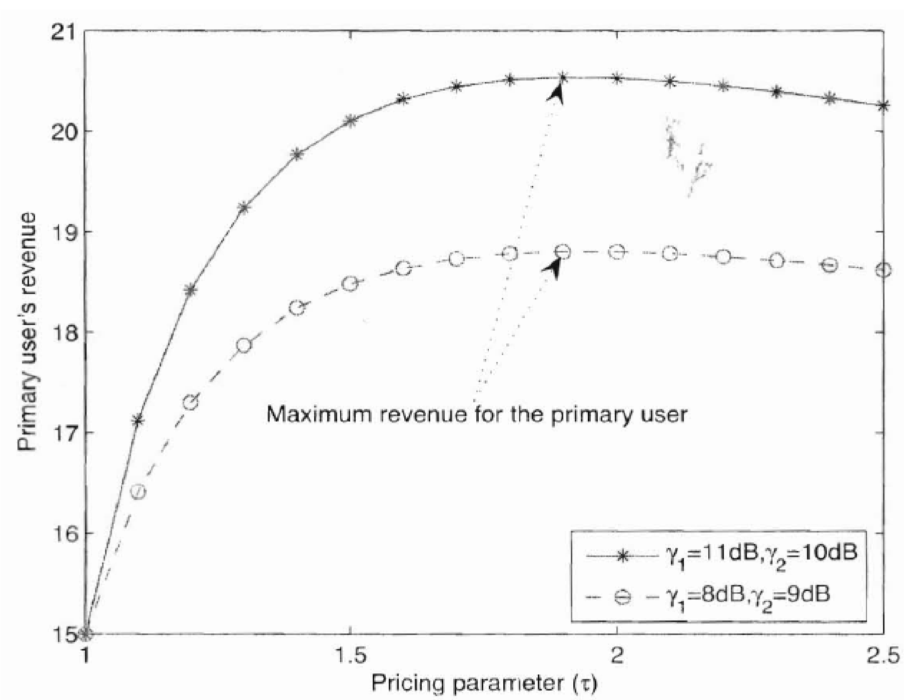


Figure 14.11 Profit of primary user under different pricing parameters

Considered Scenario:

Assumes that primary user negotiates all secondary spectrum sales, and that secondary users cannot negotiate with each other, i.e. assumes that the game is a Cournot game, that the primary user also derives value from use of spectrum, and that all users know the parameters of their economic model.

Tags:

Profitability, Secondary spectrum sales, Game theory

B.2.11 Niyato, D., Hossain, E., Cognitive Wireless Communication Networks, Chapter 14, pp 407-412, Edited by Hossain & Bhargava, Springer, 2007

Summary:

Section 14.6 considers Bertrand Game theory for the economic relationship between multiple primary users and multiple secondary users. For this condition to apply, it is necessary that the secondary user's radios must be able to adapt to the spectrum and other requirements to use spectrum from multiple primary users. The equation for profitability under these conditions is:

$$\pi_i(P) = P_i \frac{k_i^{(s)} - P_i - \Delta\left(k_j^{(s)} - P_j\right)}{1-\Delta} - \frac{d\lambda_i}{2(W_i - Q_i)^2 - 2\lambda_i(W_i - Q_i)}$$

The book defines these parameters as follows:

π_i is the profitability for player i

P is the price offered by primary user i

λ_i is the traffic arrival rate of the primary user

$k_i^{(p)}$ is the spectral efficiency of primary user i

Q_i is the portion of spectrum given to secondary users

Δ is the substitute – ability of the spectrum from various primary users by the secondary users (0 means they can switch freely, 1 means they can't switch)

W_i is the total spectrum of primary user i

This equation can be differentiated to solve for the Nash Equilibrium to find the optimum profit point.

Quantified Benefit:

Using the above equation and choosing some example coefficients of

$$\lambda_1 = 4,\ \gamma_1 = 15\,\text{dB},\ \gamma_2 = 18\,\text{dB},\ \Delta = 0.4,\ P_2 = 1$$

Then profitability of the primary user is shown in Figure 14.13.

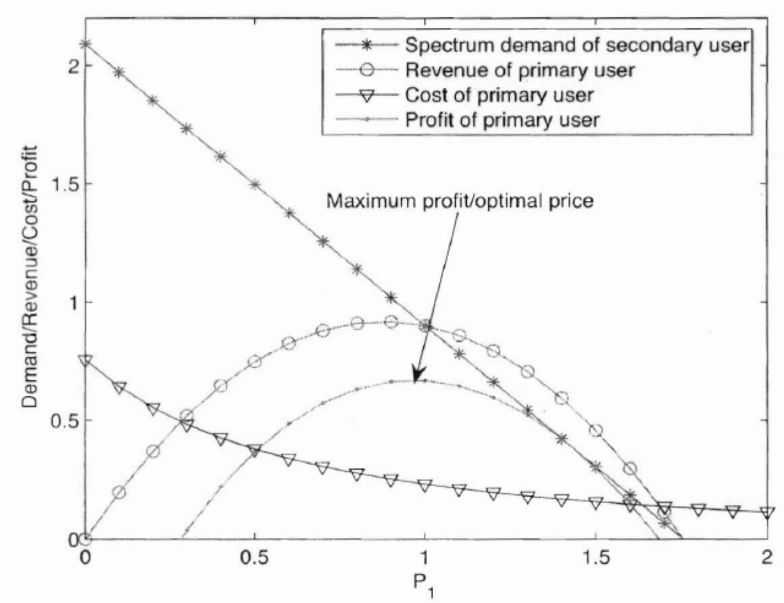


Figure 14.13 Demand function of the secondary user, and revenue, cost, and profit of the first primary user

Considered Scenario:

This model considers multiple primary users who sell spectrum to secondary users and secondary users are able to use spectrum from any of the primary spectrum sources. It also accounts for the SNR of the various channels as perceived by the secondary users.

Tags:

Profitability, Secondary spectrum sales, Game theory

B.2.12 Niyato, D., Hossain, E., "Microeconomic Models for Dynamic Spectrum Management in Cognitive Radio Networks," Cognitive Wireless Communication Networks, Chapter 14, pp 414-421, Edited by Hossain & Bhargava, Springer, 2007

Summary:

Section 14.7 considers Stackelberg Game theory for the economic relationship between a primary user and multiple secondary users. In this case, the primary user is a Wimax service selling subscriber service to WiFi nodes. In turn, the Wifi nodes are selling access to Wifi clients. In this game, the Wimax service profitability is maximized. They conclude that the price to all Wifi access points is the same regardless of their individual demand, but that as total demand rises, the price for access should increase.

Quantified Benefit:

Figure 14.19 shows the profit optimization of the WiMAX base station as it sells bandwidth to WiFi Access Point subscribers.

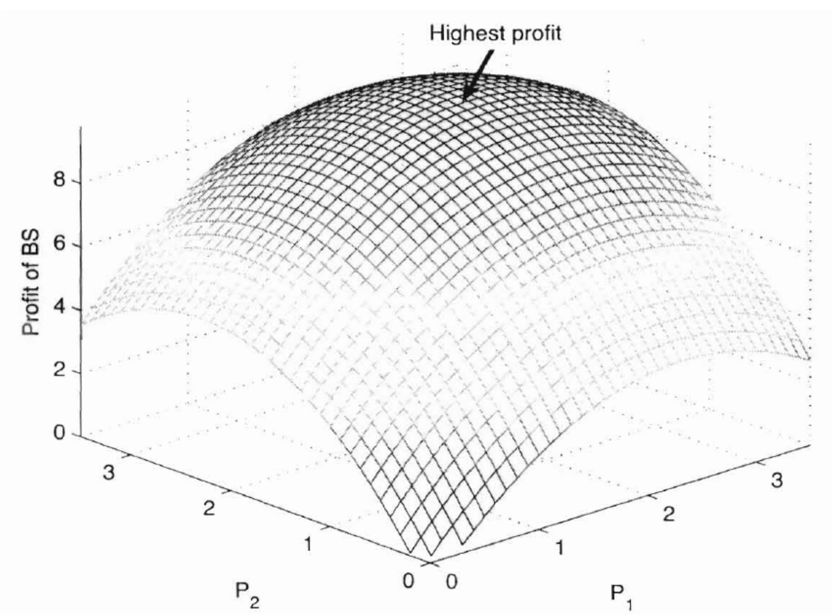


Figure 14.19 Profit function of the WiMAX BS.

Considered Scenario:

WiMAX base station selling bandwidth to WiFi access points, who in turn sell bandwidth to WiFi Clients.

Tags:

Profitability, Secondary spectrum sales, Game theory

B.2.13 Hultell, J., Zander, J., Markendahl, J., "Competition and Cooperation in Wireless Multi-Access Networks," Cognitive Wireless Networks, Chapter 6, pp 115 - 117, Edited by Fitzek & Katz, Springer, 2007

Summary:

This section of Chapter 6 gives a report about research done by the authors at Royal Institute of Technology. As such, it does not include the full configuration specification or derivation of analytic equations explaining the result. The authors arrange cooperation amongst cellular radio data service providers. They show that 90% of users experience from 70% to 180% increase in throughput when three cellular service providers cooperate.

Quantified Benefit:

The authors show that 90% of users experience from 70% to 180% increase in throughput when three cellular service providers cooperate.

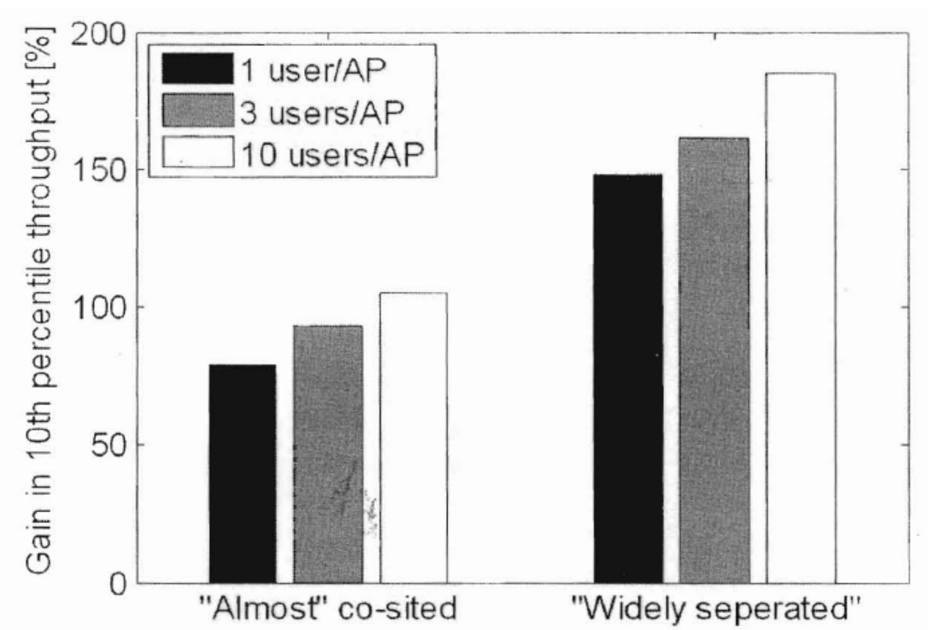


Figure 6.2: Gain in asymptotic user throughput for the 10th percentile ("coverage") for uplink transmission in a case where three operators cooperate.

Considered Scenario:

Three cellular radio service providers cooperate to provide data services, resulting in improved throughput for data users.

Tags:

Service delivery cooperation

B.2.14 Hultell, J., Zander, J., Markendahl, J., Cognitive Wireless Networks, Chapter 6, pp 115 - 117, Edited by Fitzek & Katz, Springer, 2007

Summary:

This section of Chapter 6 gives a report about research done by the authors at Royal Institute of Technology. As such, it does not include the full configuration specification or derivation of analytic equations explaining the result. The authors arrange cooperation amongst WLAN 802.11 access points. They show that users experience 65% increase in throughput when access points cooperate. Improvements are due to diversity and load share balancing.

Quantified Benefit:

The authors arrange cooperation amongst WLAN 802.11 access points. They show that users experience 65% increase in throughput when access points cooperate. Improvements are due to diversity and load share balancing.

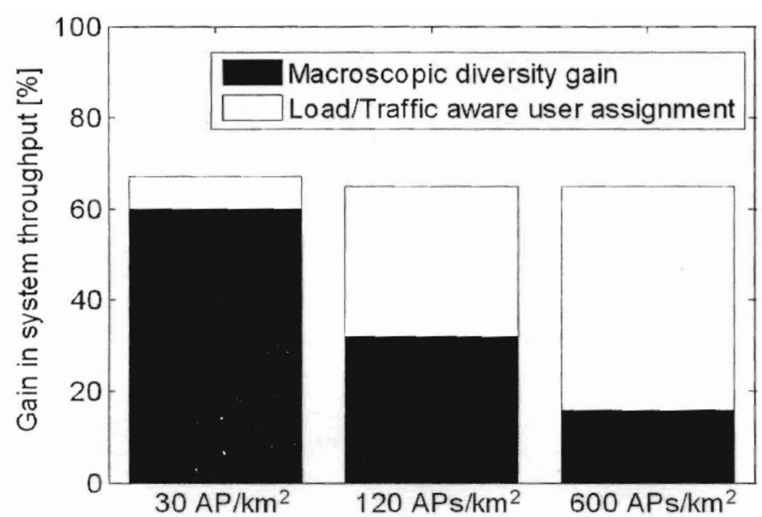


Figure 6.3 Gain in asymptotic system throughput for a geographically limited traffic hot spot where two WLAN (IEEE 802.11a) networks cooperate. As the combined system is noise limited, additional gains can be realized by load aware user assignment.

Considered Scenario:

The authors arrange cooperation amongst WLAN 802.11 access points.

Tags:

Service delivery cooperation

B.2.15 Hultell, J., Zander, J., Markendahl, J., "Competition and Cooperation in Wireless Multi-Access Networks," Cognitive Wireless Networks, Chapter 6, pp 122-123, Edited by Fitzek & Katz, Springer, 2007

Summary:

This section of Chapter 6 discusses automating the financial transactions to access spectrum. In this model, the service source holds a periodic auction (period is set to be reasonable period length but to allow changes in rate for time of day, for example for one hour), in which clients bid for access. The access price is in Price per MByte. The service provider sets a minimum acceptable price. The service provider allocates the available bandwidth ratio to the acceptable bid prices received, known as a proportional fair divisible auction. Thus, clients who pay a higher price experience lower transmission time (and thus delay and battery impact).

Quantified Benefit:

In Figure 6.5 below the author illustrates price demand elasticity and acceptance probability of the service provider. In Figure 6.6 below, the author illustrates sequential auctions in which a user raises his price per MB in order to accomplish lower delay.

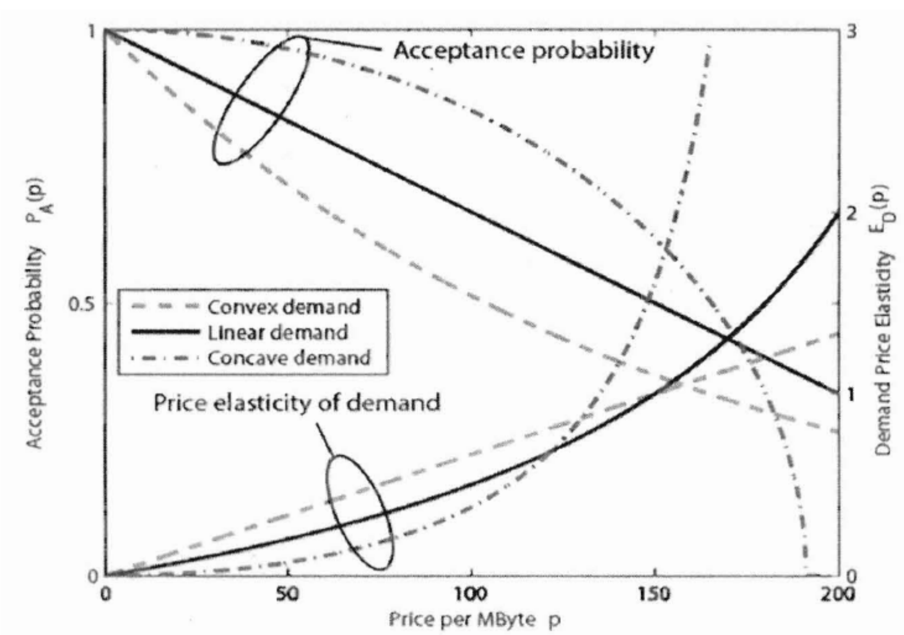


Figure 6.5 Illustration of the studied normalized demand functions (acceptance probabilities). In the studied example $\beta = \frac{1}{150}$.

This reviewer believes that the figure is incorrectly labeled, in that the rising curve vs. price is the probability of acceptance, and that demand falls with rising price.

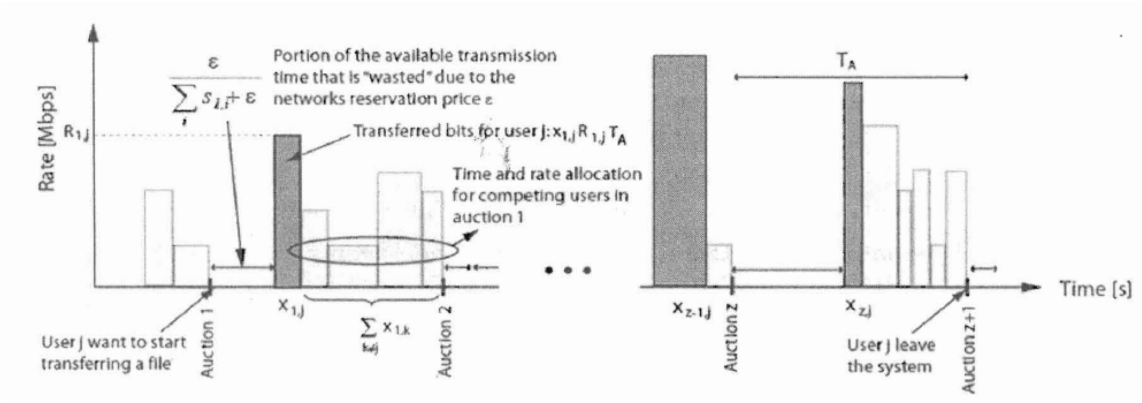


Figure 6.6 Illustration of the auction procedure associated with a file transfer. In this example, trade agent j initiates a file transfer in auction. In auction I user j is allocated a portion $x_{i,j}$ of the total available transmission time T_a and depending on its current peak data rate Ri,j the trade-agent will be able to transfer a total of $x_{i,j}R_{i,j}T_a$ bits. After participating in Z auctions the file transfer is completed and consequently the file transfer delay becomes $T_j=ZT_a$ in this case.

Considered Scenario:

Shows automated financial transactions to access spectrum.

Tags:

Service delivery auction

B.3 DySPAN 2005

B.3.1 Zheng, H. and Lili Cao, "Device-centric spectrum management," DySPAN 2005, Nov. 8-11, 2005. Paper # GS2-2.

Summary:

The paper proposes a device centric spectrum management scheme for cognitive radios where users observe the interference usage of their neighbors and act independently according to some preset spectrum access rules. The specified spectrum access rules tradeoff implementation complexity, communication costs (network overhead), fairness of resource allocation and spectrum utilization to varying degrees. Extensive network simulations and theoretical analysis

are used to quantify the benefit of the proposed scheme and compare the different allocation rules. It is shown that the rule-based approach considerably reduces communication costs when compared to collaborative approaches (which offer near-optimal allocation efficiency) while still providing good performance. Systems that implement the rule-based schemes are also proven to converge in a finite number of iterations.

Quantified Benefit:

The paper shows that network utilization and fairness, comparable to that of collaborative schemes is achieved in the presence of primary users. Comparison figures are reproduced below:

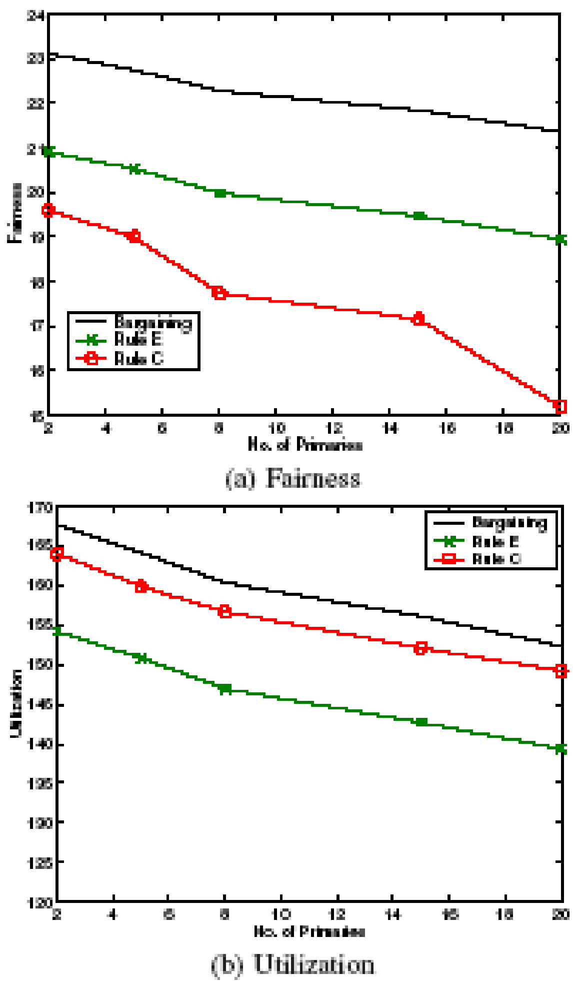


Fig. 11. Utilization and Fairness comparison of different rules assuming 20 channels, 40 secondary users and 20 primary users.

The figures show the performance of 40 secondary users with 20 channels in the presence of varying number of primary users. Bargaining refers to a collaborative spectrum access that involves a large communication cost in the network. Rule-E involves no communication cost and in a CSMA-based approach. Rule-C requires channel usage information from neighbors of a user and involves a slightly higher communication cost than Rule-E. It is seen that open spectrum access offers sufficient benefit (enables secondary users to access the spectrum). In addition, the proposed approach offers gains that are sufficiently close to a fully collaborative system without the involved communication costs.

Considered Scenario:

The simulations of the scheme are set in a mobile ad hoc network where secondary users are randomly placed on a 100x100m area. Mobility is simulated by assuming that users move to different randomly selected location at each time instant. Primary users are also randomly placed in this network. Users (primary and secondary) of the same channel conflict if they are within a distance of 20m. Secondary users do not use a channel if they can conflict with a primary user. Performance is averaged over 300 network topologies, each with 200 time instances. If β_n is user *n*'s throughput over its selected channels, the total system throughput is assumed to be $\sum_n \beta_n$ and the level of proportional fairness is assumed to be $\sum_n \log \beta_n$.

Tags:

Spectrum management/ allocation, Communication costs (network overhead)

B.3.2 S. Sankaranarayanan, P. Papadimitratos, and A. Mishra "A bandwidth sharing approach to improve licensed spectrum utilization," DySPAN 2005, Nov. 8-11, 2005. Paper # TT4-6.

Summary:

The paper develops an Ad hoc Secondary MAC (AS-MAC) protocol that allows secondary systems to operate in a non-intrusive manner with a primary GSM cellular system. The secondary system is assumed a multi-hop system and is constrained only to operate in bandwidth unutilized by the primary system, cause no performance degradation to the primary system and not exchange any signaling information with the primary system. The proposed MAC scheme senses the environment and maintains a picture of the primary spectrum usage. A control channel is then used to coordinate the use of unused spectrum among the secondary users. Via simulations, it is shown that the proposed MAC scheme allows the secondary system to utilize the unused spectrum efficiently. Further, the multi-hop network structure of the secondary system also allows for spatial reuse of the unused spectrum.

Quantified Benefit:

The following figures (reproduced from the paper) illustrate the performance benefit provided by the proposed MAC scheme for secondary users.

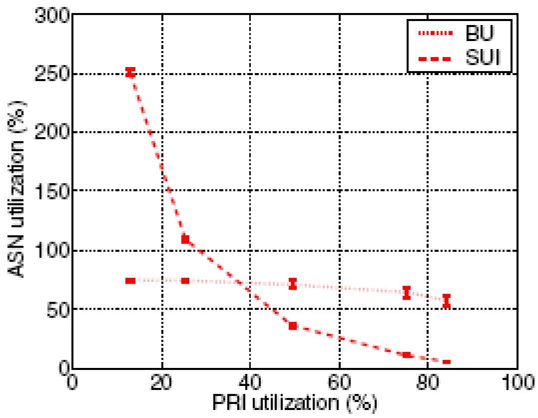


Figure 9. ***20*-node single-hop *ASN*: Utilization Performance as a function of *PRI* utilization (load).**

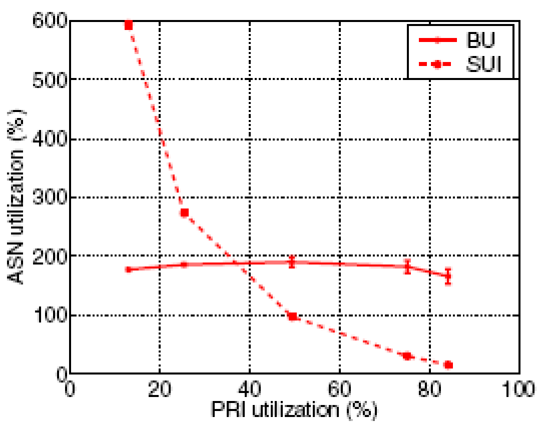


Figure 10. ***10-by-10* grid *ASN*: Utilization Performance as a function of *PRI* utilization (load).**

In the figures, the metric BU denotes "Bandwidth Utilization" or the fraction of the number of slots utilized by secondary users over the number of slots left unused by primary users. The metric SUI denotes "Spectrum Utilization Improvement". SUI= $(PRI\_ASN_U - PRI_U)/PRI_U$, where PRI_U is the percentage of slots utilized by primary user alone and PRI_ASN_U is the percentage of slots utilized when both primary and secondary systems are deployed together. In addition, ASN denotes Ad hoc Secondary Nodes and PRI denotes primary.

It is seen that a single-hop ad hoc secondary network utilizes 75% and multi-hop networks can utilize up to 180% (due to spatial reuse) of bandwidth unused by the primary system.

Considered Scenario:

The two secondary networks scenarios considered are as follows:

1) a fully connected network of 20 nodes

2) a random topology with 100 nodes having uniform random locations within a 1000m by 1000m square area.

The nodes are static (no mobility). The nominal transmission and sensing ranges are 250m and 625m respectively, with a 10dB SINR threshold for successful reception. Nodes are equipped with one transceiver and a sensing module. The margin to mitigate interference to mobiles is set at 40μs. eight primary GSM channels in use within the cell, with one of them fixed as the control traffic channel for the secondary system and the remaining seven channels are used for data traffic. The PRI traffic (voice calls) occupy one time slot every frame on the allocated uplink and the downlink.

Tags:

Spectrum efficiency, Multi-hop ad hoc secondary networks

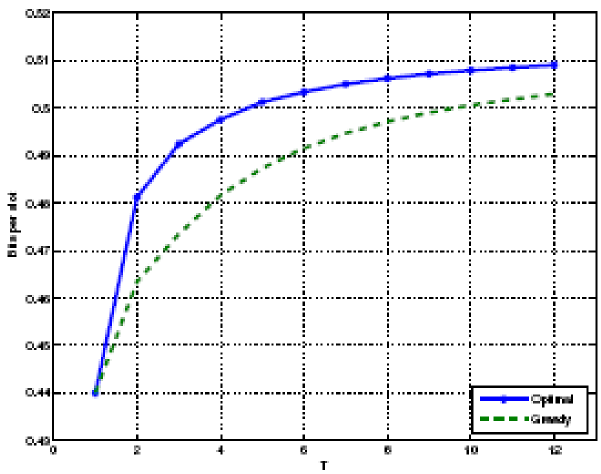
B.3.3 Zhao, Q.; Tong, L. and Swami, A. "Decentralized cognitive MAC for dynamic spectrum access," DySPAN 2005, Nov. 8-11, 2005. Paper # TT3-6.

Summary:

The paper proposes a dynamic spectrum access protocol based on a framework of Partially Observable Markov Decision Process (POMDP) where a user is able to sense a subset of the available channels. The framework is based on three components: the channel occupancy model used to predict the spectrum usage of primary and other secondary users, the performance metric (which is the average throughput in this paper) and decision theoretic model to choose which channel is to be sensed and accessed by the secondary user. Based on the framework, optimal and suboptimal decentralized strategies for accessing spectrum to maximize overall spectrum throughput are derived.

Quantified Benefit:

The performance of the optimal and sub-optimal greedy schemes is analyzed in the paper. One of the performance graphs is reproduced here. In the analysis, misidentification of spectrum opportunities is assumed to lead to collisions. The figure shows the achievable transmission rate with respect to time. It can be seen that due to the cognitive nature of the Markov scheme, the performance improves over time.



In addition, as compared to not sharing the spectrum, the proposed scheme is seen to allow a much better utilization of the spectrum. However, the caveat is that the impact of misidentification of spectrum by the secondary users (leading to collisions with the primary user) on the primary system is not taken in to consideration.

Tags:

Dynamic spectrum access, Spectrum efficiency

B.3.4 Ma, L Han, X.; Shen, C.-C., "Dynamic open spectrum sharing MAC protocol for wireless ad hoc networks," DySPAN 2005, Nov. 8-11, 2005. Paper # TT3-4.

Summary:

This paper describes a dynamic spectrum sharing MAC protocol that allows users to access arbitrary spectrum subject to spectrum availability. The protocol does not require any new centralized infrastructure and allows users to coexist with legacy users in addition to avoiding the hidden and exposed terminal issues. The protocol involves the setup of three operational bands: the control channel that allows users to negotiate/communicate their transmission frequencies, the actual data transmission channel and a busy tone band that allows different users to find occupied bands and thus eliminate hidden/exposed node issues. The size of the three bands and data rates vary depending on the availability of spectrum (unused by primary users) and channel conditions. The designed protocol can be used for both unicast and multicast communication.

Quantified Benefit:

The performance of the proposed MAC protocol is compared to that of a scheme (called the best static spectrum allocation scheme) that always uses the entire spectrum (irrespective of the primary spectrum usage). The performance comparison figure is reproduced below:

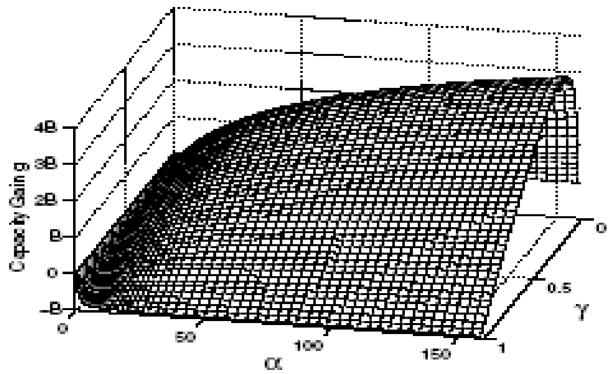


Fig. 5. Gain in achievable channel capacity of DOSS over the best static spectrum allocation scheme.

Here, γ is the portion of spectrum used by the primary user and α is the signal to noise ratio of the channel. The figure compares the capacity gain of a single secondary link that implements the DOSS protocol (and hence uses $1-\gamma$ fraction of the spectrum) as compared to the best-static allocation protocol (that uses the entire available spectrum). It is seen that the proposed protocol always does better than the best-static allocation protocol except at very low SNR or when the primary spectrum allocation is close to 1(100%). This is due to the fact that even though the proposed scheme only uses a fraction of the spectrum, it is able to achieve much higher SNR than the best static allocation scheme.

In addition, as compared to not sharing the spectrum, the proposed scheme allows much better utilization of the spectrum.

Tags:

Dynamic spectrum access, Spectrum efficiency

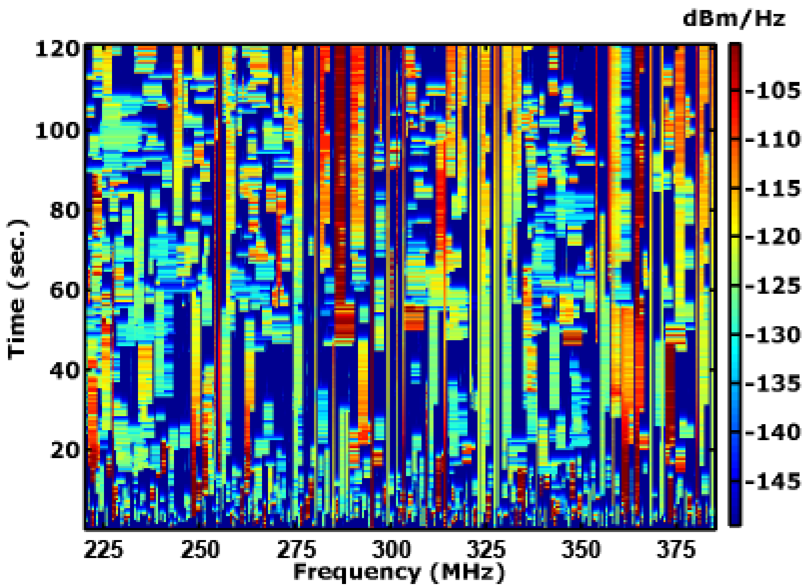
B.3.5 Seidel, S. and Breinig, R "Autonomous dynamic spectrum access system behavior and performance," DySPAN 2005, Nov. 8-11, 2005. Paper # TT3-1.

Summary:

The paper discusses the behavior of an Autonomous dynamic spectrum access (ADSA) system where nodes continually monitors local spectrum usage and adapt their spectrum according to the perceived usage as well as according to regulatory policies. The nodes use heteromorphic waveforms that allow discontiguous spectrum access by being able to aggregate multiple narrow bandwidth spectrum holes into a single wideband logical channel. The paper describes general characteristics of the proposed system but does not disclose any specific details.

Quantified Benefit:

The following figure (reproduced below) shows the spectrum used by ADSA nodes in time and frequency. The color indicates the power-level: red represents stronger signals and deep blue represents empty spectrum. It is shown that around 70% of the spectrum is used. As compared, the paper mentions, that for non-ADSA nodes spectrum usage is around 2-10%.



Considered Scenario:

The performance of the ADSA scheme is analyzed by simulating a network made up of a combination of mesh and infrastructure nodes in MATLAB. Nodes use rendezvous messages to initiate network formation and communicate frequencies to neighboring nodes. Nodes continually sense the dynamic local spectrum utilization conditions and autonomously adapt their selected frequencies and operating bandwidth to avoid causing interference to detected spectrum users. No other details of the actual simulated network are provided.

Tags:

Dynamic spectrum allocation, Spectrum efficiency

B.3.6 Zekavat, S.A. and Li, X, "User-central wireless system: ultimate dynamic channel allocation," DySPAN 2005, Nov. 8-11, 2005. Paper # TT1-2.

Summary:

The paper proposes and analyzes a user-centric wireless architecture for dynamic channel allocation (DCA) in cognitive radios (CRs). Current wireless systems are vendor-centric, where users subscribe to a particular vendor and use services provided by that vendor at all times. They are also restricted to the spectrum provided to that vendor. As opposed to this configuration, in a user-centric system, a user can choose an optimum vendor at any time instant and geographical location. The CRs choose the optimum vendor via a cost function based on the following parameters:

- channel availability,
- congestion rate,
- the vendor quality of service in terms of bit-error rate (BER) performance,
- cost per second, and
- signal power

The paper describes the system architecture and discusses the performance benefits of the proposed architecture.

Quantified Benefit:

The performance of the proposed system is analyzed in terms of the following metrics:

- Call blocking rate
- Spectrum efficiency
- Revenue of vendors

The performance table with these three metrics is reproduced below:

TABLE 1. UTILITY PERFORMANCE OF VENDOR-CENTRAL VS USER-CENTRAL.

Call arrival rate (Three vendors)	Average call blocking rate		Average spectrum efficiency		Average revenue ($/minute)	
	Vendor-central	User-central	Vendor-central	User-central	Vendor-central	User-central
vendor central $\lambda_1 = \lambda_2 = \lambda_3$ user central $\lambda_{\Sigma} = \lambda_1 + \lambda_2 + \lambda_3 = 3\lambda_1$	0.2252	0.2087	0.8323	0.841[illegible]	27.341[illegible]	2[illegible].0522
vendor central $\lambda_2 = 1.5\lambda_1 = 1.8\lambda_1$ user central $\lambda_{\Sigma} = \lambda_1 + \lambda_2 + \lambda_3 = (1+1.5+1.8)\lambda_1$	0.2545	0.215[illegible]	0.8119	0.8444	2[illegible].655[illegible]	2[illegible].1711
vendor central $\lambda_2 = 1.67\lambda_1 = 2.5\lambda_1$ user central $\lambda_{\Sigma} = \lambda_1 + \lambda_2 + \lambda_3 = (1+1.67+2.5)\lambda_1$	0.2880	0.2217	0.7859	0.847[illegible]	2[illegible].783[illegible]	2[illegible].2520

It is seen that the user-centric CR system performs better than a vendor-centric system w.r.t. all the analyzed metrics. Compared to a vendor-centric system, blocking rate, spectrum-efficiency and revenue of user-centric system are improved by 23%, 8% and 10% respectively.

Considered Scenario:

The following are assumptions used in the system simulation

- Three vendors (each owns 32 channels) provide their service to the same area;

- The vendor is available if the number of its idle channels is more than zero;
- The cost of connection per vendor is $0.35/channel/minute;
- Vendors have the same signal power and BER performance;
- The possibility of becoming over-loaded within period T for a vendor is ignored;
- Call holding time is exponentially distributed with the mean of $= \propto / 1$ 180 seconds;
- Three call generators create calls using homogenous Poisson process with rates in the range of $= \lfloor$ 50-3600 calls/hour for different vendors in vendor-central systems;
- The total call arrival rate is the same for user-centric and vendor-centric systems

Tags:

Spectrum efficiency, Network revenue

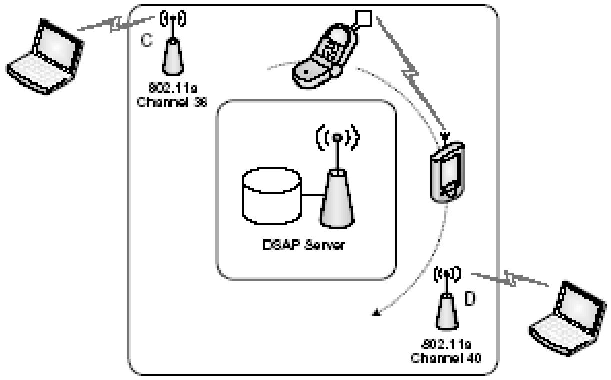
B.3.7 V. Brik, E. Rozner, S. Banerjee, and P. Bahl "DSAP: a protocol for coordinated spectrum access," DySPAN 2005, Nov. 8-11, 2005. Paper # SP1-9.

Summary:

The paper proposes a centralized spectrum management protocol, Dynamic Spectrum Access Protocol (DSAP) that ensures efficient spectrum management in unlicensed frequency bands. The centralized design is deemed feasible in home and office environments. The protocol is based on a centralized entity called the DSAP server that provides an efficient distribution of spectrum leases to users (DSAP clients) in its network by negotiating between the users. The DSAP server bases its decisions on the RadioMap, a database that holds information about all DSAP clients (including geographical locations) and channel conditions throughout the network, and an administrative policy database. The paper only provides a generalized sketch of the protocol and does not delve in to specific implementation details. However, the paper does provide performance results from experiments run on a wireless test-bed.

Considered Scenario:

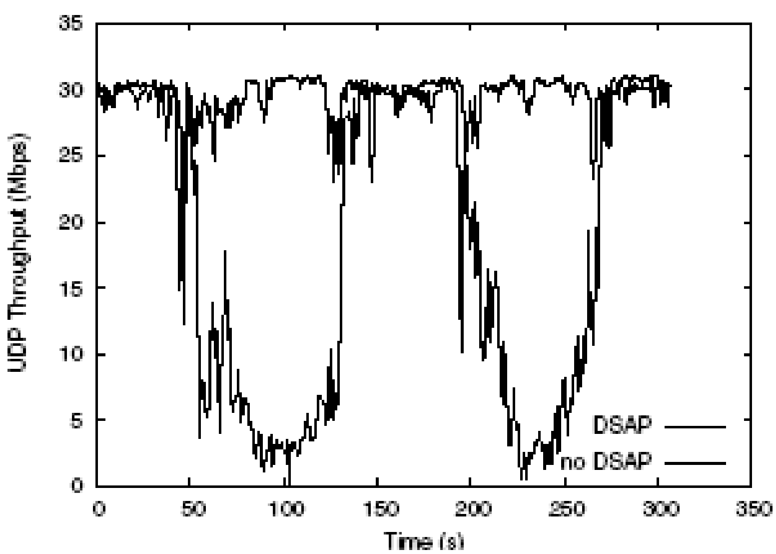
Experiments are run on a wireless test-bed composed of five machines running Gentoo Linux 2005.0 with wireless interfaces based on the Atheros AR5212 chipset. One interface on the clients was dedicated exclusively for communication with the DSAP server. The ability of the protocol to handle varying channel conditions is demonstrated via the following experiment (also illustrated in the below figure):



Nodes *A* and *B* are engaged in a UDP transfer on 802.11a channel 40. They continuously move around a square corridor at the rate of 0.75 m/s, always staying about six feet from each other. Nodes *C* and *D* sit at the opposite corners of the corridor and send UDP data to their neighbors on (non-overlapping) channels 36 and 40, respectively. *C* and *D* operate with reduced power (0 dBm) and only interfere in areas of their line-of-sight (LOS).

Quantified Benefit:

The following figure shows the performance improvement achieved by nodes A and B when DSAP is used. The performance improvement is achieved because DSAP switches nodes A and B to channel 36 when in D's LOS.



Tags:

Centralized spectrum management, Quality of service, Spectrum efficiency

B.3.8 A. Tonmukayakul and M. B H. Weiss, "An agent-based model for secondary use of radio spectrum," DySPAN 2005, Nov. 8-11, 2005. Paper # PT2-2.

Summary

The paper uses agent-based computational economics to model the interaction between transaction costs (associated with leasing costs of the spectrum or other market factors) and the potential interference in the system. The study develops aggregate outcomes and norms of behavior that are sustained over time. The model consists of two types of economic agents - spectrum consumers and spectrum access providers. Each agent has a utility function that determines the result of a spectrum transaction. Agents are assumed to have limited information about other agents and are assumed to adapt their actions by observing and learning (reinforcement learning is used as an example in the paper) from the outcomes of current transactions.

The paper shows that secondary usage of spectrum (where consumers/users have partial ownership of the spectrum) is favored in a wider range of scenarios than completely unlicensed spectrum usage or exclusive ownership of the spectrum. Also, when secondary use of spectrum is not allowed, except for the limiting scenarios with a very large number of users or large coverage regions, unlicensed use of the spectrum is preferred compared to exclusive access of the spectrum (costs to exclusive use of spectrum is more than the cost of interference to a user).

Quantified Benefit

The study shows that as the maximum coverage required by spectrum users increases, secondary use of the spectrum (where users have a varying degree of control over the spectrum) becomes more favorable than unlicensed use (where users have no degree of control over the spectrum) of the spectrum. The following two figures reproduced from the paper illustrate this.

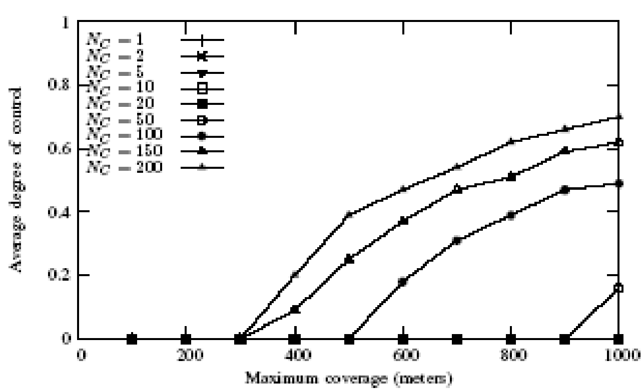


Fig. 4. Without secondary use: Average degree of control vs. Maximum coverage (for $M_1 = 1$ and $\alpha_u = 100$).

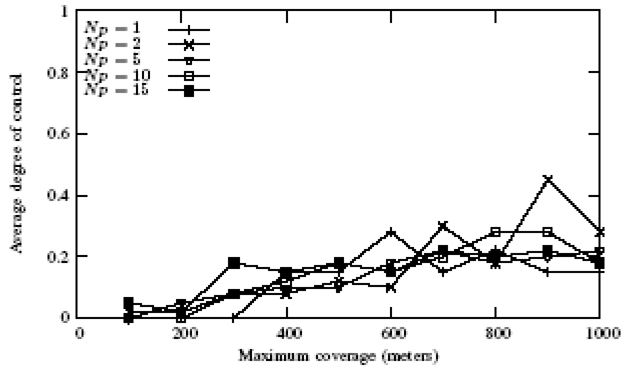


Fig. 8. With secondary use: Average degree of control vs. Maximum coverage (for $M_1 = 1$, $N_C = 10$ and $\alpha_u = 100$).

In the figures, M_1 is the number of base stations, α_u is the QOS sensitivity of consumer, N_c is the number of consumer agents and N_p is the number of provider agents.

The first figure shows average degree of control when secondary use of the spectrum is not allowed. It is seen that only when the number of spectrum users (N_c) becomes large and when the required coverage is large, exclusive use of the spectrum becomes feasible as compared to unlicensed use of the spectrum (large interference costs start to offset the large cost in obtaining exclusive access to the spectrum). However, when secondary usage of spectrum is allowed (the second figure), even with a small number of users and smaller required coverage areas, secondary use of the spectrum is preferred.

Considered Scenario

Consumer agents are randomly distributed in the region and their positions are varied in each run of the algorithm. Receivers for each agent are located within the maximum coverage area. The transmit power for each user is calculated to satisfy receiver's SNR requirement. When using unlicensed spectrum, consumer agents randomly select a frequency channel in every time step. The cost of using unlicensed spectrum is zero. If a consumer agent selects secondary use, they submit a spectrum access request to every provider agent and the agent with the lowest cost is selected. When using an exclusive license, the consumer pays the license cost and the agent (or choice of spectrum) cannot be changed until the license expires. Further, with an exclusive license, an interference free environment is provided to the consumer.

Tags:

Secondary use of the spectrum, Transaction costs for spectrum usage

B.4 DySPAN 2007

B.4.1 Kazunori Akabane, Hiroyuki Shiba, Munehiro Matsui, and Kazuhiro Uehara, "An Autonomous Adaptive Base Station that Supports Multiple Wireless Network Systems," DySPAN 2007.

Summary:

It is identified in the paper that base stations need to be more efficient and effective in using frequency spectrum and can cooperate more efficiently if they are able to use multiple channels of many wireless systems simultaneously. An autonomous adaptive base station (AABS), that adapts to various wireless systems 9similar to the way a software defined radio base station works), is proposed. The AABS autonomously selects and uses the most suitable wireless system based on user traffic and its own hardware resources. An AABS prototype is deployed to evaluate the performance of the proposed scheme. It is found that certain benefits can be achieved by using this approach.

Scenario:

The AABS prototype adapts to the Japanese personal handy-phone system (PHS) and the IEEE 802.11a wireless LAN (WLAN) system and has hardware resource capacity for four PHS CSs and WLAN APs. It monitors traffic, balances load, and controls radio parts, as its major functions. AABS implements an original resource control protocol between itself and its clients to provide a band guarantee service in the WLAN system. Band guarantee service ensures necessary throughput for particular applications, such as streaming applications.

Experimental conditions of the AABS evaluation model are summarized in Table I. Each client is connected with the traffic generator by cable, starting and ending streaming service based on instructions from the traffic generator. AABS's efficiency is evaluated by using service failure ratio and operating ratio with a fixed mean service birth rate λ and with a changing ratio of PHS and WLAN clients as our criteria.

TABLE I. EXPERIMENTAL CONDITIONS

Wireless system	PHS (3ch / CS) WLAN (IEEE 802.11a)
Resource	4
Service birth rate	Poisson distribution, $\lambda = 0.013$
Service time	Exponential distribution Mean service time = 900 [s]
Service type	Streaming service PHS : 1ch / service WLAN : 5 [Mbit/s] / service
Total clients	16
Propagation environment	Indoor, static

Quantified Benefits:

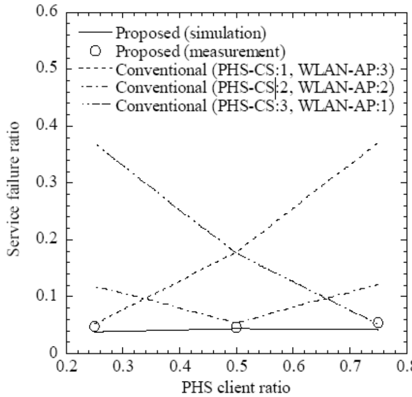


Figure 6. Relationship of PHS client and service failure ratios.

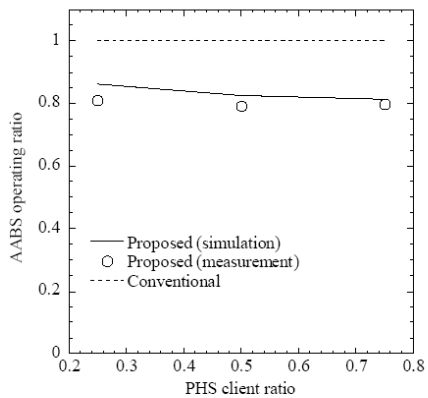


Figure 7. Relationship of PHS client and AABS operating ratios.

Using this technique, a reduction in the service failure ratio and efficient hardware resource usage is achieved. The number of PHS clients increases as the value of the PHS client ratio increases. The conventional method fixes the function and number of PHS CSs and WLAN APs and always operates them all, as shown in Figs. 6 and 7. The measured results for the prototype agree well with the simulated results. Moreover, AABS was able to support multi-link communication. It is also confirmed that AABS stably carried out high-speed communication and highly reliable communication as designed.

B.4.2 Shamik Sengupta and Mainak Chatterjee, Samrat Ganguly, "An economic framework for spectrum allocation and service pricing with competitive wireless service providers" DySPAN 2007

Summary:

A winner determining sealed-bid knapsack auction mechanism that dynamically allocates spectrum to the WSPs based on their bids is presented. Game theory is used to capture the conflict of interest between WSPs and end users, both of whom try to maximize their respective net utilities. It is shown that even in such a greedy and non-cooperative behavioral game model, it is in the best interest of the WSPs to adhere to a price threshold that is a consequence of price equilibrium in an oligopoly situation. Simulation results have shown that the proposed auction entices the WSPs to participate in the auction, makes optimal use of the common spectrum pool, and avoids collusion among WSPs. Moreover, numerical results demonstrate how pricing can be used as an effective tool for providing incentives to the WSPs to upgrade their network resources and offer better services.

Scenario:

Total amount of spectrum in coordinated access band (CAB) is assumed as 100 units, whereas the minimum and maximum amount of spectrum requested by each bidder is 11 and 50 units respectively. Min. bid per unit of spectrum is considered as 25 units.

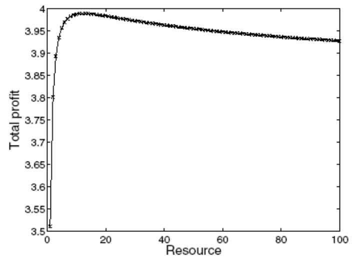


Fig. 10. Total profit of a provider vs. resource (with number of users fixed)

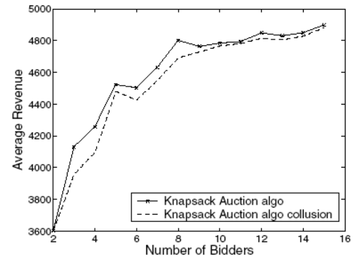


Fig. 6. Avg Revenue with and without collusion

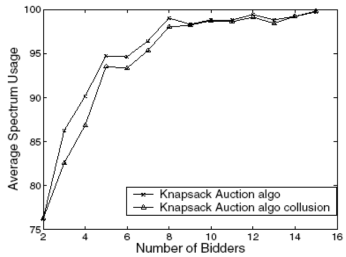


Fig. 7. Avg Usage with and without collusion

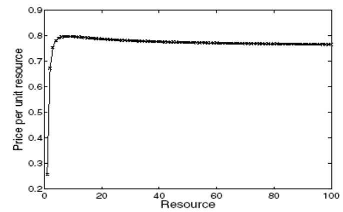


Fig. 11. Price per unit of resource vs. resource (with increasing number of users such that the ratio of a_{Ij} and C_j is fixed)

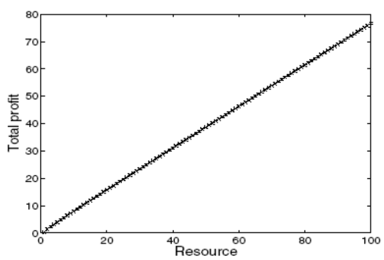


Fig. 12. Total profit of a provider vs. resource (with increasing number of users such that the ratio of a_{Ij} and C_j is fixed)

Quantified Benefits:

Figure six shows that the average revenue generated by spectrum broker with increase in number of bidders both in presence and absence of collusion. The average revenue reduces slightly at the beginning due to the presence of collusion. However, the effect of collusion decreases with the increase in the number of bidders and the revenue generated even in the presence of collusion reaches almost the same value as that of without collusion. Figure 7 presents the usage of spectrum in the presence and absence of collusion. Figure 10 shows the total profit of the provider. It can be seen that with the number of users fixed, the total profit of the provider increases until a certain resource and then decreases.

Figure 11 presents the price per unit of resource. It is shown that as the initial number of users is very low, increasing resource necessitates an initial increase in price per unit of resource. However, as the number of users increase, price per unit resource decreases providing incentive for the users. In Figure 12, the total profit of the provider is presented when the number of users increases proportionally with the resources. It is seen that the total profit is always increasing which presents a better incentive for the providers than the case with fixed number of users.

B.4.3 Timothy X Brown, Douglas C. Sicker, "Can Cognitive Radio Support Broadband Wireless Access?" DySPAN 07

Summary:

This paper presents a general analysis framework for investigating the spectrum and cost issues associated with building out a broadband wireless access network. It discusses the conditions under which cognitive radios could be viable to provide broadband wireless access (BWA) in the licensed TV bands. Demographic (urban, rural) and licensing (unlicensed, non-exclusive licensed, exclusive licensed) dimensions are explored. A general BWA efficiency and economic model for this analysis and derived parameters corresponding to each of these regimes is developed. The results indicate that in rural areas, an unlicensed model is viable and the additional spectrum would be useful despite existing unlicensed spectrum. It is also found that in the densest urban areas no model is viable. This is not simply because there is less unused spectrum in urban areas. Urban area cognitive radios are constrained to short ranges and many broadband alternatives already exist. The result is sufficient unlicensed spectrum or the cost per subscriber is prohibitive. These results are based on one set of input variables for the model. The model can be easily manipulated to account for other scenarios or different assumptions. These results provide useful input for a variety of spectrum policy issues.

Scenario:

TABLE 5
REGIME INDEPENDENT INPUT VARIABLES USED IN THE MODEL.

Variable	Value	Description
$e_{modulation}$	2.5 (bps/Hz)	Modulation efficiency
e_{reuse}	0.33	Frequency reuse factor
$e_{protocol}$	0.30	Protocol efficiency factor
$e_{loading}$	0.50	Network loading factor
k_f	\$5,000	Fixed cost of an AP
k_{om}	\$4,000	Annual operations and maintenance cost per AP
d	20%	Discount factor for NPV calculation
B_U	1Mbps	Minimum data bandwidth per user
$u_{traffic}$	100kbps	Traffic rate of active user in busy hour
u_{active}	0.50	Fraction of users active in busy hour
u_{takeup}	0.25	Take up fraction for broadband service

TABLE 5
REGIME DEPENDENT INPUT VARIABLES

Regime		Sharing Efficien.	Spectrum Cost ($/MHz-pop)	Operator Share	Market Share	Density pp/km^2	TX Range
		$e_{sharing}$	K_S	$u_{operator}$	$u_{mktshare}$	D	r
Rural	unlicensed	0.5	0	50%	50%	10	10 km
	licensed non-excl	1.0	0.2	50%			
	licensed exclusive	1.0	0.2	100%			
Urban	unlicensed	0.5	0	50%	20%	4,000	500 m
	licensed non-excl	1.0	1.0	50%			
	licensed exclusive	1.0	1.0	100%			

[2] Only includes full BTAs for the full license size that actually were sold.

Quantified Benefits:

TABLE 1
OUTPUT VARIABLES

Variable	Description
S	Total spectrum required for all BWA operators
N	Total number of APs per 1000km^2 for all BWA operators
B_{AP}	Bandwidth capacity provided by each AP
$K_{Sys}(S)$	System cost per subscriber
$K_T(S)$	Total cost per subscriber

TABLE 7
OUTPUT RESULTS IN EACH REGIME

Rural

Unlicensed

Model	S MHz	N per 1000km^2	B_{ap} Mbps	K_{sys} $/sub	K_T $/sub
MSR	16	125	1	$2,500	$2,500
MSC	317	6	10	$127	$127
MTC	n/a	n/a	n/a	n/a	n/a

(d)

Licensed Non-Exclusive

Model	S MHz	N per 1000km^2	B_{ap} Mbps	K_{sys} $/sub	K_T $/sub
MSR	8	125	1	$2,500	$2,513
MSC	159	6	10	$127	$381
MTC	112	9	7	$180	$360

(b)

Licensed Exclusive

Model	S MHz	N per 1000km^2	B_{ap} Mbps	K_{sys} $/sub	K_T $/sub
MSR	4	125	1	$2,500	$2,506
MSC	159	3	20	$64	$318
MTC	79	6	10	$127	$254

(c)

Urban

Unlicensed

Model	S MHz	N per 1000km^2	B_{ap} Mbps	K_{sys} $/sub	K_T $/sub
MSR	16	20000	1	$2,500	$2,500
MSC	127	2547	4	$318	$318
MTC	n/a	n/a	n/a	n/a	n/a

(d)

Licensed Non-Exclusive

Model	S MHz	N per 1000km^2	B_{ap} Mbps	K_{sys} $/sub	K_T $/sub
MSR	8	20000	1	$2,500	$2,662
MSC	63	2547	4	$318	$1,588
MTC	32	5085	2	$636	$1,271

(e)

Licensed Exclusive

Model	S MHz	N per 1000km^2	B_{ap} Mbps	K_{sys} $/sub	K_T $/sub
MSR	4	20000	1	$2,500	$2,581
MSC	63	1273	8	$159	$1,428
MTC	22	3596	3	$449	$899

(f)

TABLE 6
SPECTRUM REQUIREMENTS AND COST OF A STARTUP SYSTEM

Regime		S MHz	N per 1000km^2	B_{ap} Mbps	K_{sys} \$/sub	K_T \$/sub
Rural	Unlicensed	8	3	1	\$127	\$127
	Licensed Non-Exclusive	4	3	1	\$127	\$140
	Licensed Exclusive	4	3	1	\$64	\$70
Urban	Unlicensed	8	1273	1	\$318	\$318
	Licensed Non-Exclusive	4	1273	1	\$318	\$480
	Licensed Exclusive	4	1273	1	\$159	\$240

B.4.4 Tao Chen, Honggang Zhang, Gian Mario Maggio, and Imrich Chlamtac, "CogMesh: A Cluster-based Cognitive Radio Network" DySPAN 07

Summary:

This paper provides a framework to form a CogMesh network in the context of open spectrum sharing scheme. The network is constructed in a distributed way and provides coexistence with primary users of the spectrums. The basic unit of the network is the cluster, which is a sub-network formed by a group of neighbor nodes sharing common channels, and coordinated by a selected node in the cluster called cluster head. The network is constructed by interconnecting clusters after they learn each other through neighbor discovery process. This paper provides mechanisms for each node to exchange neighbor information over multiple channels efficiently. Moreover, issues in cluster formation, network formation, and topology management are addressed and corresponding solutions are provided. A distributed topology management algorithm is proposed and its performance under various channel conditions is studied.

Scenario:

Multiple nodes of the CogMesh are randomly placed in a $600m \times 600m$ 2-dimension square according to the Poisson distribution. The maximum transmission range of each node is set to $100m$. The available channels for a node are determined by its location in the square. The square is divided into 16 equal size sub-squares. Secondary users in a same sub-square share identical available channels. The available channels for secondary users in the sub-square are randomly picked from a channel pool (CP). Each sub-square has at least one available channel. Two reference algorithms are developed for performance comparison. The first is the lowest ID algorithm (Lowest ID), in which the node with the lowest ID among its neighbors has the highest priority to form a cluster. The second is the max degree algorithm (Max Degree), in which the node with max degree among its neighbors forms a cluster first.

Quantified Benefits:

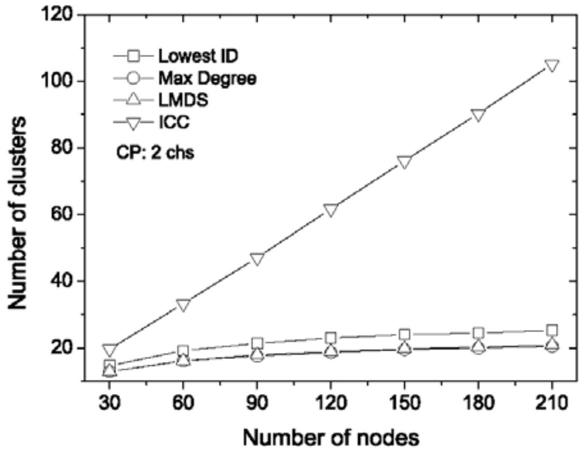


Fig. 5. Cluster statistic in stationary channel condition

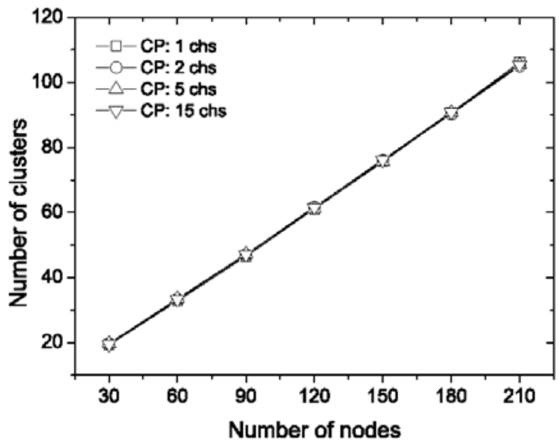


Fig. 6. Number of clusters after ICC phase, in stationary channel condition, with various spectrum holes

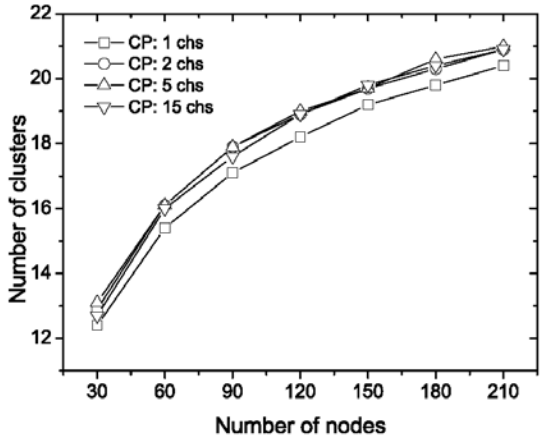


Fig. 7. Number of clusters after LMDS algo, in stationary channel condition, with various spectrum holes

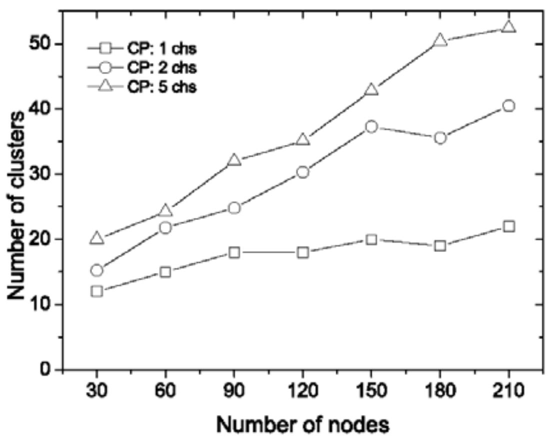


Fig. 8. Cluster statistic in dynamic channel condition, before LMDS algo

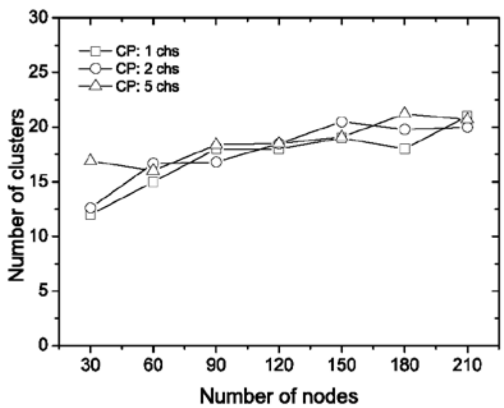


Fig. 9. Cluster statistic in dynamic channel condition, after LMDS

B.4.5 Zhu Ji and K. J. Ray Liu, "Collusion-Resistant Dynamic Spectrum Allocation for Wireless Networks via Pricing," DySPAN07

Summary:

This paper proposes a collusion-resistant dynamic pricing approach to optimize overall spectrum efficiency in the scenarios of user collusion. However, user collusion among selfish users severely deteriorates the efficiency of spectrum sharing. In this paper, we propose a collusion resistant dynamic pricing approach to maximize the users' utilities while combating their collusive behaviors using the derived optimal reserve prices. Simulation results show that the proposed scheme can achieve high spectrum efficiency under various situations of user collusion.

Scenario:

TABLE I: Collusion-resistant dynamic spectrum allocation

1. Initialize the users' beliefs and bids/asks ◇ The primary users initialize their asks as large values close to M and their beliefs as small positive values less than 1; ◇ The secondary users initialize their bids as small values close to 0 and their beliefs as small positive values less than 1.
2. Belief update based on local information: Update primary and secondary users' beliefs $\bar{r}_p$ and $\bar{r}_s$.
3. Optimal reserve price for primary and secondary users: Update primary users' optimal reserve prices ϕ^*_{r,p_i} using (4) and (6); Update secondary users' optimal reserve prices ϕ^*_{r,s_i} using (5) and (7).
4. Optimal bid/ask update: ◇ Obtain the optimal ask for each primary user by solving (8) given ϕ^*_{r,p_i}; ◇ Obtain the optimal bid for each secondary user by solving (9) given ϕ^*_{r,s_i}.
5. Update leasing agreement and spectrum pool: ◇ If the outstanding bid is greater than or equal to the outstanding ask, the leasing agreement will be signed between the corresponding users; ◇ Update the spectrum pool by removing the assigned channel.
6. Iteration: If the spectrum pool is not empty, go back to Step 2.

A wireless network covering 100 × 100 area is considered. *J* primary users are simulated by randomly placing them in the network. It is assumed that the primary users' locations are fixed and their unused channels are available to the secondary users within the distance of 50. Then, *K* secondary users are randomly deployed in the network, which are assumed to be mobile devices. The mobility of the secondary users is modeled using a simplified random waypoint model. Without loss of generality, the cost of an available channel in the spectrum pool is assumed to be uniformly distributed; the reward payoff of leasing one channel is uniformly distributed. *J* = 5 and 1000 spectrum sharing stages have been simulated. It is assumed that each primary user has four unused spectrum channels.

Quantified Benefits:

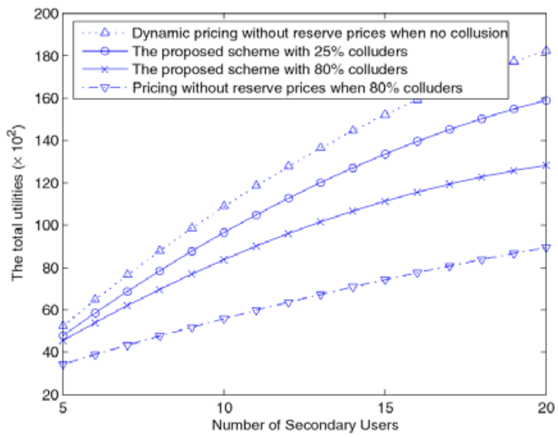


Fig. 1: Comparison of the total utilities of our dynamic pricing scheme with reserve prices and without reserve prices for different user collusion.

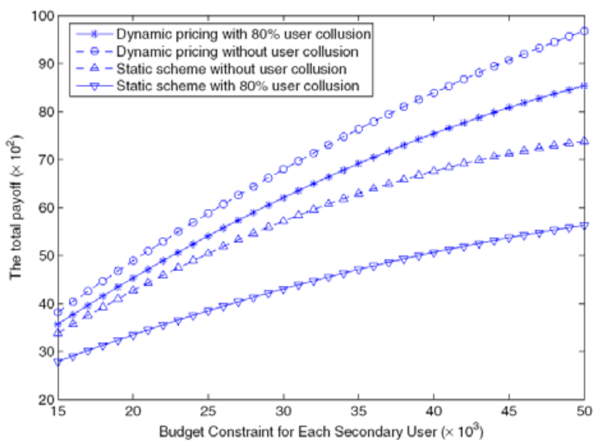


Fig. 2: Comparison of the total utilities of the proposed scheme with those of the static scheme.

B.4.6 Gunther Auer, Harald Haas, Peter Omiyi, "Interference Aware Medium Access for Dynamic Spectrum Sharing," DySPAN 07

Summary:

In this paper dynamic spectrum sharing for future mobile communication systems is addressed where multiple operators share license exempt spectrum. In such an environment cognitive radios are needed that are able to sense, as well as dynamically allocate, the available resources in a distributed manner and on a short-term basis. DSA based on busy burst (BB) signaling is proposed whose basic principle is that upon data reception transmits a busy signal in an adjacent time multiplexed slot. Through exploitation of channel reciprocity, other potential transmitters are prevented from interfering by first listening to the busy signal. Due to its decentralized nature, the considered BB-DSA protocol appears to be ideally suited for dynamic spectrum sharing in license exempt spectrum.

Scenario:

An OFDM system with 256 subcarriers and 10 OFDM symbols per frame is used for a numerical example. With a slot size of 32 × 10, there are eight parallel slots available. The size of one packet is set equal to the slot size and the throughput is normalized by the maximum number of parallel slots. With a minislot duration of one OFDM symbol, the BB-DSA minislot overhead is 10%. Perfect time and frequency synchronization is assumed. Path loss is subject to lognormal shadowing, and a path loss exponent and the shadow fading standard deviation of three and eight dB was assumed.

The network model consists of a large service area, with randomly positioned cells surrounding a central "tagged" cell. The average number of interferers controls the interference density within the service area, i.e. the receiver experiences negligible interference outside this area, due to the propagation path loss. Numerical results are obtained using an average number of interferers 6, assumed a Poisson distribution. The uninterrupted transmission time is 300 frames.

Quantified Benefits:

The BB-DSA is compared with a fixed spectrum assignment (FSA) algorithm, without any interference protection mechanism. Results show the throughput delay plots for BB-DSA and FSA for 1km cell radius. As a reference, the delay/throughput curve of the classical *M/G/*1 queue (without server vacations) is also plotted. This is the performance of the "perfect scheduling" scenario with zero slot-allocation delay and zero packet loss from interference. BB-DSA is shown to outperform the FSA scheme significantly, offering a superior delay throughput performance close to that of the ideal *M/G/*1 queue. The asymptotic throughput when the delay approaches infinity is by a factor 3-4 higher than for the case when static spectrum allocation (FSA) is used.

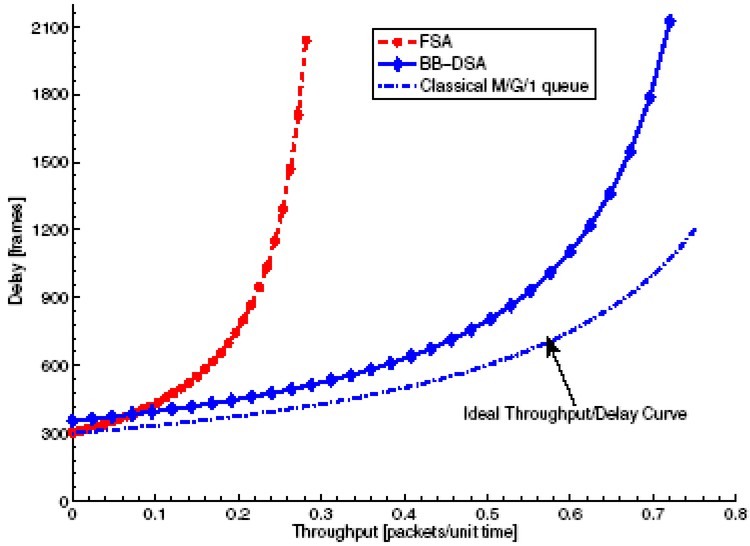


Fig. 4. Delay-throughput results for cell size $R_{\text{cell}} = 1\,\text{km}$.

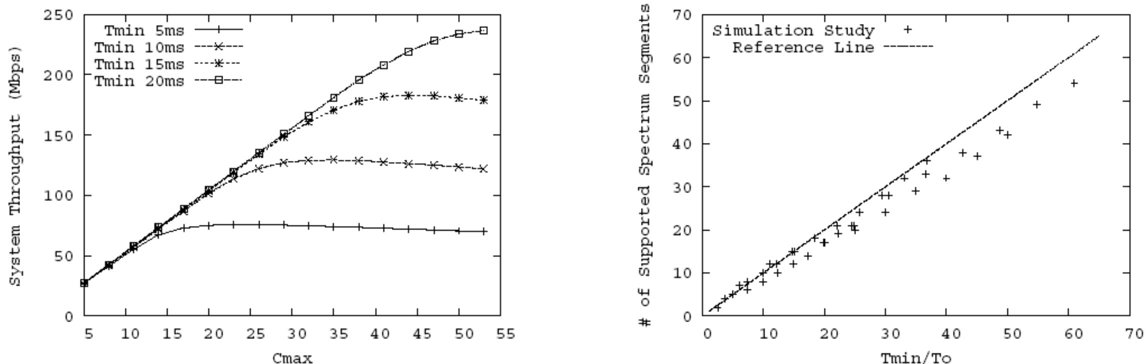
B.4.7 Yuan Yuan, Paramvir Bahl, Ranveer Chandra, Philip A. Chou, John Ian Ferrell, Thomas Moscibroda, Srihari Narlanka, Yunnan Wu, "KNOWS: Cognitive Radio Networks Over White Spaces," DySPAN07

Summary:

A system, called KNOWS that encompasses new hardware, an enhanced MAC protocol and spectrum sensing capabilities, for efficiently utilizing unused portions of the licensed spectrum for unlicensed operations is presented. KNOWS cooperatively detects incumbent operators and efficiently shares the vacant spectrum among unlicensed users. The hardware consists of a development board with a scanner/receiver radio and a reconfigurable transceiver. KNOWS' spectrum allocation engine maintains up to date information about the spectrum usage by all its neighbors, and stores it in a RAM. The MAC uses the RAM to decide, dynamically, on the portion of the spectrum to use for a given communication. The MAC also enables a spectrum reservation scheme in addition to the virtual sensing approach of IEEE 802.11.

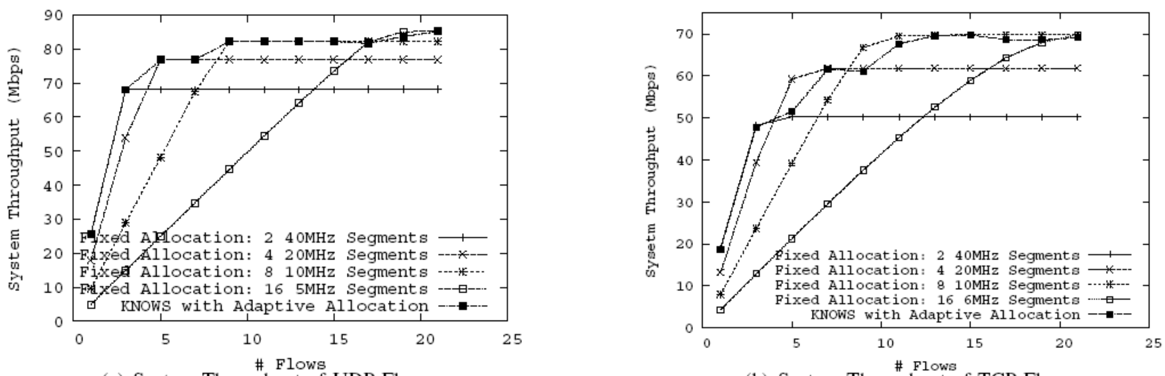
Quantified Benefits:

Simulation techniques show that KNOWS significantly increases the capacity when compared to IEEE 802.11 based systems (by about 200%).



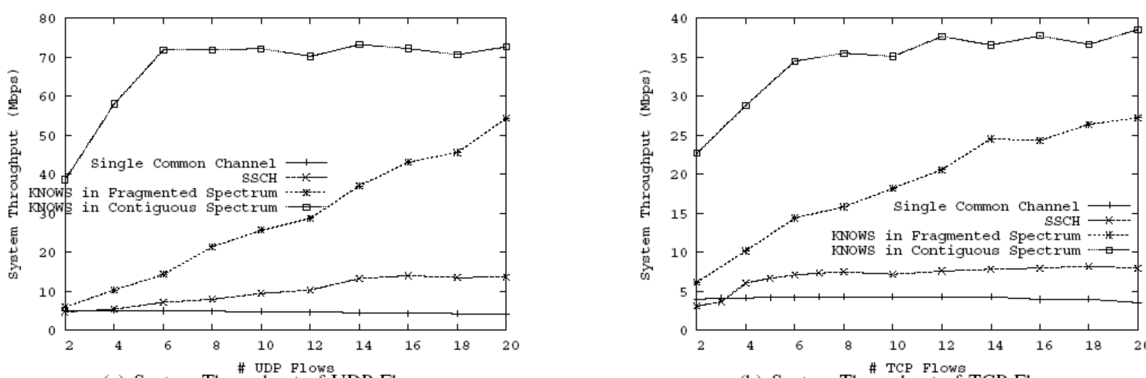
(a) Throughput with Different T_{min} (b) Verification

Fig. 7. $T_{min} = C_{max} * T_o$



(a) System Throughput of UDP Flows (b) System Throughput of TCP Flows

Fig. 8. Throughput Performance of The KNOWS System



(a) System Throughput of UDP Flows (b) System Throughput of TCP Flows

Fig. 11. Throughput Performance with Non-Disjoint Flows

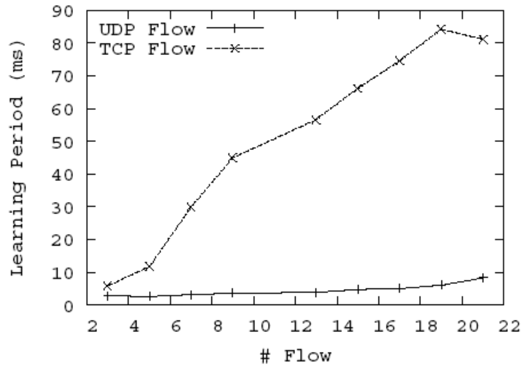


Fig. 9. Time for KNOWS to learn of the neioghbors' spectrum usage and traffic patterns

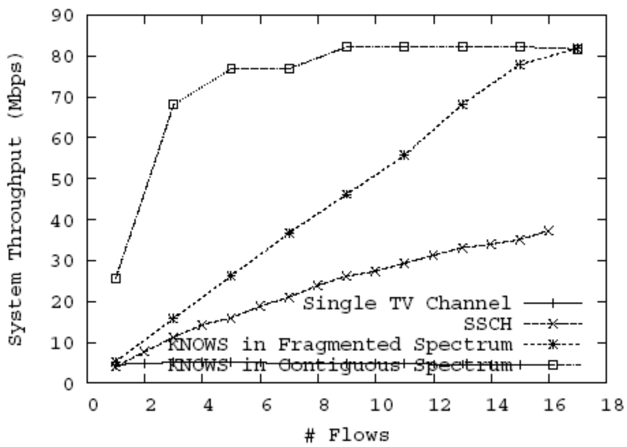
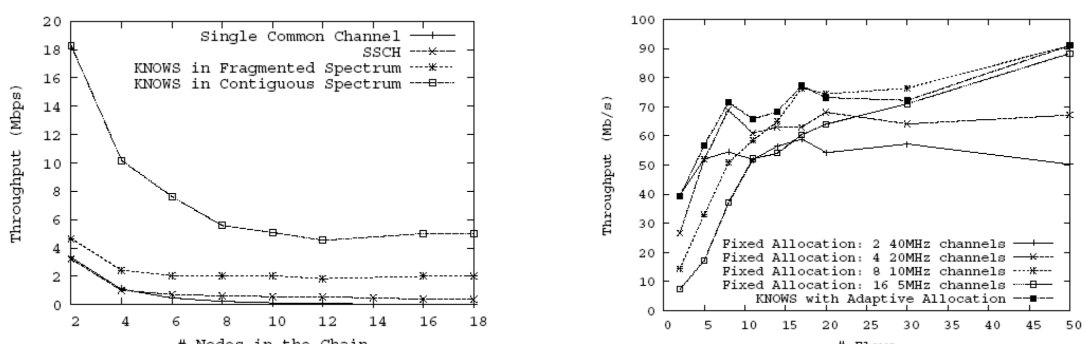


Fig. 10. System Throughput with Disjoint UDP Flows



(a) System Throughput in Chain Network (b) System Throughput in Mesh Network

Fig. 12. Throughput Performance in Mutihop Network

B.4.8 Ali Motamedi, Ahmad Bahai, "MAC Protocol Design for Spectrum-agile Wireless Networks: Stochastic Control Approach," DySPAN07

Summary:

This paper addresses this problem by proposing a distributed spectrum-agile MAC (media access control) protocol. It is a multichannel CSMA-based protocol equipped with a dynamic channel selection algorithm. The dynamic channel selection problem is formulated as a multi-armed bandit problem, and the optimal channel selection rules are derived. Finally, the advantage of the new protocol is demonstrated through simulation**.**

Scenario:

The duration of intervals (in terms of the number of timeslots they occupy) are modeled as geometric random variables with unknown parameters *qi* and *pi*, respectively. With the mentioned assumption that idle and busy intervals are geometrically distributed thus, memory less, the primary users' traffic in each sub channel can be modeled by a two state Markov chain. The two states correspond to presence or absence of a primary users' signal in that sub channel.

L: Transmission packet size

s: no. of successful packets transmitted

f: no. of collided or failed packets

b: no. of times the subchannel was sensed busy

Lc: total length of control message

α: energy cost factor

β: discount factor.

Quantified Benefits:

In order to find the approximate values of the Gittins indices for the channel selection problem the state-space was truncated by limiting the total number statistics gathered of each transmission outcome. Whenever the state of one sub channel reaches the boundaries it will remain unchanged. The Gittins indices for the channel selection problem with truncated state-space can then be calculated. Figure five shows the indices for the case where *Bmax* = *Fmax* = *Smax* = 10, *Lc* = 1, *L* = 4, β = 0.9. Two values α = 0.50, , α = 1 were chosen to observe the effect of energy factor on indices.

Figure 6 shows the average reward as a function of time. The parameters *pi* and *qi* are uniformly selected from the interval [0, 1]. Those parameters were also changed in the middle of the simulation to see how different methods react to this change and are able to converge to the *new* *best sub channel* in the least possible time. As can be seen the purposed channel selection mechanism is the fastest to converge to the new optimal sub channel after the change. To have a baseline for comparison some sensible heuristic channel selection methods were also implemented:

- Least failures: *chopt* = min*i*(*fi*)
- Most success to failure ratio: *chopt* = max*i*(*si/fi*)
- Most success to failure plus busy ratio: *chopt* = max*i*(*si/*(*fi* + *bi*))

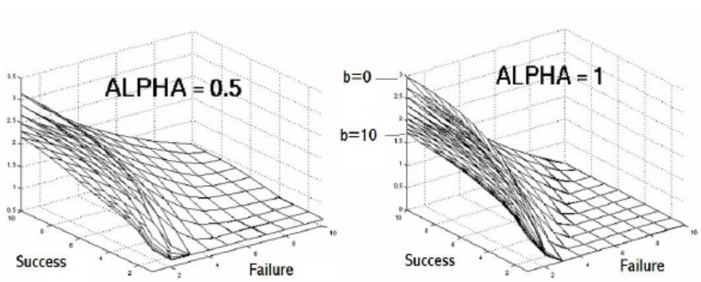


Fig. 5. Dynamic Allocation Indices.

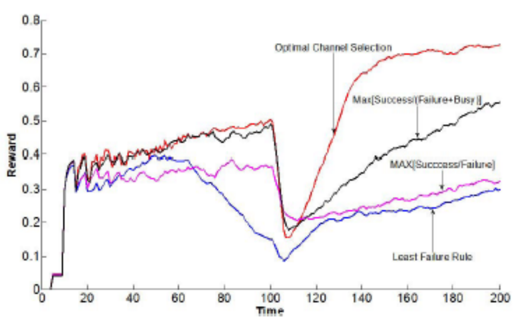


Fig. 6. The expected reward as a function of time.

B.4.9 D. Grandblaise, C. Kloeck, T. Renk, P. Bag, P. Levine, K. Moessner, J. Yang, M. Pan and K. Zhang, "Microeconomics Inspired Mechanisms to Manage Dynamic Spectrum Allocation," DySPAN 07

Summary:

This paper describes schemes, based on multiple agents that collaborate to find more efficient allocation patterns in a defined coverage area. Leveraging on microeconomics inspired mechanisms, the paper describes and analyzes schemes based on collaborating 'agents' (that can be either whole operator, or BS or end user terminal) that negotiate with each other to find the most optimized allocation pattern for a given area and allocation duration. The optimization strategies investigated include both bargaining as well as auction-based mechanisms. Both allow the negotiation of spectrum and radio resources, based on market driven incentives. The auction types investigated support dynamic allocations on different timescales, ranging from short to medium and long-term allocation scenarios. While auctions are discussed to be used for the longer-term allocations, a MAC based rental protocol is evaluated for shorter-term allocations when operated either at the BS or end user terminal level. Finally, the paper discusses how the MAC based rental protocol between BSs can be implemented.

Scenario:

A node B allocates the RRGs to bidders. The incoming data of the four QoS buffers underlie a Poisson process with arrival rate λ.

Quantified Benefits:

Figure 5 shows the comparison of the operator's revenue using either the uniform-price auction or the discriminatory auction. The average revenue per auction is measured in the sum of the quantized prices, which can take the values 1,…, 64. The discriminatory auction clearly has higher revenue than the uniform-price auction because a user has to pay the bid. In contrast, in the uniform-price auction the user has to pay at most the bid. The revenue increase for both with higher load needed, because there is a higher probability that higher bids will be submitted in the auction.

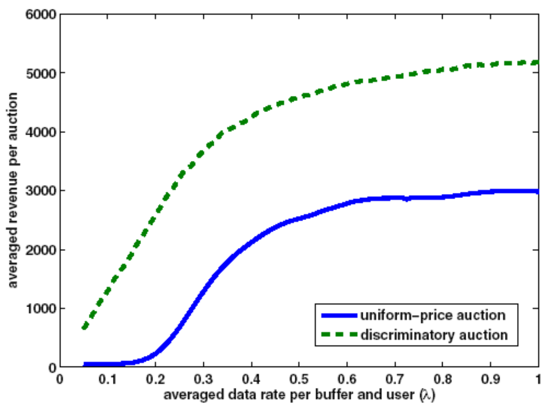


Figure 5 Comparison of two different auctions

B.4.10 Petar Popovski, Hiroyuki Yomo, Kentaro Nishimori, Rocco Di Taranto, and Ramjee Prasad, "Opportunistic Interference Cancellation in Cognitive Radio Systems," DySPAN07

Summary:

This paper deals with the problem of spectrally efficient operation of a cognitive radio (CR), here also referred to as the Secondary System (SS), under interference from the primary system (PS). It is shown that the SS should apply *Opportunistic Interference Cancellation (OIC)* and cancel the interference from the PS whenever such opportunity is created by (a) selection of the data rate in the PS and (b) the link quality between the primary TX and the secondary RX. The achievable data rate for the SS using OIC is derived. A method to achieve the maximal possible data rate for the SS is devised when PS is decodable. The power allocation for the SS is investigated when OIC is applied in multiple channels. IT is shown that the optimal power allocation can be achieved with *intercepted water filling* instead of the conventional water filling. The results show a significant gain for the rate achieved by OIC. It is shown that the solution to the power/rate allocation problem is intercepted water filling rather than the conventional water filling. The numerical results confirm that the OIC can bring rate gains in the CR systems.

Scenario:

The primary Base Station (BS) is using M channels, adapting the rate in each channel according to the scheduling policy and the channel state information (CSI) of the PS terminals. It is assumed that the rate adaptation in the PS is independent of the SS. The communication in the SS does not cause an adverse interference to the PS, since the SS is to be a short–range radio system that uses a regulated low power. The PS serves the users in *scheduling epochs*. In each epoch, the primary BS decides accordingly the transmission rate $R_{p,m}$ for the m^{th} channel. The BS broadcasts this information, such that the CR terminals learn about $R_{p,m}$ for each m. Due to the bandwidth normalization, the spectral efficiency [bps/Hz] and the rate [bps] are equivalent. A scheduling epoch lasts for N symbols, where N is sufficiently large such that the primary BS can apply capacity–achieving transmissions.

Quantified Benefits

First a scenario with $M = 1$ is illustrated. The PS has a range of D meters and it adjusts its power to have a predefined SNR of β_p for a primary receiver, at a distance D, with LOS link to the BS. The SRX is at the distance d from the BS and a primary SNR of $\gamma_p(x) = \beta_p/x^v$, where $x = d/D$ and v is the propagation coefficient. Figure 5 depicts the normalized achievable rate as a function of the normalized distance x. Two values of γ_s are used, 10 and 20 dB, respectively and γ_s is a measure of the power applied in the SS. OIC leads to higher rate when $x < 1$, but is identical to the case without interference cancellation for $x > 1$, as the PS signal cannot be decoded when the SRX is at distances $d > D$. For OIC, the rate points in the region $1/(1+\gamma_s)^{1/v} < x < 1$ are achieved by the described strategy of superposition coding.

Figure 6 compares IWF and CWF for $M = 10$ channels. For given ε (the total average energy available for transmission on all channels), the normalized achievable rate is the sum of the rates for all 10 channels and the value is obtained by averaging over 10000 iterations. In each iteration, $v_m = 1/\gamma_m$ where γ_m is an exponentially distributed variable with average value 1, such that the average secondary SNR per channel is ε/M . In each iteration, the values $\gamma_{p,m}$ is generated from exponential random variable with mean γ_p = 20dB. $\beta_{p,m}$ is generated from exponential random variable with mean value 20 dB and 23 dB, respectively, for each of the two OIC curves. It can be seen that IWF leads to significant rate improvements. When $\beta_p > \gamma_p$ the SRX has less opportunity to decode the primary, such that the improvement of IWF over CWF is decreased.

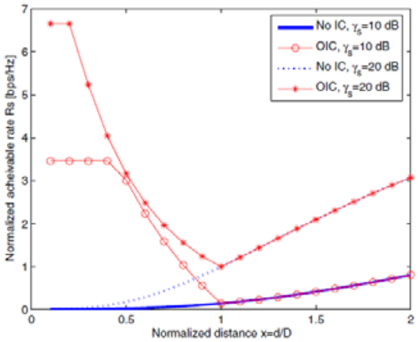


Fig. 5. Normalized achievable rate as a function of the normalized distance of the secondary RX from the primary BS. “No IC” is without Interference Cancellation. Here $\beta_p = 20$ [dB], propagation coefficient is $v = 3$.

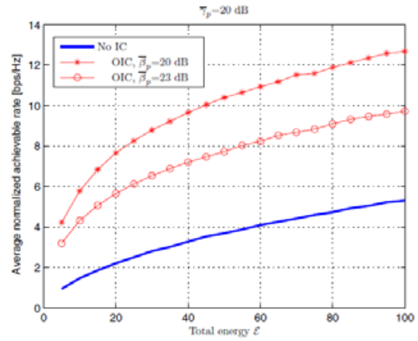


Fig. 6. Normalized average achievable rate in [bps/Hz] as a function of the average SNR $\overline{\gamma}_s = \frac{\mathcal{E}}{\nu}$ on the secondary link. The number of channels is $M = 10$.

B.4.11 Beibei Wang, Zhu Ji, and K. J. Ray Liu, “Primary-Prioritized Markov Approach for Dynamic Spectrum Access”

Summary:

In this paper, a primary-prioritized Markov approach is proposed for dynamic spectrum access through modeling the interactions between the primary users and the unlicensed users as continuous time Markov chains (CTMC). By designing appropriate access probabilities for the unlicensed users, the spectrum dynamics can be captured using CTMC models to coordinate the spectrum access of the unlicensed users optimally so that a good tradeoff can be achieved between spectrum efficiency and fairness. The simulation results show that the proposed primary-prioritized dynamic spectrum access approach under proportional fairness criterion not only provides fair spectrum sharing among unlicensed users with only small performance degradation compared to the approach maximizing the overall average throughput, but also achieves much higher throughput than CSMA-based random access approaches and the approach achieving max-min fairness.

Scenario:

Different dynamic spectrum access networks are considered where multiple unlicensed users are allowed to access the temporarily unused licensed spectrum bands on an opportunistic basis, without conflicting or interfering with the primary spectrum holders’ usage.

In the simulations, the communication bandwidth is 200 KHz, the transmission power is $p_\gamma = 2$ mW, and the thermal noise power is $n_0 = 10^{-15}$ W. The propagation loss factor is 3.6. The transmitter of user *A* is at (0m, 0m), and its receiver is at (150m, 0m). The transmitter of user *B* is at (300m, 0m), and its receiver is at (400m, 0m). The service rates of *P* (primary user), *A* and *B* (the two secondary users) are all set to be 100 m/s. The arrival rates of *P* and *B* are both chosen as 85 m/s, while the arrival rate of *A* varies from 70 to 100 m/s.

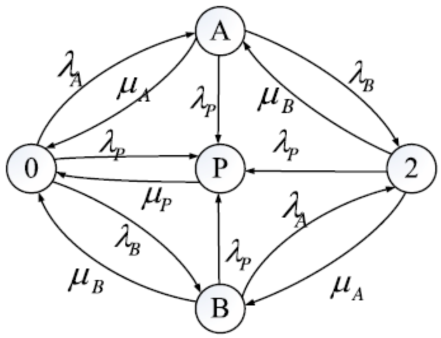


Fig. 2: The rate diagram of CTMC-5.

TABLE I: The Five States of CTMC-5

State	Description
0	No user operates in the spectrum
A	Unlicensed user A operates in the spectrum
B	Unlicensed user B operates in the spectrum
P	Primary user P operates in the spectrum
2	Both A and B operate in the spectrum

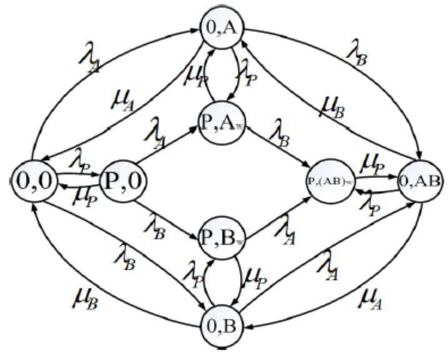


Fig. 3: The rate diagram of CTMC-8.

TABLE II: The Eight States of CTMC-8

Index	State	Description
0	$(0,0)$	Spectrum is idle
1	$(0,B)$	Unlicensed user B is in service
2	$(0,A)$	Unlicensed user A is in service
3	$(0,AB)$	Both A and B are in service
4	$(P,0)$	Primary user P is in service
5	(P,B_w)	P is in service; B is waiting
6	(P,A_w)	P is in service; A is waiting
7	$(P,(AB)_w)$	P is in service; A and B are waiting

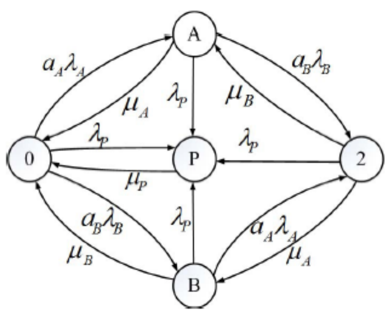


Fig. 4: Modified CTMC-5 with access control.

Quantified Benefits

In Figure 5, the utilities of both user A and B versus λ_A of the PF, maximal-throughput, and max-min optimizations for CTMC-8 is shown. Since $r_{B\,1} > r_{A\,1} > r_{B\,2} > r_{A\,2}$, for the maximal throughput optimization, user B has a higher throughput. When $\lambda_A < \lambda_B$, the difference in the throughput is very large. As λ_A increases, A has more chance to access the spectrum, so user A's throughput gradually increases. However, the interference from A to B also increases, so user B suffers a throughput degradation. For the max-min optimization, both users almost have the same throughput, which increases as λ_A increases. This is because the system has to accommodate the user with worse channel condition, and user *A* has an increasing spectrum allocation. For the PF optimization, the difference between *A* and *B*'s throughput is smaller than that of the maximal-throughput optimization. Also, the increment of *A*'s throughput is larger than the decrement of *B*'s throughput as λ_A increases. This shows that the PF optimization is fairer than the maximal-throughput method.

In Figure 6, the overall throughput of two unlicensed users versus λ_A with different optimization goals for CTMC-8 is shown. Because the max-min method compensates the user with worse channel condition, it has the worst performance, especially when user *A* further suffers a lower access when λ_A is very small. The PF method has the performance between the maximal-throughput method and max-min method, while the maximal-throughput method is less fair. In addition, the performance loss of the PF method to that of the maximal throughput method is small. Therefore, the primary-prioritized PF dynamic spectrum access is a good tradeoff between the fairness and efficiency.

In Figure 7, the overall throughput of the PF dynamic spectrum access for CTMC-8, CTMC-5 and the throughput of the non-persistent CSMA random access versus λ_A is shown. In CSMA, the propagation delay is set to be 0.005. It is seen that the PF access approaches for both the two CTMCs have better performances than the CSMA as λ_A increases. As λ_A increases, the overall throughput of the PF access approach for both the CTMCs increases, while the throughput of CSMA decreases. This shows that the proposed PF access approach has a larger capability than the CSMA approach to accommodate more traffic. We can see that the spectrum utilization of CTMC-8 is higher than that of CTMC-5, since the arrival rates are identical for the two cases while CTMC-8 has a larger overall throughput. However, as λ_A increases, the performance increment of CTMC-8 compared to CTMC-5 gradually decreases.

In Figure 9, the overall throughput of the PF dynamic spectrum access for CTMC-8, CTMC-5 and that of the CSMA-based random access protocol, averaged over random locations is shown. It can be observed that even under the randomized settings, the proposed dynamic spectrum access approaches still show better performances and larger capabilities to accommodate more traffic than the CSMA-based random access protocol. In addition, CTMC-8 achieves more efficient spectrum utilization than CTMC-5 as in the case with fixed transmitter receiver positions.

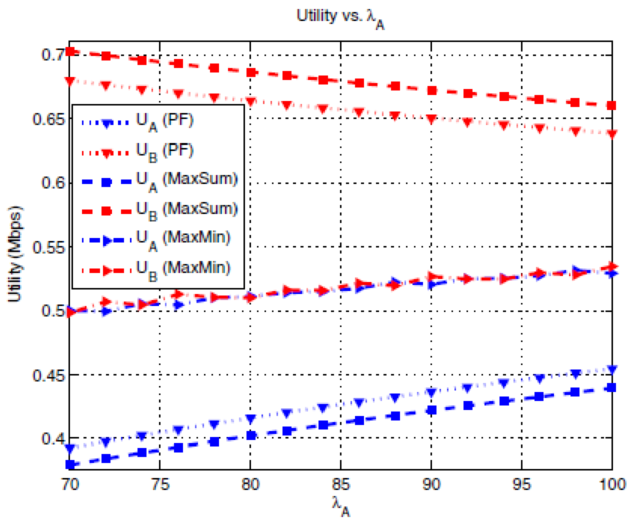


Fig. 5: Each unlicensed user's throughput (Mbps) vs. λ_A.

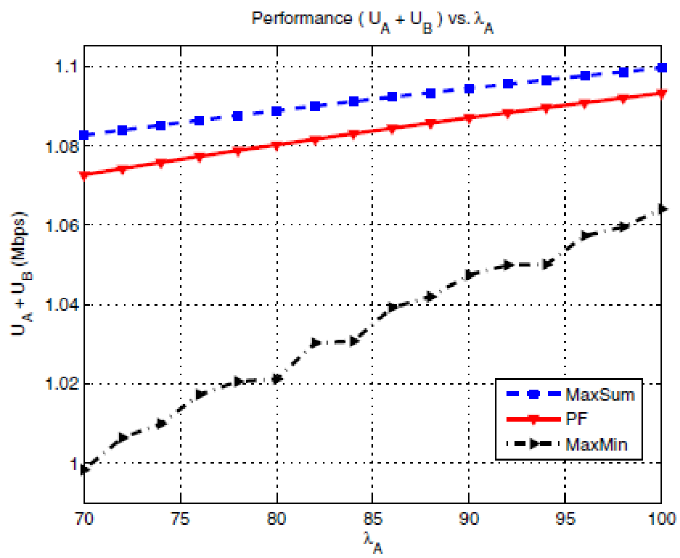


Fig. 6: Overall throughput (Mbps) vs. λ_A.

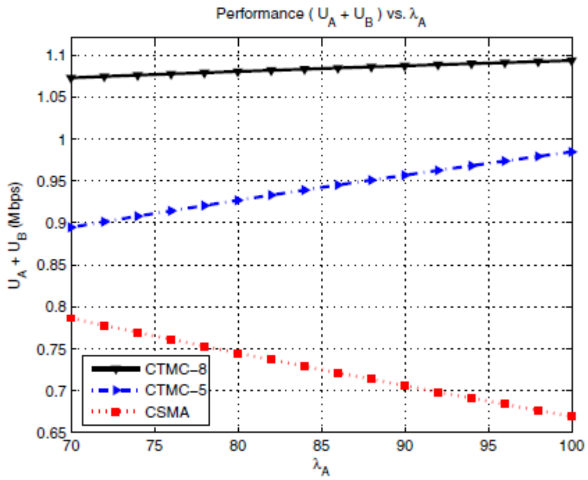


Fig. 7: Comparison of the overall throughput vs. λ_A for CTMC-5, CTMC-8 and CSMA.

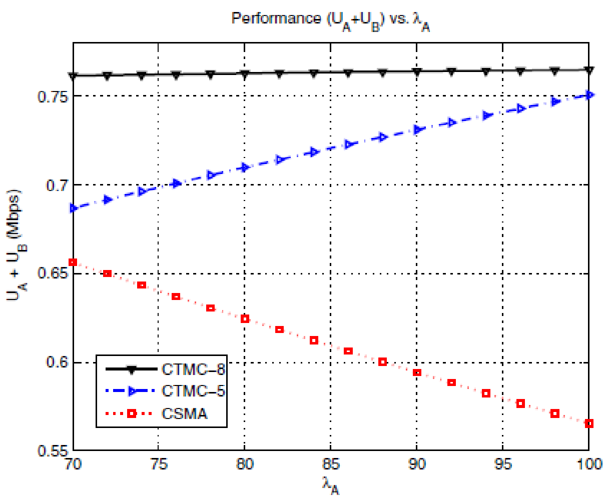


Fig. 9: Comparison of the overall throughput (Mbps) vs. λ_A for CTMC-5, CTMC-8 and CSMA in random locations.

B.4.12 Rocco Di Taranto, Kentaro Nishimori, Petar Popovski, Hiroyuki Yomo, Yasushi Takatori, Ramjee Prasad and Shuji Kubota, "Simple Antenna Pattern Switching and Interference–induced Multi–hop Transmissions for Cognitive Radio Networks"

Summary:

This paper proposes a simple antenna switching and a relay technique for cognitive radios using adaptive array antenna to reduce the interference from the primary system effectively. While the adaptive array antenna can create null towards the direction of primary system, the created antenna pattern can result in non–optimized pattern between cognitive nodes. In order to solve such a problem, this paper first introduces a simple antenna pattern switching. With this

technique, each cognitive radio node is equipped with three antennas and each node tries to select the antenna configuration resulting in the best antenna pattern for each link. Furthermore, a combination between the above simple antenna switching and the interference-induced multi–hop transmission is proposed where the multi–hop transmission is utilized when a link in the network suffers from the low transmission quality due to the created antenna pattern. Numerical results show that the proposed techniques can significantly improve the achievable data rate in cognitive networks.

Scenario

The co-existence between a primary system with a long–range communication and a secondary system1 with a short–range transmission is considered. The primary system has a *license* to utilize a certain spectrum band, such as the cellular and TV broadcast networks. Secondary network tries to use the primary band while avoiding the interference from/to the primary systems. The spectrum reusability within the primary service area depends on the amount of interference that the primary and the secondary system cause to each other. The broadcast transmissions, e.g. TV systems, are considered as the primary systems. The secondary network consists of several nodes that have array antennas, used to cancel the interference from the primary systems. It is assumed that the secondary system can generate an interference cancellation pattern by using the channel state information between the primary and secondary systems. The secondary nodes try to transmit signals to each other while creating null pattern toward the interference from the primary system. In order to simplify the problem, it is assumed that the transmissions of cognitive radios are regulated so that they do not cause interference to primary receivers. To realize the interference cancellation, an adaptive array is adopted. A two-element linear array antenna realizes the adaptive array, in order to achieve hardware simplification for the secondary devices. However, when the cognitive receiver creates a null toward the direction of the primary interference, it can happen that the cognitive receiver does not have enough gain toward the cognitive transmitter because of the null pattern. In this case, there is loss in the received signal power at the cognitive receivers. Since this situation arises by the linear antenna symmetry, such a grating null cannot be eliminated. In order to solve this problem, some new techniques are proposed using the antenna switching and relay transmissions.

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Frequency	5GHz
Transmit power of the primary system	33 dBm
Transmit power of the secondary system	19 dBm
Antenna gain of the secondary system	10dBi
Antenna gain of the secondary system	2dBi
Modulation schemes	QPSK
Angular spread	0–360 deg.
Path loss coefficient	3.5
SNR at between secondary nodes	20 dB

Quantified Benefits

Figure 5 shows the average achievable rate of the proposed and conventional schemes against the angular spread. As it can be seen in Figure 5, for small values of angular spread, the probability that secondary transmission is degraded is very high. It is shown that an improvement can be obtained by the proposed method in the average transmission rate larger than 9 bit/sec/Hz. With the small angular spread, the signal is received at the receiver from a limited direction. Therefore, if the secondary transmitter is located in the direction of the grating null, the signal quality is largely degraded. On the other hand, with the larger angular spread, the signal is received more uniformly from different angles, which reduces the degradation due to the grating null. Moreover, it can be seen that the achievable transmission rate is significantly improved by the proposed scheme regardless of the value of angular spread.

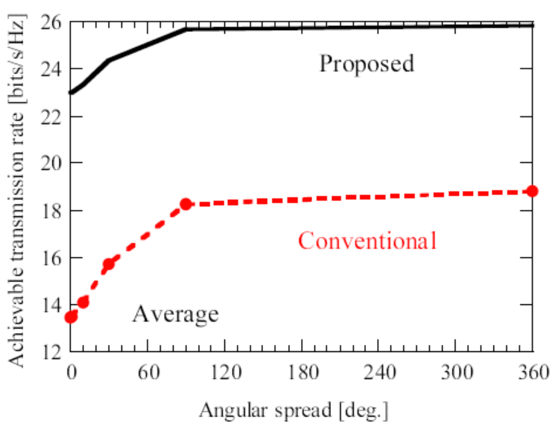


Fig. 5. Achievable transmission rate vs. angular spread by using the proposed scheme

B.4.13 Liangping Ma, Chien-Chung Shen, and Bo Ryu, "Single-Radio Adaptive Channel Algorithm for Spectrum Agile Wireless Ad Hoc Networks," DySPAN07

Summary:

This paper presents the Single-Radio Adaptive Channel (SRAC) algorithm that enables dynamic spectrum access in multi-hop wireless ad hoc networks where each node has only one half-duplex radio (transceiver). It provides a feasible dynamic channelization mechanism to make the best of the available spectrum, relaxes the radio communication conditions to enhance network connectivity, and exploits the broadcast nature of the wireless medium to provide efficient multicast support. Designed as a relatively independent module, SRAC can upgrade various existing single-radio legacy Medium Access Control (MAC) protocols to be dynamic spectrum access capable, achieving efficient use of the spectrum, relaxing their operating conditions, and naturally supporting multicast applications. The SRAC algorithm is characterized by three features: (a) dynamic channelization in response to jamming, primary spectrum users and channel load, (b) “cross channel communications”, and (c) as-needed use of spectrum. In this paper, the performance of SRAC through analysis and QualNet simulations is evaluated.

Scenario

The SRAC algorithm is implemented as a relatively independent module, and integrated it with the CSMA/CA MAC protocol in QualNet 3.8, which captures the major features of IEEE 802.11 Distributed Coordination Function (DCF) while not getting into unnecessary complex issues such as dynamic rate control in the current QualNet 802.11 DCF code. In addition, a module to simulate jammers and primary spectrum users is also implemented.

Quantified Benefits

The CSMA/CA MAC protocol employs CSMA and RTS/CTS mechanisms to reduce collision. The radio propagation path loss is modeled as Two-Ray; the physical layer raw data rate is 1Mbps for RTS/CTS and SRAC specific control frames, and 2Mbps for other transmissions (per atomic channel).

Unicast

The network topology is shown in Figure 9, where node 1 sends CBR traffic to node 3 via relay node 2, starting from time 0.5 second and ending at time 30 seconds. The jammer starts at time 10 seconds and lasts to the end of the simulation. The routing protocol is AODV. The CBR packet size is 512 bytes. Figure 10 shows that at CBR sending rate 100 packets/s, without SRAC, the CBR traffic flow stops shortly after time 10 seconds when the jammer starts, while with SRAC, it continues. The ripple in the throughput for the case of SRAC is due to the communication overhead caused by notification and acknowledgement message exchange. The CBR sending rate is then increased to 200 packets/sec. The throughput as a function of time is now plotted in Figure 11. The drop in the throughput after the start of the jamming is because the network already reaches its capacity, and there is no spare capacity, as in Figure 10, to completely compensate for the artificial packet loss (i.e., due to a node not being always on a channel).

Multicast

The multicast routing protocol is On-Demand Multicast Routing Protocol (ODMRP), and the multicast application is Multicast CBR (MCBR). For clarity, a simple network topology is the initial focus, as shown in Figure 12, where the nodes are evenly spaced. Nodes 5, 6, 4, 7, 8, 12 form a multicast group. Node 5 sends MCBR traffic to the other nodes in the multicast group. The MCBR application starts at time 20 seconds, and stops at time 100 seconds, with data rate of 2 packets/sec. The jammer starts at time 50 seconds. The physical layer parameters such as transmission powers are set the same as those in the unicast simulations. We run the same scenario 10 times with different random seeds to obtain an average. It is seen in Figure 13 that with SRAC, the average total number of packets received by the MCBR receivers are 94.61% higher than that without SRAC. Note that for those nodes that are affected by the jamming, i.e., nodes 4, 7, 8 and 12, the gain is even higher. In fact, if there were no jamming, 800 packets would be received in total at most by the MCBR receivers. With SRAC, a total number of 793 packets are received under the jamming attack.

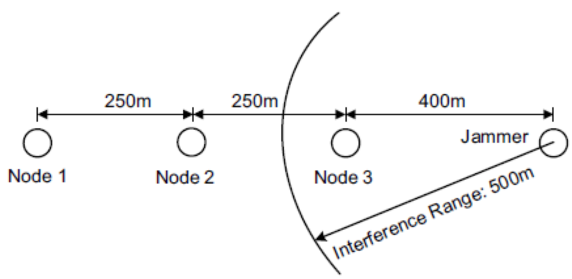


Fig. 9. Network setup for the unicast simulations.

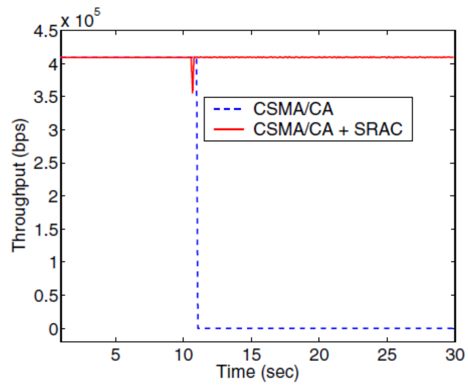


Fig. 10. Throughput for the CSMA/CA MAC protocol with and without SRAC for 100pkts/sec CBR traffic generator.

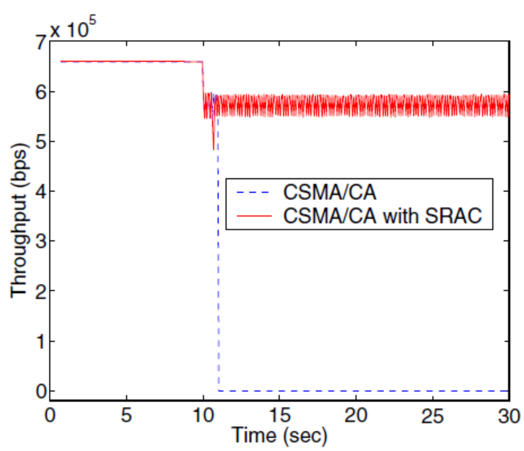


Fig. 11. Throughput for the CSMA/CA MAC protocol with and without SRAC for 200pkts/sec CBR traffic generator.

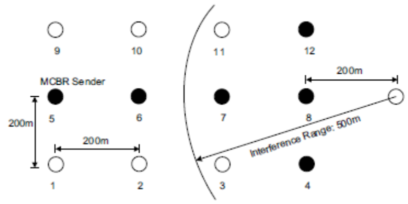


Fig. 12. Network setup for the MCBR multicast application, where solid black circles represent the nodes in the multicast group.

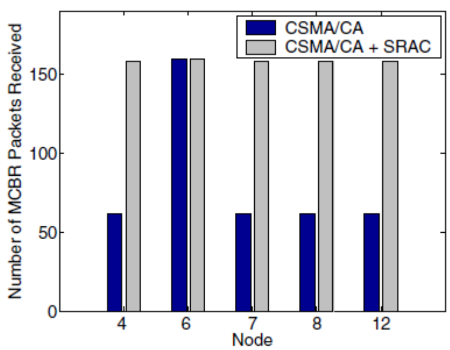


Fig. 13. The number of MCBR packets received by each multicast group member, where node 6 is not affected by jamming while others are.

B.5 Milcom 2006

Twenty-four papers were surveyed as satisfying initial criteria, but none satisfied all of the final requirements for inclusion.

B.6 Milcom 2007

B.6.1 Youping Zhao, David Raymond, Claudio da Silva, Jeffrey Reed, Scott Midkiff, "Performance Evaluation of Radio Environment Map-Enabled Cognitive Radios Coexisting with Incumbent Users," Milcom 2007

Summary:

(From abstract) "In recent years, cognitive radio (CR) has been introduced as a new paradigm for enabling much higher spectrum utilization by dynamically accessing and sharing the spectrum with incumbent radio devices. This paper proposes an innovative and practical spectrum-sharing approach and evaluates its performance. The goal is to minimize CR's harmful interference to incumbent primary users and to maximize the utility of spectrum-sharing networks by exploiting the proposed radio environment map (REM). REM-enabled CR adaptation algorithms are developed for various operational environments, namely, the open area and the dense urban area. This paper also compares the performance gain when using the Global REM and the Local REM, respectively. The impact of imperfect REM information due to node mobility and REM dissemination delay is simulated. By exploiting the REM information, CR can make situation-aware adaptations in transmit power, transmit timing, routing protocol, and topology, thereby reducing interference to primary users. More importantly, the painful hidden node or hidden receiver problem can be mitigated with the help of the Global REM. REM-enabled CR could be a cost-efficient and reliable approach to "waterfilling" underutilized spectrum in both space and time domains**.**

Comment: Compares various CR SU REM based strategies/scenarios to non CR SU performance.

Quantified Benefit:

Improvement in Average SINR at PU's

Considered Scenario:

"First, we explore the potential of "waterfilling" the underutilized spectrum and enabling multi-scale heterogeneous wireless systems to coexist peacefully with the REM-enabled CRs. Secondly, through performance evaluation, we demonstrate the benefits of REM-enabled cognitive spectrum-sharing networks in refarming previously licensed bands, e.g., the TV broadcasting bands, where various incumbent PUs exist." Both "global" and "local" REM are used.

Tags: Global and Local Radio Environment Maps, Spectrum sharing

B.7 SDR Forum 2002

B.7.1 J. Kleider and G. Abousleman, "Joint Source-Channel Matching for Jamming and Fading Using an OFDM Variable QoS Source Channel Design," SDR Forum Technical Conference 2002, San Diego, November 11-12, 2002, 0.1.0-012.

Summary:

The paper presents "a channel adaptive technique, combined with an intelligent quality-of-service (QoS) manager, to maximize reception quality while minimizing the required transmitted signal energy. The technique uses multicarrier (MC) modulation and assigns high priority data to the best frequency domain segments of the transmit spectrum. We utilize a joint source-channel matching method that optimally matches the application layer information to the physical layer transmission capabilities. This is performed by searching for the most desirable "match" between the physical layer channel performance and the allocation of the voice, data, and/or video information to the MC sub-channels."

Quantified Benefit:

2 – 11 dB improvement in Peak SNR (PSNR).

Considered Scenario:

"We applied the iterative image quality optimization procedure and evaluated the quality at various QoS strategies using objective (Peak SNR) and subjective (visual) measures. To assure a fixed image delivery rate, we assigned 130 MC blocks per image, and a MC block (symbol) time of approximately 256 μsec. This supports a 30 image/sec frame rate, which is sufficient for high-quality video applications. The total number of MC subchannels per block is equal to 256. In Table 1, we compare three transmission methods: $VQoS^M$, $VQoS^1$, and FQoS/QAM. $VQoS^M$ and $VQoS^1$ both use adaptive modulation, with the $VQoS^1$ system having a single QoS region (i.e., $q = 1$). The FQoS/QAM system adapts the fixed modulation order (given the channel bit error rate), such that the peak SNR (PSNR) is maximized for each transmitted image. Figure 4 shows the average PSNR results for each channel. The reported PSNR was determined by averaging 20 different transmissions through each channel. By performing the proposed algorithm over many channels, including those shown in Figure 4, we found the $VQoS^M$ optimization process can result in a performance improvement of at least 2 dB. The $VQoS^M$ method was found to perform better than $VQoS^1$ in all channels, with increasing ΔPSNR as the channel degrades (compare ΔPSNR between channels 1 and 3). Figure 5 shows the visual quality of the 512 X 512 Lenna image for $VQoS^M$ and FQoS/BPSK, when transmitted through channel 3. In this example, the improvement (ΔPSNR) is greater than 11 dB."

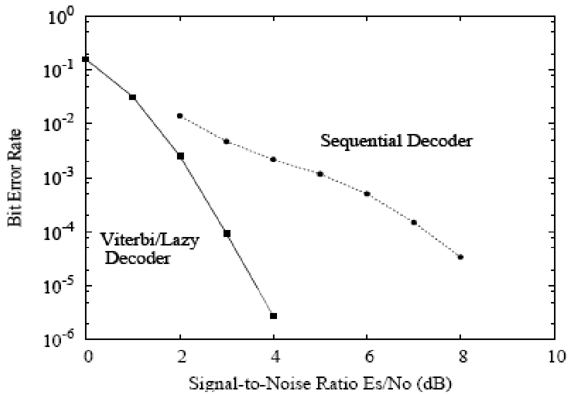
Tags:

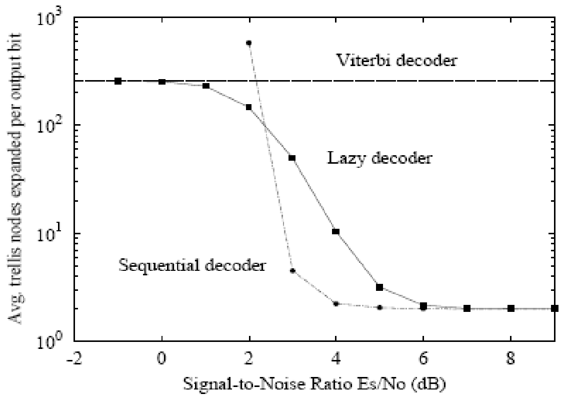
SNR, link adaptation

B.7.2 M. Frigo, "Algorithmic Advances for Software Radios," SDR Forum Technical Conference 2002, San Diego, November 11-12, 2002, 01.3-001.

Summary:

Presents a modified version of the A* decoder for convolutional codes which they call the "lazy Viterbi decoder." The lazy Viterbi decoder maintains a priority queue of nodes, keyed by accumulated metric such that only the most promising nodes are expanded. This has the effect of greatly reducing the number of trellis nodes per output bit as SNR improves while preserving performance as illustrated below.





Quantified Benefit:

Significantly reduced cycles in the best case (high SNR) without sacrificing cycles in the best case (k is # states, L is trace-back length).

Algorithm	Best case	Worst case
Viterbi	$\Theta(2^k)$	$\Theta(2^k)$
A^*	$\Theta(\log L)$	$\Theta(2^k \log(L2^k))$
Lazy Viterbi	$\Theta(1)$	$\Theta(2^k)$

Specific measurements

Decoder	Constraint length	Athlon XP cycles/bit	Pentium III cycles/bit	PowerPC 7400 cycles/bit	StrongARM cycles/bit
Lazy	6	193	201	200	226
Viterbi Optimized	6	275	316	239	310
Karn Unoptimized	6	1041	1143	626	892
Lazy	7	198	205	203	232
Karn Optimized	7	530	558	486	641
Karn Unoptimized	7	1806	2108	1094	1535
Karn SSE	7	107	108	N/A	N/A
Lazy	9	217	235	225	343
Karn Unoptimized	9	6300	8026	3930	5561
Karn SSE	9	307	310	N/A	N/A

Considered Scenario:

The order of magnitude results are general. The table of measurements is formed as follows:

“Times are expressed in cycles per decoded bit. Code for constraint length 6: TIA/EIA-136 code, polynomials 0x2b, 0x3d. Constraint length 7: “NASA” code 0x6d, 0x4f. Constraint length 9: IS-95 code 0x1af, 0x11d. Processors: 1466MHz Athlon XP 1700+, 600MHz Intel Pentium III, 533MHz PowerPC 7400, 200MHz StrongARM 110. All programs compiled with gcc-2.95 -O2 -fomit-frame-pointer and the most appropriate CPU flags.”

Tags:

Algorithm adaptation. FEC.

B.8 SDR Forum 2003

B.8.1 I. Dagres and A. Polydoros. “Dynamic transceivers: Adaptivity and reconfigurability at the signal-design level,” SDR Forum Technical Conference 2003, November 17-19, 2003, Orlando, paper #EU1-002

Summary:

OFDM-based, short-range indoor adaptive radio transceiver design for slowly varying channels. Provides a general framework for dynamic signal design and proposes two algorithms for satisfying QoS requirements wherein power, constellation, and code size are varied.

Algorithm 1:

1. Select the code rate, constellation size based on the target bit rate.
2. Read the required uncoded BER (from a look up table) based on the target BER.
3. Find the average SNR needed in order to reach the required uncoded BER
4. Compute the power needed in order to achieve the required average SNR, based on the current average SNR.

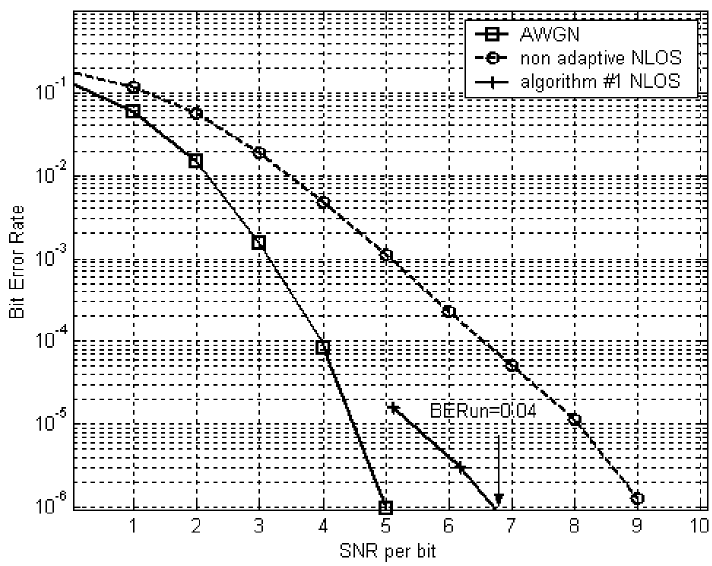
5. If required power > maximum available power, re-negotiate QoS (lower the requirements) and go to step 1; else output the power/constellation size/code rate

Algorithm 2:

1. Select the competitive triplets of: {code rate, constellation , WSCE%}, based on the target rate.
2. Read the required uncoded BER (from a LUT) for each of the choices.
3. Find the average SNR needed in order to get the required uncoded BER for each choice.
4. Compute the power in order to achieve the required average SNR based on the current average SNR for each choice.
5. If required power > max available power for all the triplets, then re-negotiate QoS and go to step 1; else, output the triplet with the min power requirement.

Quantified Benefit:

2 dB for Algorithm 1:



"An average 2dB additional gain is achieved by using the second algorithm versus the first one. "

Considered Scenario:

"The main simulation system parameters are based on the WF Platform. It has 128 sub-carriers in a 50M-Hz bandwidth (100 active for tx), and the channel model is fully described in [7]. There are two channel scenarios, one line of sight (LOS) with coverage about 100m, and one with no line of sight (NLOS) with coverage about 10m. Both experience deep fades over the 50MHz band, and can be considered static over a frame period (1 frame equals 178 OFDM symbols). The adopted constellations schemes are BPSK, 4-QAM, 16-QAM and 64-QAM, adaptively chosen based on the target throughput requirements. It uses a parallel- concatenated turbo coding scheme with variable rate via three puncture patterns (1/2,2/3,3/4) [8]. The recursive systematic code polynomial used is $(13,15)_{oct}$. Perfect channel estimation and zero phase noise are also assumed herein. Simulation results using algorithm #1 for adaptive transmission power minimization are presented in Figs. 3. The performance gain of the proposed algorithm is shown for BPSK, the code rate equals ½, and the code information block length is 50 bits (**N** = 100bits)."

Tags:

Adaptive modulation and coding (AMC), SNR, QoS

B.9 SDR Forum 2004

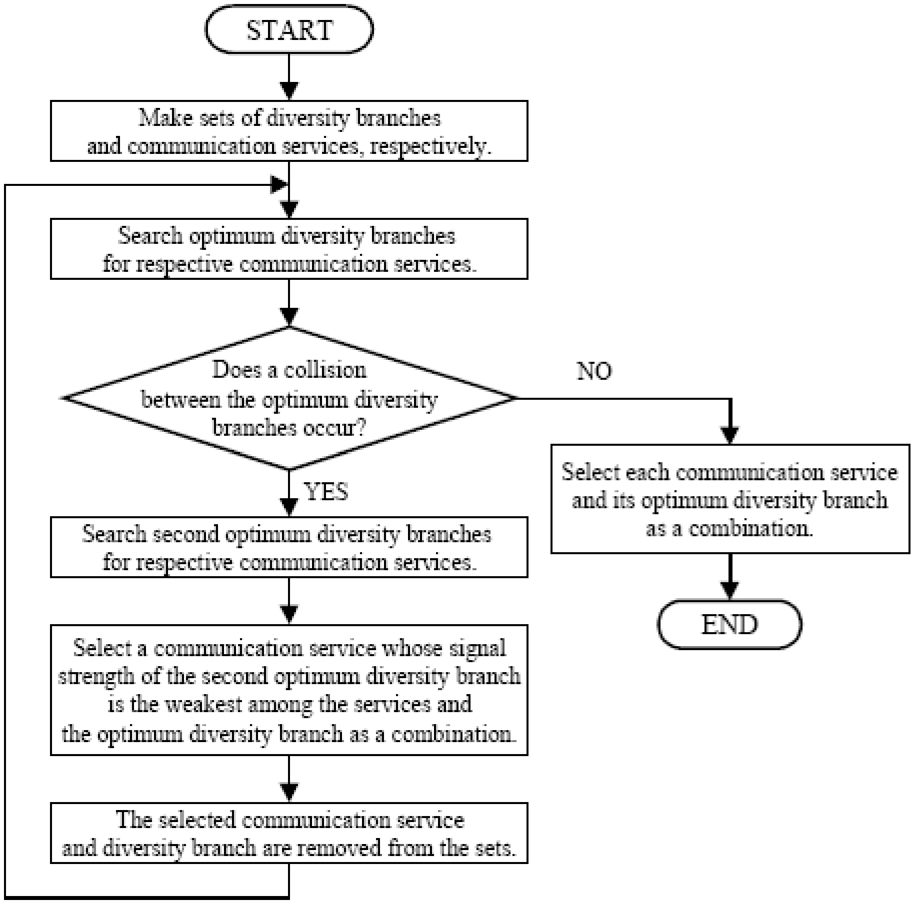
B.9.1 N. Suzuki, K. Ito, N. Itoh, "A Novel Multi-Service Simultaneous Receiver with Diversity Reception Technique by Sharing Branches," SDR Forum Technical Conference 2004, November 15-17, Phoenix, paper # 4.3-4

Summary:

Proposes improving simultaneous multi-waveform reception by exploiting diversity. Begins by noting the need for simultaneous reception particularly for discussed 4G standards, reviews traditional multi-service architectures (which use various TDM or FDM approaches) and briefly reviews principles of diversity reception. The paper then describes its proposed receiver architecture, which can be briefly described as a multiple RF/IF chain receiver with selection diversity where the radio is permitted to choose any M chains where M is the number of waveforms and M is presumably less than the number of RF/IF chains. This method also assumes a chain cannot simultaneously receive two waveforms.

The paper then reports on a simulation of the proposed architecture and compares it to traditional diversity reception schemes. Here, a traditional diversity scheme to receive M waveforms assigns n unique fixed branches to each waveform for a total of Mxn branches. Simulations show that with three receiver chains and their selection diversity algorithm the flexibility to choose among all three is better than the scenario where there are four branches where each waveform is assigned two fixed branches.

The proposed algorithm is as shown below:



The short version is:

(1) Each communication service is received by any one of diversity branches, namely, selection diversity is assumed.

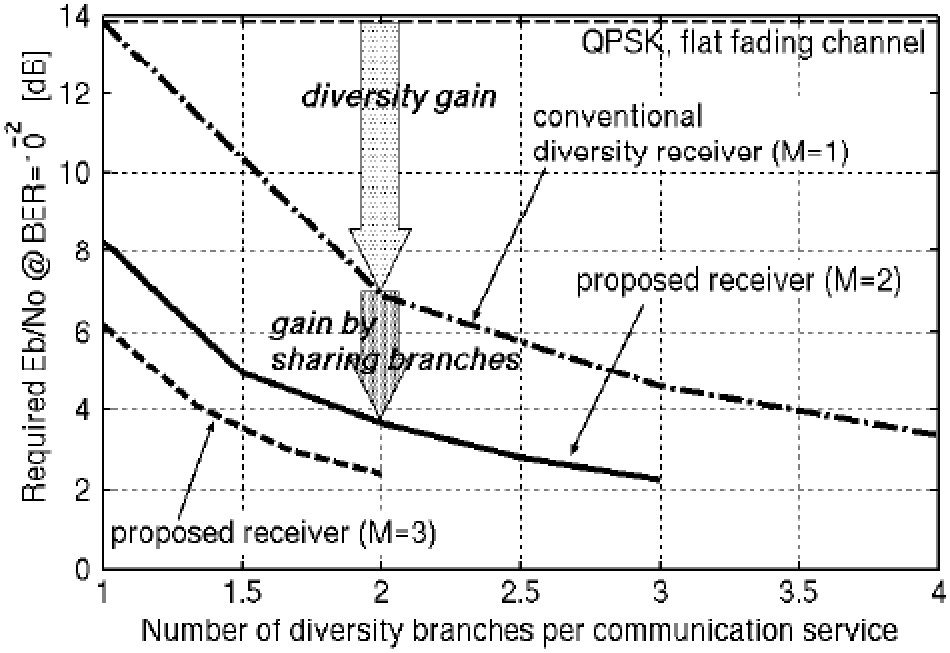
(2) Each communication service can select the optimum diversity branch when a collision between the optimum diversity branches does not occur.

(3) The communication service, whose signal strength of the second optimum diversity branch is the weakest among communication services, can select the optimum diversity branch when a collision between the optimum diversity branches occurs.

It is compared to a multi-waveform receiver where each waveform is assigned a fixed set of transceivers.

Quantified Benefit:

~3 dB over traditional (fixed) selection diversity



Considered Scenario:

The performance of the proposed multi-service simultaneous receiver sharing diversity branches is evaluated by simulation. The simulation parameters are described in Table 1. All modulation types of communication services are the same QPSK to evaluate the basic characteristics of the diversity reception. It is assumed that all communication services have the same symbol rate and synchronize the services to simplify the simulation. It is also assumed that the frequency offset is zero, the symbol synchronization and the phase tracking are perfect, and the combinations of a diversity branch and a communication service are selected every symbol based on the algorithm in Section 4, in order to evaluate the ideal performance. The whole hardware complexity of receivers is evaluated by the total number of branches N_t.

Table 1: Simulation parameters.

Modulation type (all services)	QPSK
Channel model	slow flat fading
Number of services for simultaneous reception M	from 1 to 3
Number of diversity branches N_t	from 1 to 6

Tags:

Performance, QoS

B.9.2 R. Abou-Jaoude, W. Koenig, J. Luo, M. Dillinger, "Dynamic Network Management in Reconfigurable Systems- HSDPA Power and Code Allocation," SDR Forum Technical Conference 2004, November 15-17, Phoenix, paper # 1.3-2.

Summary:

In this paper, the shared channel capability that will be included in the first UMTS evolution (known as the High Speed Data Packet Access (HSDPA)) is considered for the delivery of the data to users in the network and in the moving hotspot. The power allocation, controlled by the network's management subsystem, tries to adapt to the load changing in time and in space.

Quantified Benefit:

Reduced latency, improved throughput

Table 3: Gains in terms of response time (seconds)

Response Time	Hotspot cell	Other cells
70th percentile	0.34 sec less	0.13 sec more
80th percentile	0.75 sec less	0.24 sec more
90th percentile	2.18 sec less	0.58 sec more

Table 4: Gains in terms of throughput

Throughput	Hotspot cell	Other cells
40th percentile	0.72 Mbps more	0.0010 Mbps less
70th percentile	0.37 Mbps more	0.0013 Mbps less
90th percentile	0.36 Mbps more	0.0030 Mbps less

Considered Scenario: (maybe half the paper is just describing the simulation setup)

We consider the data services provided by the shared channel in UMTS, the HSDPA. Users are scheduled each three slots, and their throughput depends on their received signal, which determines which modulation and coding to select for transmission. It consists of 15 spreading codes, which can be attributed to one or divided between more at each scheduling instance. To simplify the simulation model, in a first step, we assume that users of a cell will not be multiplexed at one time in the code domain, but each will receive all 15 codes when scheduled. Since the purpose here is not to design an optimum scheduler, the benefits of the dynamic network management and reconfiguration are not affected. The adaptive power allocation at each base station involves a shift of resources between dedicated services such as voice with variable power and shared services such as background traffic with constant power. Moreover, it involves a reconfiguration of the base station's DSP and ASIC boards to allow for a faster decoding of the information depending on its type. In the case of HSDPA, the base station has additional functionalities such as the fast scheduling (assigning resources to users on a 3-slot frequency), modulation and coding schemes selection, and H-ARQ as a fast retransmission mechanism. The power assignment is done at the network management level on a less frequent basis, though not standardized by 3GPP. In our proposal, the network manager sets frequent signals during the day to base stations as to which fraction of their available total power to allocate to HSDPA, and if necessary to reconfigure HW and SW to work under the dedicated or the shared mode. Figure 2 shows the network deployed considered in our analysis.

A set of 12 cells with uniformly distributed users is created, and one of the cells contains an additional hotspot of users. This is similar to a weekday case, where users head to work during the day and concentrate the use of resources in one region, the hotspot being mobile in case other events take place in other cells.

The user arrival rate for such a system is Poisson distribution with rate R. Although the service demands for all users can be assumed to be negative exponentially distributed, capacity degradation due to signal attenuation, fading and interference from co-channel interferers makes the service time distribution to be not exponential any more. We assume every customer has the capability of processing all 15 spreading codes simultaneously, and all customers (mobile stations) access the shared radio resources in a pure time sharing context. By exploiting this fact, the HSDPA base station works like a single server and assigns radio resource in terms of minor intervals to mobiles when it is scheduled to be served. Therefore, such system can be modeled by the M/G/1 with processor sharing discipline.

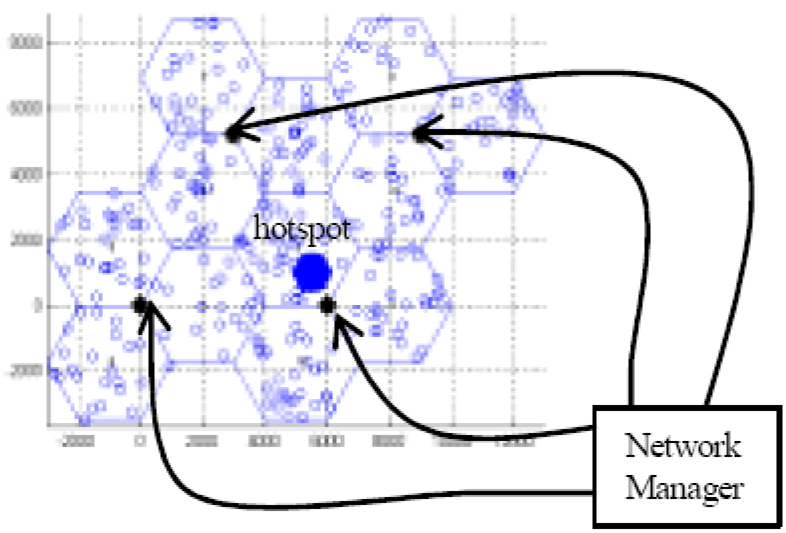


Figure 2: Network layout and power commands

Table 2: Simulation parameters

Number of cells	12 - hexagonal
Sector configuration	120° - directional antennas
Average users per cell	50
Average users in hotspot	150
Channel used	HSDPA
Base station power	25 Watts
Power for HSDPA	60%
Cell radius	2000 m
Hotspot radius	500 m
File size d	100 kbits
Arrival rate λ	32 users/s

Tags:

Cognitive Network, throughput, latency

B.10 SDR Forum 2005

B.10.1 J. Luo, C. Kloeck, K, Moessner, D. Grandblaise, P. Demestichas, G. Dimitrakopoulos, E. Mohyeldin, O. Sallent, P. Cordier. "Inter-operator Flexible Spectrum Management vs. Roaming," SDR Technical Conference 2005, November 14-18, Orange County, paper # 4.3-04.

Summary:

Paper generally discusses "Flexible Spectrum Management". Part way through, it cites some gains for spectrum pooling and dynamic channel assignment and compares it to fixed channel assignment.

Quantified Benefit:

"The spectrum efficiency gain is achieved by pooling spectrum between different radio access technologies given intra σi,i and inter σi,j spectrum reuse distance constraints between base stations operating different technologies. One analysis of pooling has been recently published in [10]. For PBlocking = 5%, pooling scheme outperforms single system based strategies assuming non seamless roaming. Pooling scheme, FCA with channel borrowing and DCA improves respectively the number of served users of 144%, 66%, 66% compared to Simple FCA. Additional FSM gains results for some other scenarios have also been shown in [11]."

Considered Scenario:

Actually references other papers, so scenario is captured in quote above.

Tags:

Capacity

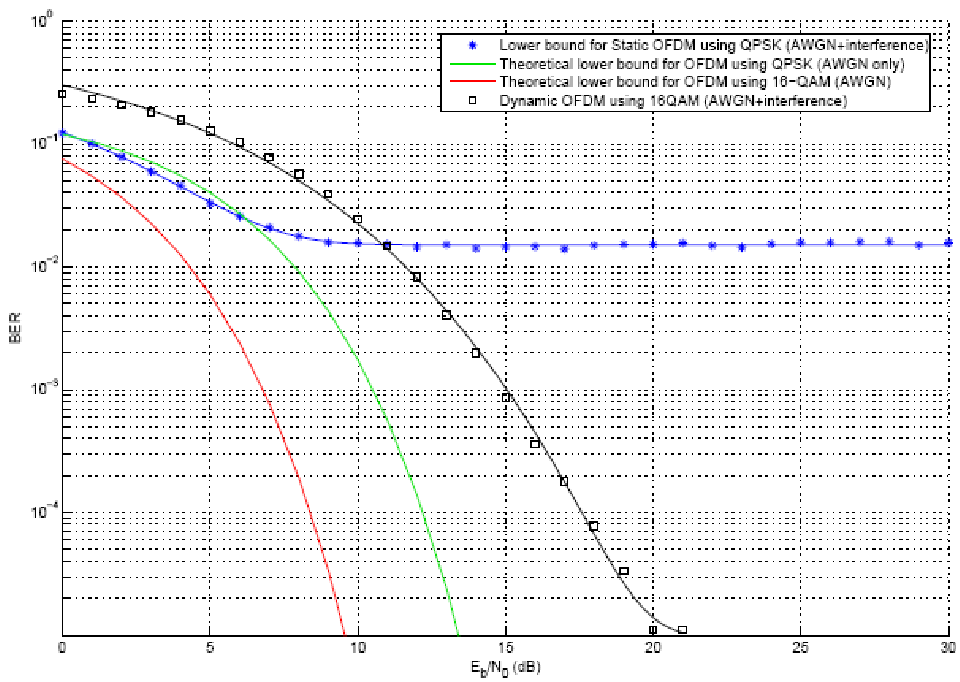
B.10.2 Keith Nolan, Linda Doyle, Donal O'Mahony, Philip Mackenzie. "Fluid Wireless – Dynamic Spectrum Allocation and Spectrum-Monitoring Application Using Reconfigurable Radio and OFDM," SDR Technical Conference 2005, November 14-18, Orange County, paper # 4.4-04.

Summary:

The radio (implemented on GPP) uses OFDM to provide multiple access and dynamic spectrum access. As was described in the 2004 paper, available interference is determined by a PSD calculated from the system's FFTs and free subcarriers exploited. BER curves are given for the system for AWGN channels and in the presence of interference.

Quantified Benefit:

Improved BER performance in presence of jammer.



[I'm nearly certain that the AWGN BER curves in Fig 5 are mislabeled. The red line is actually QPSK (labeled as 16-QAM) and the green line is 16-QAM (labeled as QPSK).]

Considered Scenario:

"A baseband channel model is used to evaluate the performance of the interference-avoidance dynamic OFDM technique. The channel model experiences interference from a FM transmission comprising three tones of equal power and common to both source and destination MUDERS transceivers. This interference source has a peak power of 2.9dBm and the centre frequency is located within the desired OFDM transmission band.

Two scenarios are examined. The first scenario is a traditional static implementation of OFDM using QPSK as the sub-carrier modulation technique. All of the possible subcarriers are employed regardless of the wireless channel conditions. For this test scenario, 128 subcarriers were used. The peak power of this OFDM signal is 0.16dBm. The second scenario employs the interference-avoidance sub-carrier allocation technique using 16-QAM on $SC\ N$ valid subcarriers. The second scenario involves the same interference-affected AWGN channel model but the OFDM signal is changed. In this case, the threshold value $thresh\ P$ is equal to approximately 1% of the maximum estimated peak power of the interfering signal."

Tags:

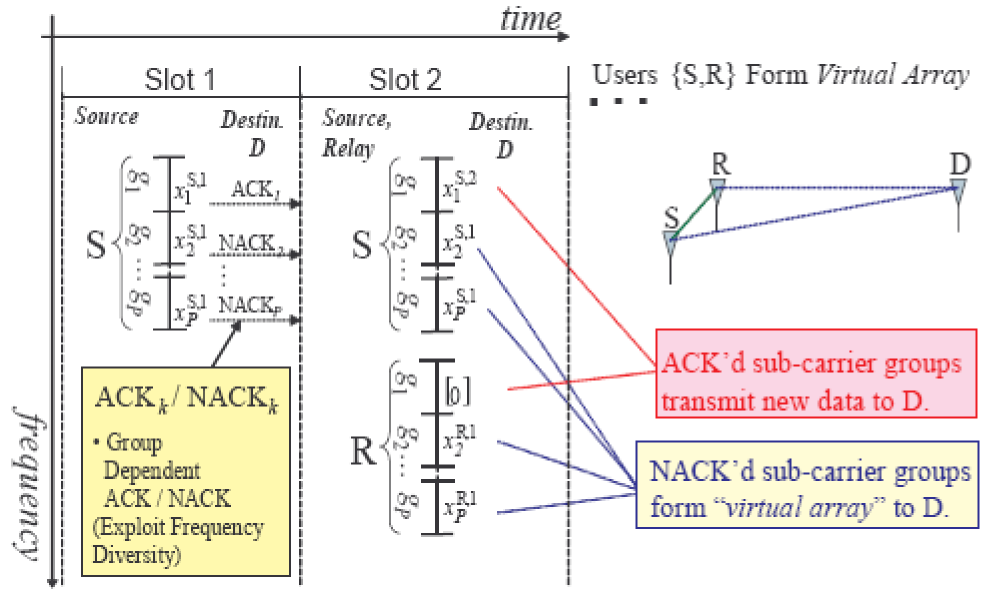
Interference avoidance, BER, Jammer mitigation

B.11 SDR Forum 2006

B.11.1 Anderson, K., J. Kleider, T. Wang, G. Giannakis, "Transmit Diversity Enhancement for Tactical Wireless Networking using Multi-carrier Distributed Space-Frequency Coding," SDR 06 Technical Conference, November 13-17, 2006, Orlando, paper # 2.3-01.

Summary:

Describes the design and implementation of a virtual transmit array using a source and relay node to effect transmit diversity using an OFDM signal and Alamouti encoding modified to be over space and *frequency* instead of space and time.



To combat channel imperfections, the authors use preamble code and pilot symbol aided modulation. The authors also include a MAC protocol in which data is initially transmitted by the source node, acknowledged by the destination if received correctly; if that fails the relay node (which also received the initial packets) and the source node retransmit in the second time slot. To overcome timing issues, the authors suggest separating the synchronization and decoding steps which they find to give better performance. Note that this technique requires unique synchronization preambles to be assigned to each node in the transmit array. They also make use of a maximum likelihood decoder to preserve channel diversity.

The authors describe the packet and waveform structure and simulation results based on a COST 207 typical urban channel model as implemented on a distributed MIMO test bed (computers running over the simulated channel model).

Quantified Benefit:

"[A] 9-dB and 7-dB SNR improvement is possible at a BER = 10^{-3} for 4-QAM and 16_QAM"

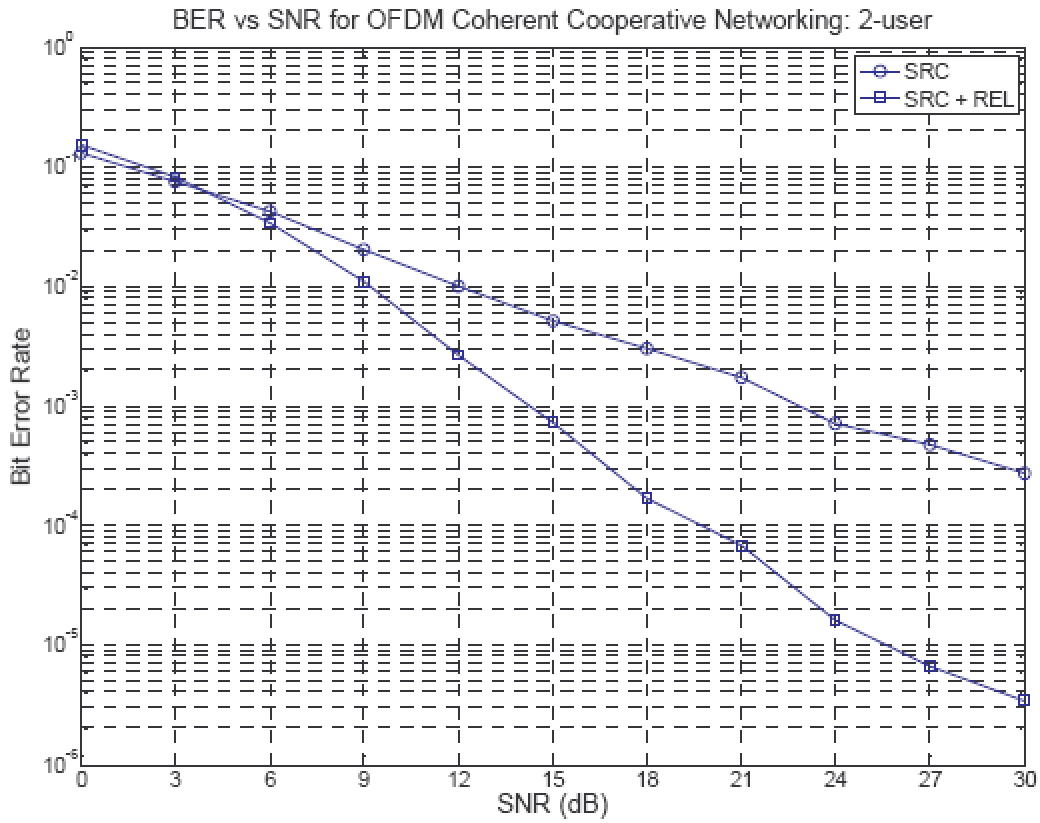


Figure 5: 4-QAM OFDM D-STC BER performance.

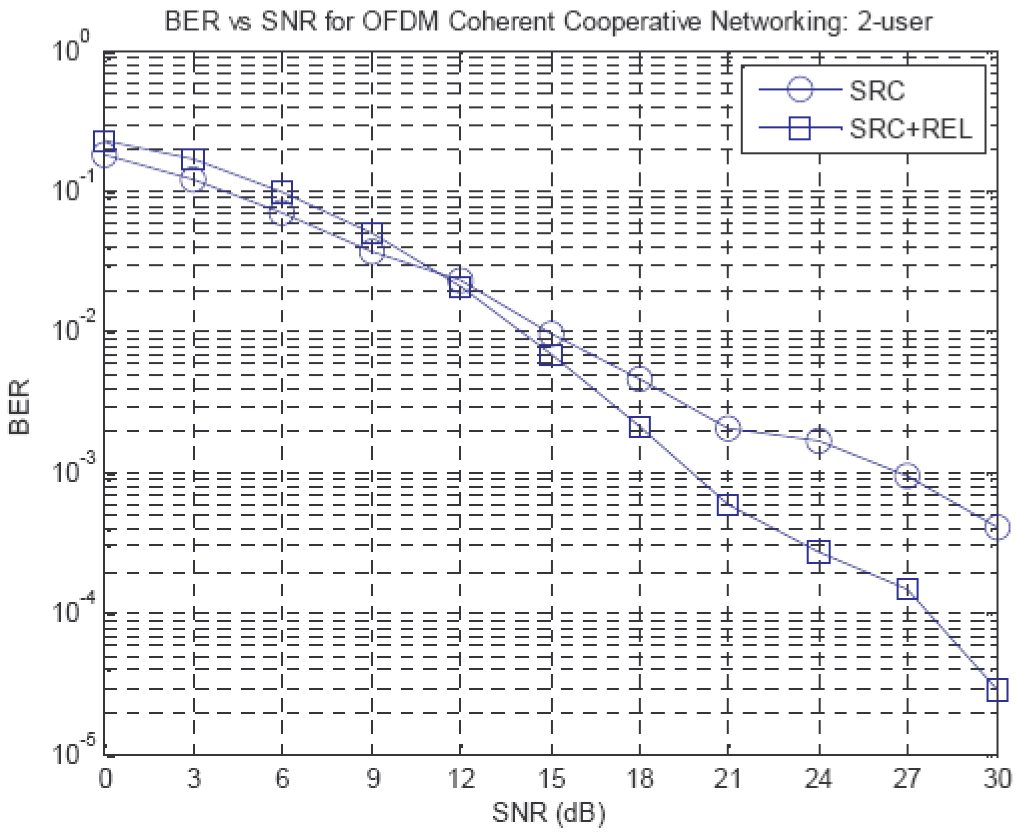


Figure 6: 16-QAM OFDM D-STC BER performance.

Considered Scenario:

"During test bed evaluation of fading performance, we utilized the stochastic zero mean Gaussian Stationary Uncorrelated Scattering (GSUS) model to induce time varying frequency selective fading according to a COST 207 typical urban (TU) delay profile [13]. The test bed was setup to induce independent multipath profiles from S to D and R to D, respectively. To provide a good statistical representation of a time-varying multipath channel, but consistent with the MRC structure in (5), the channel was held approximately constant during a 2-slot time period, but then changed independently over each subsequent 2-slot interval. While the channel may not change as rapidly on successive 2-slot intervals in practice, this allowed us to test many different multipath channel realizations without excessive simulation time. From Figure 3, paired symbols [*s*0, *s*1]T are coded across sub-carriers, such that *fn* = (*fs*/*N*)**Nst*/2. This ensures that the correlation, along the diagonal entries of ***h*** is less than 1, and allows us to test the diversity performance of the ML decoder. Using the GSUS channel model, we simulated the OFDM system using 4- and 16-QAM modulations, with a random timing offset of less than 128 samples and a frequency offset equal to or less than 300 Hz. The synchronization offsets from each transmit node to the receive node are assumed independent.

Our testing platform ("test bed") consists of two dual pentium computers; each computer is populated with two Red River Waverunner Plus cards. Each Waverunner card adds software defined transceiver capability mounted in the PCI backplane. Each transceiver card acts independently and, therefore each computer can be considered as a two channel transceiver. Hence, our setup can support a 2 X 2 MIMO configuration or any combination of 4 channel SIMO or MISO. The transceiver card uses a carrier frequency of 70 MHz and can operate in both a narrowband or wideband configuration. Both receiver and transmitter have SMB connectors to input or output RF energy to external amplifiers and antennae. Our test bed has been run with combinations of antenna's, attenuators and internal and external channel emulators.

The test bed does not run in real time because we run Matlab for baseband processing to achieve faster development cycles, combined with 'C' code that controls the Waverunner card. Our Matlab code generates the baseband transmit signal and, on reception, processes the baseband receive signal, which enables us to invoke our own internal channel models if desired or to use external channel simulators. The interaction between the waverunner card and Matlab takes place through DMA transfers to onboard

Waverunner FIFO. The Waverunner provides digital filtering, A/D, D/A processes and up/down conversions.

In Figures 5 and 6, BER performance for the coherent distributed space-frequency coded OFDM system using 4- and 16-QAM, respectively are shown. Two curves are plotted in each figure, one trace exhibits statistics on S results only (denoted by the legend "SRC") and the second trace is for combined S and R results (denoted by the legend "SRC + REL"). For S only, the diversity order = 1, while for S + R, the diversity order = 2. Thus, we see that when the *virtual array* is formed to D using S + R a full diversity order = 2 is realized. This is evident for both the 4- and 16-QAM modulations.

Tags:

Bit error rate, Performance / QoS, Synthetic MIMO,

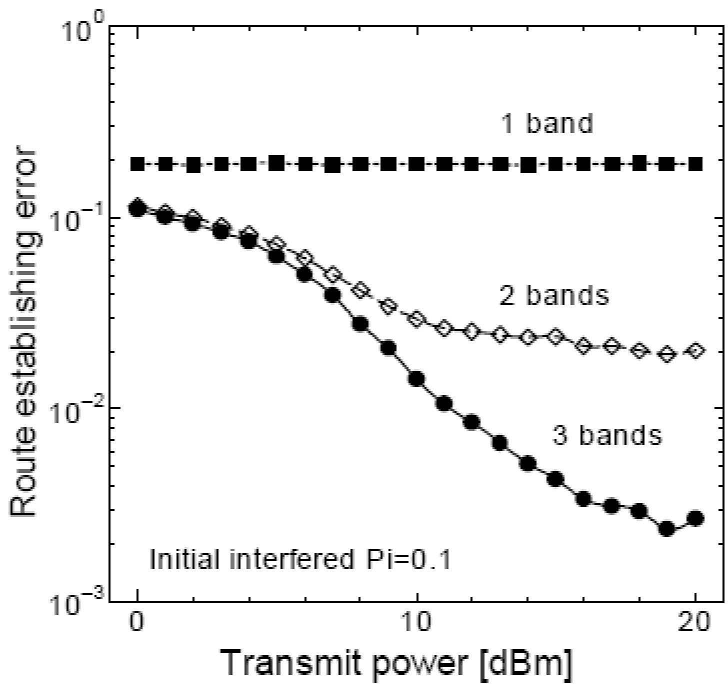
B.11.2 Fujii, T., "Multi-band Routing for Ad-hoc Cognitive Radio Networks," SDR 06 Technical Conference, November 13-17, 2006, Orlando, paper #3.2-01

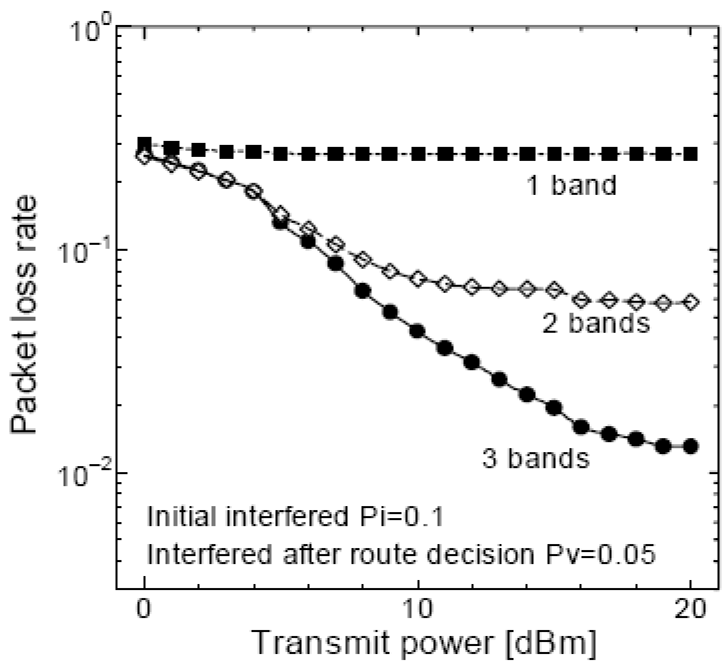
Summary:

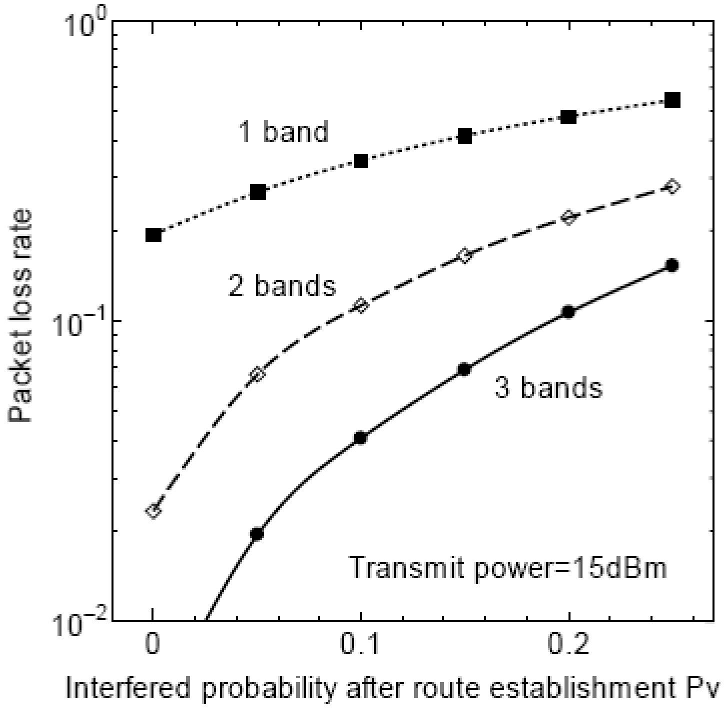
Proposes an algorithm for performing routing using multiple bands. Basically, the approach involves typical route flooding to establish routes, but across all available bands. These routes are then ranked by each node in terms of preference. As routes may or may not be available in different bands because of fading or the presence of primary users, nodes work down their list of routes in descending preference until a workable route is found. Simulations confirm that having additional redundant routes increase the likelihood of having a complete route and reduce the likelihood of dropped packets. Increasing transmission power of the nodes also increases connectivity.

Quantified Benefit:

Packet error rate reduction by factor of 10 (2 bands) or 100 (3 bands) at higher power.







Considered Scenario:

"In order to evaluate the performance of the proposed system, we show the results of computer simulations. In this simulation, we prepare three difference frequency bands as 750MHz, 2.4GHz and 5GHz. The original routing method for ad-hoc networks using only one frequency band for transmitting the data packet from the source node to the destination node. In this paper, the conventional routing method is shown as "1 band." In the proposed method, the plural routes are established by using plural frequency bands. Here, the routes with parallel two and three frequency bands are named as "2 band" and "3 bands," respectively. We consider 200m times 200m squared simulation area as shown in Fig. 3. We set a source node and a destination node at the center of this simulation area with 100m apart each other. 100 relay nodes are set at the random position in this simulation area. The simulation conditions are shown in Table 1. In this paper, we only consider the path loss and the fading and shadowing are not considered. The path loss attenuation factor is set as three and the attenuation level is different in each frequency band according to the propagation theory. The noise level of each node is -95dBm and the threshold signal to noise ratio (SNR) level for the packet without error is decided as 10dB. Therefore, if the received SNR of each packet is more than 10 dB, we regard the packet can be successfully transmitted.

In the routing period, the routing is continued if the RREQ is received with SNR more than 10dB. The antenna gain of each antenna is set as 0dBi. In simulations, in order to assume the interference from the primary system with time variance transmission, we consider Pi=10% initial link loss between the nodes in each frequency band. Moreover, we consider variable link status between the nodes by using the probability of changing interference situation after establishing the route as Pv. If Pv is set as 5%, the link status is changed as the probability of 5% from the connected link without error to the disconnected link with error or from the disconnected link to the connected link. The packet collision among the cognitive terminals is not considered in this simulation.

First we show the probability of route establishment error by changing the number of prepared frequency bands as shown in Fig. 4. In this simulation, we compare the performance among 1 band (750MHz) system, 2 bands (750MHz and 2.4GHz) system, and 3 bands (750MHz, 2.4GHz and 5GHz) system. In this simulation, even if one route is established by using three frequency bands, we decide that the route establishment is succeeded. It can be seen from the figure, we can confirm that the performance of the route establishing error can be reduced by preparing the plural routes. This is because the link loss due to the interference from the primary systems can be avoided by using the different frequency bands."

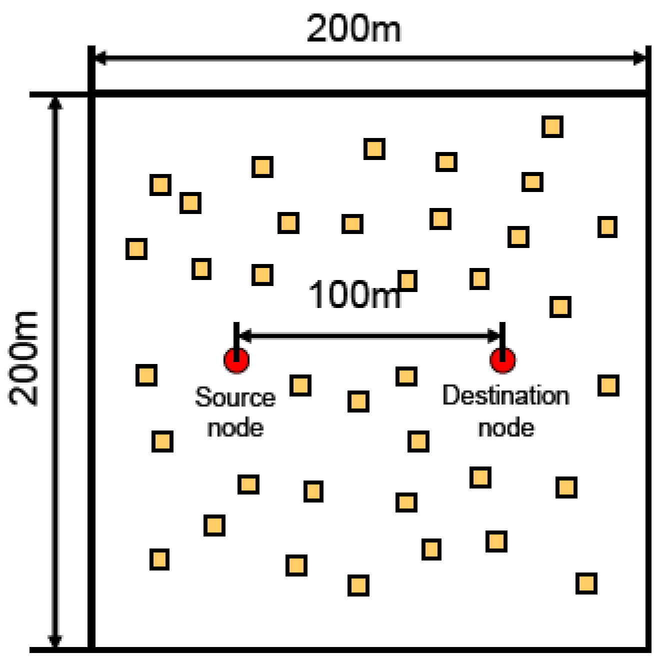


Fig.3 Simulation area.

Table 1 Simulation conditions.

Transmit power	Parameter
Path loss attenuation factor	3
Noise level	-95dBm
Threshold SNR for packet success	10dB
Number of frequency bands	Maximum 3
Initial link loss probability Pi	10%
Link status change after route establishment Pv	Parameter

Tags:

Routing, Packet error rate

B.12 SDR Forum 2007

B.12.1 J. Neel, "Synthetic Symmetry in Cognitive Radio Networks," SDR Forum 2007, Denver CO, Nov 5-9, paper # 3.6-02.

When designing a cognitive radio network, it is important to consider how deployed cognitive processes will interact in a network. Without sufficient planning, the interaction of even relatively benign-looking algorithms can yield undesirable behavior. However, by ensuring the network's observation processes satisfy the bilateral symmetric interference (BSI) condition, relatively unsophisticated distributed selfish algorithms will converge to optimal radio resource allocations.

Because CRT has further developed techniques for arbitrarily combining these conditions, virtually any network running virtually any waveform could allocate its layer 1 and layer 2 parameters at run-time using low-complexity non-cooperative distributed algorithms while achieving interference levels equivalent to those realized by centrally planned or massively cooperative algorithms. Using this approach, a metropolitan WLAN network could automatically adapt itself post deployment, as various private networks are deployed, rather than engaging in extensive pre-planning. Femtocells could be left to sort out their own allocation decisions instead of consuming network resources. Sensors could be arbitrarily dropped without priors or collaboration and still form optimal networks. Network management tasks could be greatly curtailed freeing up personnel for other activities. In the military space, MANETs such as those envisioned by WAND can be greatly simplified by using BSI-based distributed processes for layer 1 and 2 decisions while other processes handle layer 3 and policy decisions. Similarly, networks where nodes adjust their positions to improve communications (such as is envisioned in LANDroids) could also benefit from these BSI-based techniques.

B.12.2 Thilakawardana, D., K. Moessner, "Enhancing Spectrum Productivity through Cognitive Radios facilitating Cell-by-Cell Dynamic Spectrum Allocation SDR Forum 2007, Denver CO, Nov 5-9, paper # 3.6-02.

Randomly selected dynamic hotspots were considered and they were alive for 1-2 hours, commencing at different DSA intervals during the eight hour simulation period. Both DSA and FSA exhibits decrease in QoS as the traffic load increases; however, the rate of decrease of DSA is much lower than the FSA. According to the Fig. 6, the maximum user densities that can be supported by DSA and FSA schemes at 98% QoS are 170 and 100 Ms/cell/hour respectively. This indicates that the cell-by-cell DSA can support extra 70 more users/cell/hour than the FSA scheme giving a spectral efficiency of 42%. This is a 4% higher than the previously studied contiguous dynamic spectrum allocation [10]. A genetic algorithm based cell-by-cell DSA scheme has been studied in this paper to enhance system spectral efficiency while minimizing the spectrum usage, specifically to release network's spare spectrum for the benefit of cognitive radios. A novel 2D encoding scheme was proposed to map the DSA problem into artificial chromosomes, which significantly increase the convergence time as scheme prevents forming illegal chromosomes. The DSA scheme showed a spectral efficiency gain of 42% over FSA under a non-uniform traffic distribution. This study presents the first step towards understanding the application of genetic algorithms as a solution approach to the cell-by cell dynamic spectrum allocation. The developed simulator, GENEDYSA at this stage only supports a single radio access network and in future, the simulator will be extended to handle multi radio technologies.

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B.12.3 Salazar, J., V. Marojevic, I. Gomez, A. Gelonch, COMPUTING RESOURCES IN FLEXIBLE RADIO ENVIRONMENTS, Paper # 4.3-02.

Within this work has been observed how the decisions of cooperation between radio and computing resource management are strongly influenced by the environment, the status of the system and the given constraints such as minimum required performance, real-time deadlines and quality of service (QoS) parameters. The approach shall be based on a dynamic reconfiguration of the software defined radio platform. It has been stated that the application of some resource management strategy, which take into account the availability of the computing resources of the terminals, grants a better performance in terms of both, the system capacity and the computational load, because the most suitable algorithm(s) to execute the requested service(s) and the optimal parameters for its execution is chosen.

B.12.4 Chantaraskul, S., D. Thilakawardana, K. Moessner, Genetic Algorithm Approach for the Decision-making Framework in Opportunistic RADIO, Paper # 3.2-04.

This work focuses on the narrower definition of Cognitive Radio (CR), where the environment knowledge is restricted to spectrum awareness. This radio concept is termed as Opportunistic Radio (OR). The main concern of OR in here is the development of the decision making framework and its approach.

The focus of the decision making engine proposed here is the implementation of multi-objective decision making using Genetic Algorithms (GA) to provide the optimum solution for the spectrum utilization. With the implementation of GAs, beside the multiple objective optimization benefit brought into the decision making, the system also benefit from fast.

B.12.5 Volos, H., C. Phelps, R. Buehrer, INITIAL DESIGN OF A COGNITIVE ENGINE FOR MIMO SYSTEMS, Paper # 3.4-02.

This paper proposed a CE for MIMO systems. MIMO systems can exploit multiple antennas using a variety of techniques. The selection of which technique to use under certain conditions, is not always a straightforward task. In addition to proposing the CE, results from a partial implementation using a GA were presented. A GA was employed to find the best scheme to operate under certain conditions. Even though the GA searches only part of the search space, searching consumes resources as it is a trial and error process. Therefore, it is desired that the searching process be as efficient as possible. By addressing this issue, the need to use learning techniques for indentifying important system performance predictors (such as channel metrics) was indentified. Furthermore, it was concluded that searching and learning should both be employed as they provide different advantages to the CE’s performance.

B.12.6 Trogolo, A., P. Goria, E. Buracchini, A RADIO RECONFIGURATION ALGORITHM FOR DYNAMIC SPECTRUM MANAGEMENT ACCORDING TO TRAFFIC VARIATIONS, Paper # 3.6-04

This paper focused on the context of the multi-RAT deployments in the same geographical areas, pointing out the new opportunity for network operators owning two or more RATs to manage the resources of the deployed RATs jointly, in order to adapt the network to the behavior of the traffic and maximize the capacity globally. In the paper, a new algorithm for the hardware and radio resource optimization to be used in a network deployed with reconfigurable base stations has been described. The aim of this new algorithm is to give network operators a mean for optimally managing the radio and hardware resources among different RATs and increasing the overall capacity of the whole network. In case of GSM network, the paper presented some preliminary performance results that highlighted the quality of the algorithm.

B.12.7 Jaeger, D., M. Vondal, f. harris, Low Complexity Architectures for Multi-Carrier Cognitive Radio Design, Paper # 3.3-03.

Many techniques exist to reduce the complexity, and therefore the cost, of multicarrier cognitive radio implementations. Adaptive, sparse realizations of an Interpolated Tree Orthogonal Multiplexing (ITOM) architecture offer very attractive resource efficiencies due to the computational economy inherent in the half-band filter. Exploiting the symmetry and null coefficients of the filter saves significant resources and provides for adaptive bandwidth flexibility. Cognitive processing capability allows radios to operate in crowded signal environments where the available spectrum varies in bandwidth and center frequency offsets. In many applications where adaptability is highly desirable, the radio hardware is often limited in available resources, e.g., size, power consumption and processing ability. This paper presented several different techniques that we have used to reduce the complexity of multicarrier radio architectures while minimizing resource usage. By considering the system as whole and applying strategic constraints to both the transmitter and receiver, a designer can obtain substantial simplifications while retaining flexibility and functionality.

B.12.8 Yasuda, H., T. Fujii, HIGH CONTRIBUTION NODE SELECTION FOR COGNITVE RADIO NETWORKS Paper # 3.6-03

"In this paper, we have proposed a node selection method for secondary cognitive radio. The proposed method limits the number of nodes used for the reestablishing the route from the source node to the destination node with avoiding an affection of the primary interference on the secondary multi-hop relay network. We derive the performance of the proposed method by using computer simulations. The proposed method can select the nodes which are suitable for relay the data from the source node to the destination node. We have proposed a node selection method for secondary cognitive radio. The proposed method limits the number of nodes used for the reestablishing the route from the source node to the destination node with avoiding an affection of the primary interference on the secondary multi-hop relay network. We derive the performance of the proposed method by using computer simulations. The proposed method can select the nodes which are suitable for relay the data from the source node to the destination node."

B.12.9 Shiba, H, K. Akabane, M. Matsui, K. Uehara, EVALUATION OF MULTILINK COMMUNICATION METHOD COLLABORATING WITH RESOURCE MANAGEMENT FUNCTION OF AN AUTONOMOUS ADAPTIVE BASE STATION, paper # 4.3-05 .

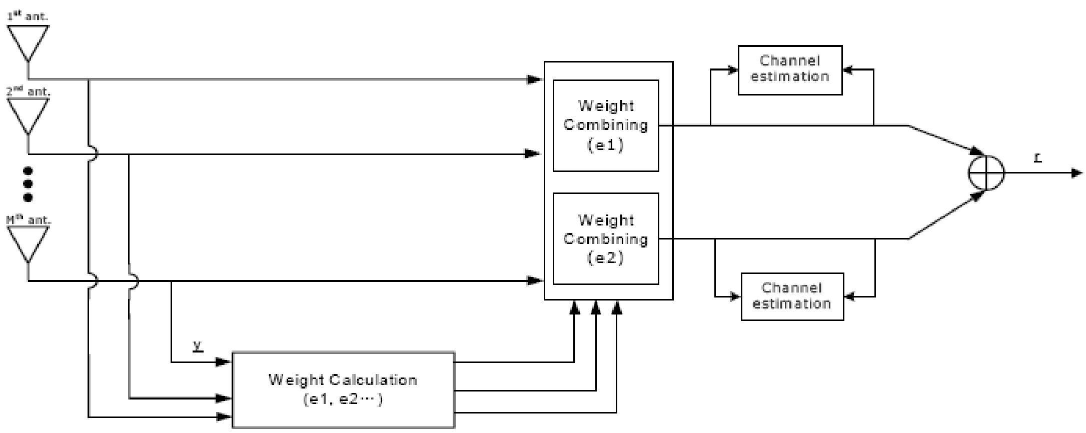
"We proposed an ML communication method that operates in cooperation with the resource management function of AABS. The proposed method works by selecting a wireless link and reserving it in collaboration with the ML server and AABS. In addition, the proposed ML communication method enables consolidation of the base station function of AABS without interrupting service to the user. To test the efficiency of the proposed method, we evaluated the service failure ratio and the AABS operating ratio by computer simulation. The results showed that application of the proposed ML communication method can reduce the service failure ratio without increasing the AABS operating ratio. In other words, the proposed ML communication method can increase the traffic load in AABS because it uses AABS's hardware resources more effectively."

B.13 SDR Forum 2008

B.13.1 Chang-eui Shin, Yusuk Yun, Seungwon Choi, "A Beamforming Algorithm for Collaborative MIMO System with Array Antenna," SDR 08 Technical Conference, October 26-30, 2008, Washington DC, paper #2.4-4.

Summary:

Proposes steering smart antenna algorithms in OFDM cellular environments towards multiple eigenvectors instead of a single eigenvector. Each eigenvector is trained on an independent multi-path component so that two beams are formed (one for each multipath component) and the outputs coherently combined via maximum ratio combining. This is illustrated below and in the following equation.



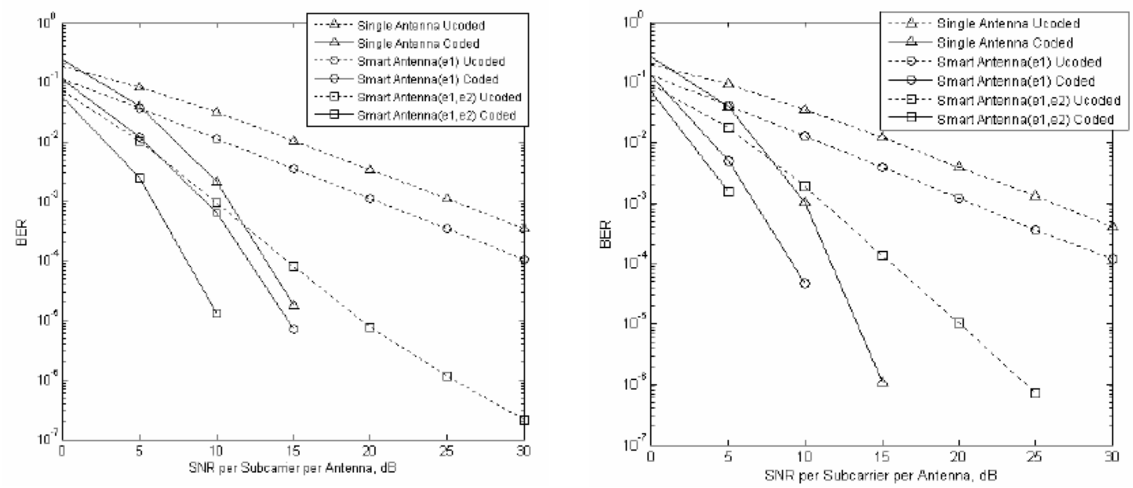
MRC combining formed from two channel estimates (h), two eigenvectors (e) and input samples (y).

$$\begin{aligned} r &= \underline{e_1}^H \cdot \hat{h}_1 \cdot \underline{y} + \underline{e_2}^H \cdot \hat{h}_2 \cdot \underline{y} \\ &= (\underline{e_1}^H \cdot \hat{h}_1 + \underline{e_2}^H \cdot \hat{h}_2) \cdot \underline{y} \\ &= (\underline{e_1}^H \cdot \hat{h}_1 + \underline{e_2}^H \cdot \hat{h}_2) \cdot (s \cdot \underline{\widetilde{H}} + \underline{n}) \end{aligned}$$

This allows the OFDM-based system to exploit beam forming and diversity gains simultaneously.

Quantified Benefit:

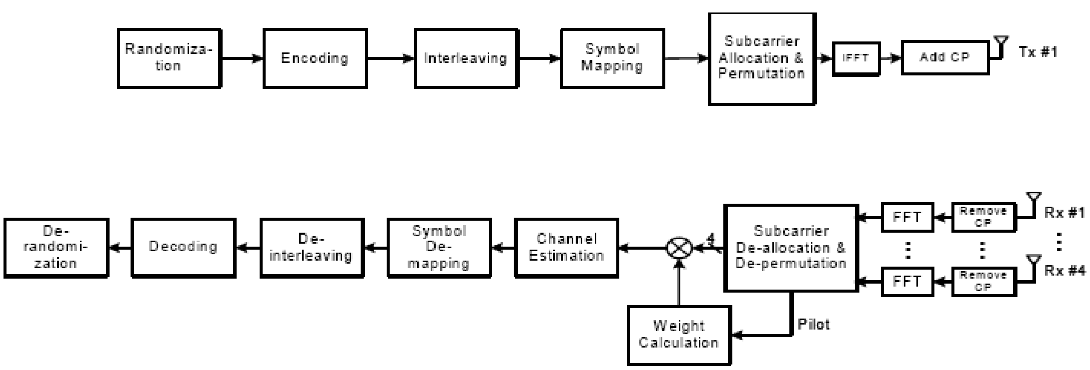
"But beam forming technique of using two eigenvectors (e1, e2) presents much better performance than beam forming technique of one eigenvector (e1). For the BER 10^{-3}, the beam forming technique of using two eigenvectors (e1, e2) obtains about 3dB and 1.5dB gain in SNR compared to beam forming technique of using one eigenvector (e1) in vehicular and pedestrian channel environment, respectively."



Looks like they screwed up their comparison to the single antenna (as "SNR per Antenna" implies a 3 dB gain going from 1-2 antennas so it is not the traditional apples-to-apples comparison for a given input SNR). However, this is not relevant to the 1 eigenvector versus 2 eigenvectors approach for the same number of antennas.

Considered Scenario:

A WiMAX/WiBro uplink as shown below with the parameters shown in the table below.



Parameters	Value
Subcarrier Permutation Mode	PUSC
Carrier Frequency	2.3 GHz
Channel Bandwidth	8.75 MHz
FFT Size	1024 point
Number of Data Subcarriers	720
Number of Pilot Subcarriers	120
TDD Frame Length	5ms
CP(Cyclic Prefix) Ratio	1/8
Doppler Frequency	127 Hz
Data Modulation	QPSK
Channel Coding (Coding Rate)	Convolutional Coding (1/2)
Number of Tx Antennas	1
Number of Rx Antennas	1 or 4
Number of Used Slots	20

Tags:

Smart antennas, BER

B.13.2 Soamsiri Chantaraskul, Klaus Moessner, "Opportunistic RADIO for multi-channel usage in WLAN Ad hoc networks," SDR 08 Technical Conference, October 26-30, 2008, Washington DC, paper # 1.6-1.

Summary:

This paper proposes an implementation of opportunistic radio for multi-channel usage in the IEEE 802.11-based ad hoc networks. Terminals in mobile ad hoc networks have to organize and manage the network since there is no base station to act as the central control unit. For this reason, terminals in current WLAN ad hoc networks employ the approach of "listen before talk" which means that once the network is set up, only one channel can be observed and used throughout.

B.13.3 Shyamalie Thilakawardana, Klaus Moessner, "Spectrum Management in Public and Government Security (P&GS) Systems; Making use of 'Quiet' times," SDR 08 Technical Conference, October 26-30, 2008, Washington DC, paper # 5.6-3.

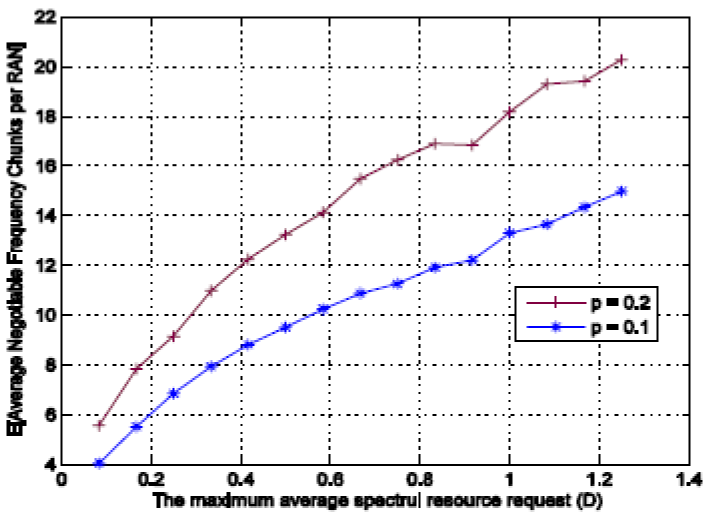
Summary:

Proposes allowing two different networks sharing the same technologies to negotiate the allocation of spectrum between the two networks dynamically.

"Also in this paper spectrum negotiation between P&GS systems on a short term basis is investigated with respect to dynamic traffic parameters such as variance and correlation factor. Even though the impact of variance of spectral resource request plays a major role in the successful spectrum negotiation, in the case of varying correlation factors it can be seen that traffic correlation does not play a major influence in spectrum negotiation [??!!??]. At the same time higher variances in the offered traffic load patterns creates more opportunities for spectrum negotiation."

Quantified Benefit:

Unfortunately, the quantifications given are to compare the impact of various traffic demand correlations between the two negotiating networks to estimate how much spectrum could be made available without negatively affecting the network releasing its spectrum. For example,



However, it cites (Nancy Jesuale, ‘Spectrum policy issues for state and local government,’ International Journal of Network Management’ 16: 89-101, 2006) which says that 40-50% of public safety spectrum is generally unused. If one assumes a ruthless pre-emption sort of protocol, then all of this spectrum could be made available.

Tags:

Spectrum access, spectrum negotiation.

B.14 DySPAN08

B.14.1 Ali O. Ercan, Jiwoong Lee, Sofie Pollin, and Jan M. Rabaey, “A Revenue Enhancing Stackelberg Game for Owners in Opportunistic Spectrum Access,” DySPAN 2008, Oct. 14-17, 2008.

Summary:

The paper proposes an algorithm for conducting opportunistic spectrum leasing from primary users to secondary users based on a three-player Stackelberg game between the spectrum owner

(PO), the primary users (PUs) and the secondary users (SUs). In the algorithm, the PO adjusts the monthly subscription fees for PUs, SUs, and the probability of interference while the PUs and SUs attempt to maximize their value. SUs are allowed to sense the channel and opportunistically utilize it when it is not being used by any PU, while keeping the interference to the PUs below a maximum.

Via simulation, they showed that by allowing opportunistic spectrum access with a non-zero tolerated interference probability to the primary users, the spectrum owner can enhance its revenue. In exchange for the degraded QoS of the PUs due to the interference from SUs, the PO offers the PUs a lower subscription fee. The enhancement of the revenue comes from the subscription fee of the SUs and the fact that the spectrum is utilized better.

Quantified Benefit:

Opportunistic spectrum access increases primary user per-channel revenue by 14%, even though primary user subscription fees were reduced by about $2 per user as shown in Table II reproduced below.

Optimal	w/OSA	w/o OSA
p_{tol}	5.31%	–
m_p (monthly)	$29.84	$31.5
m_s (monthly)	$5.89	–
PO revenue (monthly, per channel)	$1,786.4	$1,575.4
SU utilization	47.6%	–
PU acceptance prob. (p_p)	1	1

Considered Scenario:

The simulated benefit assumes an EDGE-like network and the GSM towers and population of San Francisco County. Additional parameters are summarized in Table I, reproduced below.

Parameter	Explanation	Value
C	Channel capacity	50 Kbps
M_p	Number of potential PUs	50
M_s	Number of potential SUs	50
$B = 1/p$	Mean channel busy time	180s
q	PU call generation rate	10 per day
α	Value of $1 in bits for a typical PU	5 MB/$
K	Value of primary service relative to secondary	5
p_{D}	PU detection probability (by SU)	0.9
p_{FA}	False alarm probability (by SU)	0.01
T_s	Sensing time for PU detection	10 ms

Tags:

Network resource management, Spectrum efficiency, Sales value

C Appendix: Acronym List

2G	2nd Generation Cellular System
3G	3rd Generation Cellular System
3GPP	3rd Generation Partnership Project
4G	Fourth Generation Cellular System (IMT Advanced)
AABS	Autonomous Adaptive Base Station
ACT-R	Adaptive Control of Thought--Rational
ADSA	Autonomous Dynamic Spectrum Access
AI	Artificial Intelligence
AM	Amplitude Modulation
AMC	Adaptive Modulation Coding
AP	Access Point
API	Application Programmers Interface
ARQ	Automatic Repeat Request
ASIC	Application Specific Integrated Circuit
AS-MAC	Ad-hoc Secondary MAC
AT&T	American Telephone and Telegraph
AUSTIN	Assuring Software Radios have Trusted Interactions
BB	Busy Burst
BB-DSA	Busy Burst DSA
BER	Bit Error Rate
BLAST	Bell Labs Layered Space-Time Algorithm
BS	Base Station
BSI	Bilateral Symmetric Interference
BWA	Broadband Wireless Access
C5ISR	Command Control Communications Computers Combat Systems Intelligence Surveillance and Reconnaissance
CAB	Coordinated Access Band
CBR	Case Based Reasoning
CDMA	Code Division Multiple Access
CE	Cognitive Engine
CECA	Critique-Explore-Compare-Adapt
CERDEC	Communications Electronics Research Development and Engineering Center
CJ	Cognitive Jammer
COMSEC	Communications Security
CP	Channel Pool
CPC	Cognitive Pilot Channel

CPU	Central Processing Unit
CR	Cognitive Radio
CRN	Cognitive Radio Network
CrownCom	Cognitive Radio Oriented Wireless Networks Communications
CRWG	Cognitive Radio Working Group
CSI	Channel State Information
CSMA	Carrier Sense Multiple Access
CSMA-CA	Carrier Sense Multiple Access Collision Avoidance
CTMC	Continuous Time Markov Chain
DARPA	Defense Advanced Research Projects Agency
dB	Decibel
DCA	Dynamic Channel Allocation
DCF	Distributed Coordination Function
DoD	Department of Defense
DSA	Dynamic Spectrum Access
DSAP	Dynamic Spectrum Access Protocol
DTV	Digital TV
DySPAN	Dynamic Spectrum Access Networks
Eb/No	energy per bit to noise power spectral density ratio
ECA	Exclusive Carrier Assignment
ECMA	European Computer Manufacturer's Association
EDGE	Enhanced Data Rates for GSM Evolution
EMT	Emergency Medical Technician
EVDO	Evolution Data Optimized
FCC	Federal Communications Commission
FDM	Frequency Division Multiplexing
FEC	Forward Error Correction
FER	Frame Error Rate
FM	Frequency Modulation
FQoS	Fixed QoS
FSA	Fixed Spectrum Assignment
FSA	Flexible Spectrum Access
FSA	Fixed Timeslot Allocation Scheme
GA	Genetic Algorithm
GIG	Global Information Grid
GoS	Grade of Service
GPP	General Purpose Processor

GPS	Global Positioning System
GSM	Global Standard for Mobile (Communications)
GSUS	Gaussian Stationary Uncorrelated Scattering
H-ARQ	Hybrid ARQ
HSDPA	High Speed Data Packet Access
HSPA	High Speed Packet Access
HW	Hardware
IEEE	Institute for Electrical and Electronic Engineers
IMT	International Mobile Telecommunications
I/O	Input / Output
IP	Internet Protocol
IPTV	Internet Protocol TV
IQ	Intelligence Quotient
ISM	Industrial Scientific and Medical
ITOM	Interpolated Tree Orthogonal Multiplexing
ITU	International Telecommunications Union
IWF	Iterative Water Filling
JTRS	Joint Tactical Radio System
JSTeF	JTRS Science and Technology Forum
LAN	Local Area Network
LOS	Line of Sight
LTE	Long Term Evolution
MAC	Media Access Control
MANET	Mobile Ad-hoc Network
MC	Multicarrier
MCBR	Multicast CBR
Milcom	Military Communications
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
MLM	Modeling Languages for Mobility
NGMN	Next Generation Mobile Networks
NLOS	Non Line of Sight
ODMRP	On Demand Multicast Routing Protocol
OFCOM	Office of Communications (UK)
OFDM	Orthogonal Frequency Division Multiplex
OFDMA	Orthogonal Frequency Division Multiple Access
OIC	Opportunistic Interference Cancellation

OODA	Observe Orient Decide Act
OPEX	Operational Expenses
OR	Opportunistic Radio
OSA	Opportunistic Spectrum Access
OSCR	Open Source Cognitive Radio
OTA	Over The Air
OWL	Web Ontology Language
OWL-DL	OWL-Description Logic
PA	Power Amplifier
PAR	Project Authorization Request
PCI	Physical Cell ID
PHS	Personal Handy-phone System
PHY	Physical Layer
PO	Primary Owner
POMDP	Partially Observable Markov Decision Process
PRI	Primary System
PS	Primary System
PSNR	Peak SNR
PSSIG	Public Safety Special Interest Group
PU	Primary User
PUE	Primary User Emulation
QCH	Quorom Based Channel Hopping
QoS	Quality of Service
QPSK	Quadrature Phase Shift Key
RACH	Random Access Channel
RAT	Radio Access Technology
RDF	Resource Description Framework
RDFS	RDF Schema
REM	Radio Environment Map
RF	Radio Frequencies
ROC	Receiver Operating Characteristic
RFI	Request for Information
RRM	Radio Resource Management
RTT	Radio Transmission Technology
RX	Receive
SCA	Shared Carrier Assignment
SDR	Software Defined Radio

SDRF	Software Defined Radio Forum
SEC	Secondary System
SECWG	Security Working Group
SEVILLE	Security Via Lower Layer Enforcements
SINR	Signal To Interference Plus Noise Ratio
SNR	Signal To Noise Ratio
SOAR	State, Operator And Result
SON	Self-Organizing Networks
SRAC	Single Radio Adaptive Channel
SS	Secondary System
SSR	System Strategy Reasoner
SU	Secondary User
SW	Software
TDD	Time Division Duplex
TDM	Time Division Multiplexing
TRANSEC	Transmission Security
TX	Transmit
TU	Typical Urban
TV	Televison
TVBD	TV-Band Devices
TVWS	TV White Space
UAV	Unmanned Aerial Vehicle
UHF	Ultra High Frequency
UNII	Unlicensed National Information Infrastructure
US	United States
UWB	Ultra Wide Band
VQoS	Variable Quality of Service
WAND	Wireless Adaptive Network Development
WCDMA	Wideband Code Division Multiple Access
WInnF	Wireless Innovation Forum
WLAN	IEEE 802.11a Wireless LAN
WNAN	Wireless Network After Next
WPAN	Wireless Personal Area Network
WRAN	Wireless Regional Area Network
xG	DARPA's Next Generation Program
XML	Extensible Markup Language
XTM	XML Topic Maps