Future Directions in Cognitive Radio Network Research

NSF Workshop Report

Edited by: Peter Steenkiste, Douglas Sicker, Gary Minden, Dipankar Raychaudhuri

March 9-10, 2009

Executive Summary

Wireless technology is proliferating rapidly, and the vision of pervasive wireless computing and communications offers the promise of many societal and individual benefits. While consumer devices such as cell phones, PDAs and laptops receive a lot of attention, the impact of wireless technology is much broader, e.g., through sensor networks for safety applications and home automation, smart grid control, medical wearable and embedded wireless devices, and entertainment systems. This explosion of wireless applications creates an ever-increasing demand for more radio spectrum. However, most easily usable spectrum bands have been allocated, although many studies have shown that these bands are significantly underutilized. These considerations have motivated the search for breakthrough radio technologies that can scale to meet future demands both in terms of spectrum efficiency and application performance.

Cognitive radios offer the promise of being a disruptive technology innovation that will enable the future wireless world. Cognitive radios are fully programmable wireless devices that can sense their environment and dynamically adapt their transmission waveform, channel access method, spectrum use, and networking protocols as needed for good network and application performance. We anticipate that cognitive radio technology will soon emerge from early stage laboratory trials and vertical applications to become a general-purpose programmable radio that will serve as a universal platform for wireless system development, much like microprocessors have served a similar role for computation. There is however a big gap between having a flexible cognitive radio, effectively a building block, and the large-scale deployment of cognitive radio networks that dynamically optimize spectrum use. Building and deploying a network of cognitive radios is a complex task. There is a growing concern that conventional academic research in this area has reached a point of diminishing returns and that further progress in the above areas will depend on a new approach involving multi-institutional research teams working with real-world experimental deployments of cognitive radio networks.

The purpose of this NSF sponsored workshop (held in Arlington, VA on March 9-10, 2009) was to bring together a group of technology and policy researchers who have been involved with early cognitive radio projects, and to explore how we can make the transition from cognitive radios to cognitive radio *networks*. Specific goals of the workshop were:

- Identify the broad cognitive radio network technology vision and research opportunities.
- Articulate some of the key research questions and challenges (i.e., the “science agenda”) that need to be addressed in order to build networks of cognitive radios.
- Define the required experimental infrastructure to carry out the science agenda.
- Develop a coherent plan on how the research community could proceed and make progress with this vision and agenda.
- Define the broader impacts of cognitive radio network research, both in terms of social value and educational outreach programs.

This report provides a summary of the discussions at this workshop, addressing each of the above topics. After a brief introduction in Section 1, Section 2 outlines the strategic opportunities and challenges presented by cognitive radio technology. Dynamic spectrum access (DSA) is identified as an important near-term opportunity for efficient spectrum usage and introduction of new wireless services. DSA is currently an active field (as evidenced by the recent formation of a major IEEE conference called DySpan) and involves both technology and policy considerations. There are many important research issues in DSA including spectrum management policy, market economics, spectrum co-existence algorithms and protocols, and enabling radio technologies. The second and longer term opportunity is that of cognitive radio networks (CRNs), a term that refers to adaptive and self-organizing radio networks that are capable of responding to environmental changes such as interference, device density and end-user application requirements. CRNs with DSA capabilities have the potential for dramatically improving spectrum efficiency and wired network capacity. While very restricted forms of cognitive adaptation and spectrum agility are found in existing wireless networks (such as WiFi), much more aggressive adaptation across wider spectrum bands and more radical runtime protocol optimizations have the potential to achieve major gains in spectrum efficiency and network performance. After identifying DSA and CRN as strategic opportunities, Section 3 provides an overview of the research agenda associated with these topics. Major research themes being pursued by the community are identified as:

- Spectrum policy alternatives and system models
- Spectrum sensing algorithms
- Cognitive radio architecture and software abstractions
- Cooperative wireless communications
- DSA technology and algorithms
- Protocol architectures for CRNs
- Cognitive algorithms for adaptation and resource management
- Network security for CRNs
- Cognitive networks and the Internet

A brief discussion about the state-of-the-art and future research challenges is given for each of the above themes. This is followed by Section 4 which makes the case for large-scale deployment in real-world settings as a necessary next step for further progress on the DSA and CRN research topics introduced above. CRNs are very complex systems and while developing all the components is important, a major challenge is figuring out how they fit together and work together under realistic conditions. In other words, we need to evaluate the performance of complete CRNs at reasonable scale and study emergent behavior in large-scale networks. Without this level of evaluation, it will not be possible to justify the necessary spectrum policy changes or to convince industry to make the necessary investments. Section 4 includes further details on evaluation methodologies applicable to cognitive radio systems, and identifies specific testbed requirements that would improve the community's research capabilities. A summary of available experimental platforms is given, and the section concludes with a discussion of alternative models for deployment and management of an experimental CRN infrastructure.

Section 5 provides a discussion of how a research initiative or program on cognitive radio may be organized, including consideration of available models such as a regular NSF solicitation, consortium style testbed projects, and multiple collaborative project grants. Broader impacts are discussed in Section 6, where we identify several educational, social and industry benefits. These include contributions to FCC spectrum policy, public safety communications and first-response scenarios, Internet access for underserved communities, education in tribal lands and early-stage technology transfer to industry. The use of cognitive radio technology for extending broadband access to rural and tribal regions was considered an important benefit of a research program on cognitive radio networks.

The workshop concluded with a call to NSF to create a signature program that will develop the science and technology needed for the design, development and deployment of cognitive radio networks that can be deployed safely on a large scale. A key component of this research agenda is the development of the tools, including both testbeds and analytical tools, that are needed to evaluate CRN technologies. Another important aspect of the proposed research agenda is the deployment of "in-situ" cognitive radio networks in real-world application scenarios such as broadband Internet access and vehicular systems. The resulting technology evaluation must be rigorous enough that the results can be used to support policy changes that are needed for CR network deployment. The proposed program will invigorate the research in the key CRN research areas listed above by providing a context for the design and evaluation of algorithms, protocols and devices, thus dramatically increasing the potential impact of the research. The proposed research program is also expected to accelerate the emergence of key enabling technologies for cognitive radio such as wideband radio front-ends, programmable radio architectures and related protocol stack software.

The summary recommendations of the workshop are as follows:

- The rapid proliferation of wireless technologies is expected to increase the demand for radio spectrum by orders of magnitude over the next decade. This problem must be addressed via technology and regulatory innovations for significant improvements in spectrum efficiency and increased robustness and performance of wireless devices.
- Emerging cognitive radio technology has been identified as a high impact disruptive technology innovation, that could provide solutions to the “radio traffic jam” problem and provide a path to scaling wireless systems for the next 25 years.
- Significant new research is required to address the many technical challenges of cognitive radio networking. These include dynamic spectrum allocation methods, spectrum sensing, cooperative communications, incentive mechanisms, cognitive network architecture and protocol design, cognitive network security, cognitive system adaptation algorithms and emergent system behavior.
- A major hurdle to continued progress in the field is the inability to conclusively test, evaluate, and demonstrate cognitive networking technology, at scale and in real-world deployment scenarios. This calls for the development of a set of cognitive networking testbeds that can be used to evaluate cognitive networks at various stages of their development.
- The research community represented by the workshop participants urges NSF to consider creation of a new collaborative research project or research program to address the cognitive networking opportunities identified here. In addition to support for the long-term research agenda, we believe that there is also an immediate need for shared cognitive radio network testbeds that can serve as shared research infrastructure for the whole community.

1 Introduction and Workshop Background:

Wireless technology is rapidly proliferating into all aspects of computing and communication. There are over 3 billion wireless devices in use today (mostly cell phones and mobile computers), and that number is expected to increase to ~100 billion by the year 2025 [1]. This phenomenal growth in wireless usage will be driven by new applications that embed computing power into the physical world around us, helping to make the world safer and more accessible. Radio technology will be at the very heart of the future computing world - one in which billions of communicators, mobile devices and sensors/actuators are connected to the global Internet and serve as the foundation for many exciting new classes of applications. This vision of pervasive wireless at the edge of the Internet is an appealing one with many societal and individual benefits. However, the anticipated exponential growth of wireless devices and applications is contingent on our ability to design radio technologies that continue to work well with increasing deployment density – in particular, radio systems must change, and change rapidly, to cope with 2-3 orders of magnitude increase in density from ~10-100 devices/Km^2 today to ~1000-10,000 devices/Km^2 in 2025. Given the fact that spectrum is a finite resource, this calls for disruptive technology innovation in the radio field

Cognitive radios offer the promise of being just this disruptive technology innovation that will enable the future wireless world. Cognitive radios are fully programmable wireless devices that can sense their environment and dynamically adapt their transmission waveform, channel access method, spectrum use, and networking protocols as needed for good network and application performance. We anticipate that cognitive radio technology will soon emerge from early stage laboratory trials and vertical applications to become a general-purpose programmable radio that will serve as a universal platform for wireless system development, much like microprocessors fulfill that role for computation. There is however a big gap between having a flexible cognitive radio, effectively a building block, and the large-scale deployment of cognitive networks that dynamically optimize spectrum use. Building and deploying a network of cognitive radios is a complex task. The research community working on cognitive radio networks needs to understand a wide range of issues including smart antenna technology, spectrum sensing and measurement, radio signal processing, hardware architectures including software-defined radio (SDR), medium access control (MAC), network discovery and self-organization, routing, adaptive control of mechanisms, policy definition and monitoring, and learning mechanisms. This is a very wide range of technologies to harness and apply, and hence understanding and properly controlling the behavior of the resulting system is a challenging research task.

The purpose of this NSF sponsored workshop (held in Arlington, VA on March 9-10, 2009) was to bring together a group of technology and policy researchers who have been involved with early cognitive radio projects, and to explore how we can make the transition from cognitive radios to cognitive radio *networks*. Specific goals of the workshop were:

- Identify the broad cognitive radio network technology vision and research opportunity.
- Articulate some of the key research questions and challenges (i.e., the "science agenda") that need to be addressed in order to build networks of cognitive radios.
- Define the required experimental infrastructure to carry out the science agenda.
- Develop a coherent plan on how the research community could proceed and make progress with this vision and agenda.
- Define the broader impacts of cognitive radio research, both in terms of social value and educational outreach programs.

1.1 Prior Meetings

The last organized meetings on this topic were held under the auspices of the NSF GENI planning effort in 2005 and 2007. The "Wireless Mobile Planning Group (WMPG)" report [2] was published as part of that effort, and included a discussion of cognitive radio technology and related opportunities. However, GENI was focused on end-to-end Internet architecture with limited focus on emerging wireless technologies such as radios. The organizing committee and participants of this workshop have continued to have informal discussions of a community-wide research initiative on cognitive radio over the years and have submitted a number of related proposals in the area to existing NSF programs. This workshop was motivated by fast growing interest and emergence of key enabling technologies in the cognitive radio technology area. The workshop was intended to review the state of NSF supported research in the area and to obtain a fresh research roadmap and related experimental infrastructure requirements.

1.2 Workshop Logistics

The workshop was held in Arlington, VA at the Westin Gateway Hotel on March 9-10, 2009. Professors Gary J. Minden of the University of Kansas and Dipankar Raychaudhuri of Rutgers University served as co-chairs. They were assisted by Profs. Peter Steenkiste (CMU) and Doug Sicker (U Colorado) in recording the workshop proceedings and producing this report. The workshop attendees were:

Name	Organization
Gary J. Minden	The University of Kansas
Dipankar Raychaudhuri	Rutgers University
Charles Bostian	Virginia Tech
Tim Newman	Virginia Tech
Doug Sicker	The University of Colorado
Dirk Grunwald	The University of Colorado
Joseph B. Evans	The University of Kansas
Gunes Ercal-Ozkaya	The University of Kansas
Peter Steenkiste	Carnegie Mellon University
Ivan Seskar	Rutgers University
Narayan Mandayam	Rutgers University
Taieb Znati	National Science Foundation
Alhussein Abouzeid	National Science Foundation
Victor S. Frost	National Science Foundation
Preston Marshall	DARPA (now at USC/ISI)
Jon Peha	FCC and CMU
Joseph Heaps	National Institute of Justice

The meeting consisted of a working dinner on Monday, March 9, 2009 and an all-day meeting on Tuesday, March 10, 2009. The Tuesday meeting consisted of short presentations from the participants followed by a general discussion that developed the ideas and concepts presented in this report.

Although this was a small workshop, we recruited two junior faculty (one female) – Gunes Ercal-Ozkaya and Tim Newman - from our institutions to introduce them to the research organization process. One visited with NSF program directors while near NSF. Two new NSF program directors, Victor Frost and Alhussein Abouzeid, also attended the workshop.

The rest of this report is organized as follows. Section 2 is an overview of the cognitive radio network vision and challenges. Section 3 outlines the research agenda for cognitive radio networks. Section 4 identifies available cognitive radio experimental platforms and future needs. Section 5 addresses broader impacts in education and public safety applications. Finally, Section 7 reports the workshop conclusions and recommendations.

2 Cognitive Network Opportunities and Challenges

The key technology enabler for cognitive wireless networks is the “software defined radio (SDR)” which first started to emerge in the 1990’s and is now at the pre-commercial stage, perhaps 2-3 years away from consumer deployments. SDR technology brings radio electronics into the digital age [11], thus opening up many new degrees of freedom in wireless system design. In the near-term, agile/programmable radios with spectrum sensing capabilities can share spectrum dynamically across multiple systems and services. This mode of operation is generally termed “dynamic spectrum access (DSA)” and is representative of the first wave of R&D and commercial activity on cognitive radios. Wireless systems with DSA have been encouraged by FCC policies, which now permit shared spectrum access in the TV white space [12]. In the longer term, programmable SDR technology will make it possible to build adaptive wireless networks in which both the radio waveform and networking protocols can be dynamically selected to deal with current operational requirements. These adaptive networks will achieve even higher spectrum efficiency and performance through the use of distributed cognitive algorithms to control adaptation and cooperation. The following sections provide further details about high-level cognitive radio opportunities and challenges, starting with the spectrum policy and regulatory perspective. The policy and regulatory issues raised by DSA create a unique set of challenges for cognitive radio networks.

2.1 Spectrum Policy and Economics

The anticipated explosion of wireless applications creates an ever-increasing demand for radio spectrum. Unfortunately, spectrum is a finite resource. Because of the tremendous societal value of the finite spectrum, its use is carefully managed at the national and international level. The Federal Communications Commission (FCC), for U.S. commercial entities, and the National Telecommunications and Information Administration (NTIA), for federal agencies, manage radio spectrum policy and regulation in the United States. These agencies coordinate the use of radio frequency spectrum within the United States. The U.S. Department of State, in collaboration with the FCC and NTIA, coordinates the use of radio frequency spectrum in the U.S. with other nations. Worldwide radio frequency spectrum use is managed through an international treaty process [8].

The goal of the FCC and NTIA is, broadly speaking, to manage the spectrum in a way that optimizes the benefit for the society at large. This has historically been done by statically allocating spectrum bands for certain uses. Some spectrum has been allocated for functions that are critical to society. Examples include frequency bands for use by safety and emergency services, first responders, and aviation. Other frequency bands are allocated for commercial use, e.g., cell phone service and radio and TV broadcasting. Finally, a limited amount of spectrum is unlicensed and can be used (subject to some constraints) by anybody. Interesting enough, some of the unlicensed bands are the most heavily used ones, because it is much easier and cheaper for users to access these bands.

Static allocation of frequency bands has many advantages. A first benefit is simplicity: once allocations have been made, there is no ambiguity about who can use the spectrum and enforcing policy is relatively easy. Second, radios have historically been fixed functionality devices that have been designed for a specific frequency band. As a result, using a specific frequency band requires a significant investment in infrastructure that can only be used in that band. Such an investment only makes sense if there is some guarantee of continued access to that band. Giving exclusive licenses encourages investments in infrastructure, which ultimately benefits society in the form of new services. Finally, dedicating frequencies to specific uses simplifies equipment and deployment and often leads to better service quality. The reason is that a single operator can manage deployment, without needing to be concerned about arbitrary competing users.

While static allocation has many advantages, it can lead to very inefficient use of the spectrum, and many studies have shown that many allocated frequency bands are significantly underutilized [3]. One reason is that spectrum use is often localized (e.g., around airports, etc.), leaving many frequency bands unused in significant parts of the country. Since most easily usable spectrum bands have been allocated, creating a spectrum shortage that hinders the growth of new wireless application domains, it is imperative that more efficient spectrum allocation strategies are explored. The fact that many frequency bands are underutilized suggests that a more dynamic allocation or use of the spectrum would be more efficient. For example, if the licensee (sometimes called the primary user) is not using a band in a certain area, other “secondary” users could opportunistically use the spectrum. This spectrum management approach, called Dynamic Spectrum Access (DSA), could open up vast amounts of spectrum, stimulating the deployment of new applications.

The potential benefits of DSA have been widely recognized in many contexts:

- An NTIA initiative on spectrum policy for the 21st century, which includes a specific plan for phased deployment of a pilot testbed [4];
- DARPA next generation (XG) program [5];
- The IEEE Dynamic Spectrum Access Networks (DySPAN) Conference, a recently formed (2005) international conference which supports dissemination of both policy and technology results in the field [2].

The challenge in deploying dynamic spectrum principles is that of significantly improving spectrum utilization efficiency without losing the benefits associated with static spectrum allocation. Clearly a first challenge is to develop wireless devices and networks that can opportunistically operate in different frequency bands. Other challenges are in the spectrum policy domain. How can we develop policies for dynamic spectrum access that lead to efficient spectrum use, are practical, protect the rights of license holders, and maintain service quality? There are also significant economic considerations. Policies must protect the interests of primary users, who have made significant investments in infrastructure. Moreover, it must be economically attractive to manufacturers and service providers to develop and deploy equipment for opportunistic spectrum access by secondary users.

Both the opportunities and challenges of dynamic spectrum access can be illustrated using the recent FCC white space ruling. Broadcast TV only uses alternating channels in the spectrum in any location, so the skipped channels can be safely reused in nearby regions. These unused TV white spaces are an attractive target for dynamic spectrum access, since they operate at an easy to use frequency, and their availability is fairly static and applies to a large area. In May 2004, the FCC released a Notice of Proposed Rulemaking (NPRM 04-186) on "Unlicensed Operation in the TV Broadcast Bands" that proposes that certain unlicensed devices make use of TV white space. While this may appear easy to do, there is in fact a lot of complexity involved, since devices must be able to determine whether a channel is occupied or not and transmit power must be limited to avoid interfering with TV receivers. Another issue is that even though the rulemaking began more than four years ago, there still are no devices on the market to use white spaces and there have been no major deployments or even trials.

The deployment of DSA is clearly a complex problem [6], given the many technology, spectrum policy and economic challenges. Many studies in the early part of this decade have observed the tight coupling between wireless technology, spectrum policy and economics in DSA networks [7a-h]. The general chairs of DySPAN identified the following major trends in spectrum management as:

- All easily usable spectrum is now allocated and in many case to more than one application, but in most cases, it is still not heavily used,
- New applications, providing enormous benefits and pleasure to human-kind is driving ever increasing demand for more spectrum,
- Existing and new applications are being ever more widely deployed,
- The demand for more data carrying capacity and data transmission performance is almost insatiable,

- Hardware and software technology is enabling ever more complex policies and functionality especially supported by wide band frequency agile radios, software defined radio technology, and high speed, low power and low cost processing capabilities,
- The rise of sophisticated government spectrum sharing policies and related legal regimes, and
- Micro-economic theories and practices that support dynamic spectrum pricing models.

The facts — that radio spectrum is a finite resource, the demand for wireless communications is increasing, and the configuring, managing, and innovating in this large, dynamic technology is challenging — call for disruptive technology innovation in the radio networking field.

2.2 Cognitive Radio Networks

DSA networks pose a number of challenges in wireless networking and communications. The first and most obvious challenge is that we need radios that can operate in multiple frequency bands – most radios used today were design for a particular band. Second, we need radios that can "decide" which frequency band to use since it is in most cases unrealistic that the user will be able to pick the right band. This is typically a two step process: radios need to determine what frequency bands are available, given the appropriate FCC rules, and the radios then need to decide what band is the most suitable. A final challenge is to configure the wireless network appropriately. Specifically, the wireless devices will need to agree on how to realize various physical, link, and network layer functions in a way that makes best use of the available spectrum, while also satisfying the policy constraints that apply in the selected band.

Cognitive Radio Networks (CRNs) are a perfect fit to realize the above functionality. Broadly speaking, CRNs are networks that can sense their operating environment and adapt their implementation to achieve the best performance. "Operating environment" should be interpreted very broadly, and includes the signal propagation environment, node density, traffic load, mobility, and, in the case of DSA networks, available spectrum. While today's wireless networks (e.g., WiFi) already use very restricted forms of cognitive optimization (e.g., rate adaptation) and spectrum agility (e.g., channel selection), much more aggressive adaptation, such as across wider spectrum bands and more radical runtime protocol optimizations, are needed to dramatically improve spectrum efficiency and wireless network capacity. In the last decade, there has been a significant amount of research in CRNs, looking at adaptation at the physical (modulation and coding), link (adaptive MAC protocols) and network (collaborative network formation, routing) layer. Much of this research can be leveraged in DSA networks.

CRNs require a radio device that is very flexible, so it can radically change various protocol functions at runtime. Software-defined radios (SDRs) are an ideal platform for CRNs. Most radios today implement virtually all physical layer processing and some MAC protocol functions in hardware, limiting the degree of runtime adaptivity to a small predefined set of changes, e.g., choosing between a handful of transmission rates. SDRs, on the other hand, attempt to do as much processing as possible in the digital domain. However, due to the limitations of analog/digital converters, digital processing capacity and power constraints, a combination of analog and digital processing is still used. An analog circuit (front-end) converts the signal between the radio carrier frequencies and an intermediate frequency. The signal at the intermediate frequency is digitized so all other processing can be done digitally in software, making it easy to change at runtime. Even the analog circuits are designed to be flexible. For example, oscillator frequencies, receiver attenuation, transmit power, filter center frequencies, and receiver gain may all be under the control of SDR software. While cognitive networks do not strictly require SDRs, the flexibility offered by SDRs is very attractive, especially when prototyping and evaluating cognitive networking technology.

A CRN may consist of a set of SDR devices that, collaboratively, incorporate multiple sources of information to dynamically adapt their transmission waveforms, channel access method, and networking protocols as needed for co-existence and good system/application performance. The promise of cognitive networks is improved use of spectrum resources, reduced engineering and planning time, and adaptation to current operating conditions. Some features of cognitive radio networks include:

- Sensing the current radio frequency spectrum environment: This includes measuring which frequencies are being used, when they are used, estimating the location of transmitters and receivers, and determining signal modulation. Results from sensing the environment can be used to determine radio settings.
- Policy and configuration databases: Policies specifying how the radio can operate and physical limitations of radio operation can be stored in the radio or made available over the network. Policies might specify which frequencies can be used in which locations. Configuration databases would describe the operating characteristics of the physical radio. These databases would normally be used to constrain the operation of the radio to stay within regulatory or physical limits.
- Self-configuration: Radios may be assembled from several modules. For example, a radio frequency front-end, a digital signal processor and a control processor. Each module should be self-describing and the radio should automatically configure itself for operation from the available modules. Some might call this “plug-and-play.”
- Mission-oriented configuration: Software defined radios can meet a wide set of operational requirements. Configuring a SDR to meet a given set of mission requirements is called mission-oriented configuration. Typical mission requirements might include operation within buildings, substantial capacity, operation over long distances, and operation while moving at high speed. Mission-oriented configuration involves selecting a set of radio software modules from a library of modules and connecting them into an operational radio.
- Adaptive algorithms: During radio operation, the cognitive radio is sensing its environment, adhering to policy and configuration constraints, and negotiating with peers to best utilize the radio spectrum and meet user demands.
- Distributed collaboration: Cognitive radios will exchange current information on their local environment, user demand, and radio performance between themselves on a regular basis. Radios will use their local information and peer information to determine their operating settings.
- Security: Radios will join and leave wireless networks. Radio networks require mechanisms to authenticate, authorize and protect information flows of participants.

CRNs operate in a rich environment. The agility of underlying SDR platforms provides a level of flexibility well beyond conventional radio and networking platforms.

In the next section, we review areas of research relevant to spectrum policy, DSA technology and CRNs. We aim to identify and overcome technical barriers to large-scale deployment of cognitive systems and networks.

3 Research Agenda for Cognitive Radio Networks[1]

By their very nature, DSA and CRNs spans a range of disciplines. The physical layer involves high performance radio frequency circuits. We need to control and manage those circuits to gain flexibility and new capabilities. Once out of the analog domain, we need to analyze and process received communication signals. We need to limit bandwidth, be efficient in our utilization of radio frequency spectrum, deal with differences between the transmitter and receiver, handle radios in motion, adapt for the physical communications from the transmitter to the receiver, allocate radio resources for efficient communications, learn how and when to share information, re-route network traffic as links go up and down, and know how to adapt to the current situation in this complex radio communications environment. Wireless networks are challenging systems because of the complex nature of signal propagation. DSA further exacerbates those problems since spectrum use is even more dynamic and unpredictable. Cognitive networking research is inherently a multidisciplinary endeavor that must address not only traditional wireless networking challenges, but also the rational control and management of the spectrum, a distributed and dynamic resource, which raises complex policy and economic issues.

We attempt to capture the task ahead in the cognitive research roadmap in Figure 1.

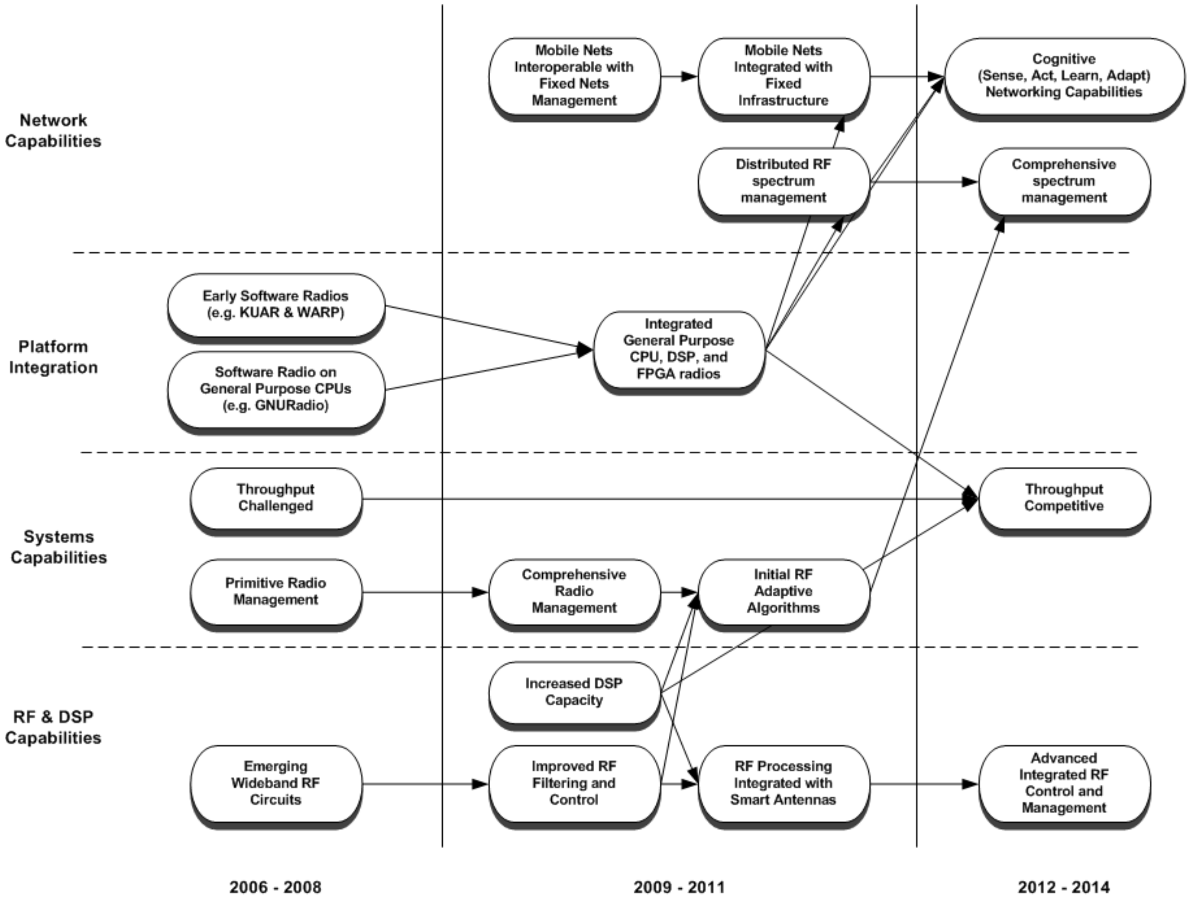


Figure 1 Cognitive Radio Research Roadmap.

In the following sub-sections we describe a limited set of the research needed to build comprehensive cognitive radio networks.

---

[1] Parts of this section are derived from the GENI Technical Document on Cognitive Radio Networking, GDD-06-20, September, 2006 (This GENI Technical document was written by several of the authors of this workshop report).

3.1 Spectrum Policy Alternatives and System Models

Advanced technology only thrives in an economic and policy regime where it returns value and does so without impeding other technologies or innovation. The success of CRNs in the marketplace depends on national policy changes in the U.S. and regulators throughout the world. Research is required to support such policy reform. Policies will not change without substantial demonstration of the value and impact of CRN technologies. The CRN research community must demonstrate improved performance over other technologies and assured operation of adaptive and flexible CRNs. Advances in CRNs could make a wide variety of improved spectrum utilization and sharing approaches possible and cost-effective [9]. A given spectrum sharing model may require sharing among equals, or it may give some wireless systems primary rights and others secondary status. A model may mandate cooperation among systems from different administration domains, or it may rely on mere coexistence of such systems. A model may assume that systems are licensed, or unlicensed, or a mix of the two. A model may assume a more active role for the regulator, or for some third party operating infrastructure, or it may not. Policy-relevant research should address the technical regulations governing how devices in a given band are, or are not, allowed to operate, risks of interference and congestion under different regulatory approaches, liability in the event of harmful interference, the role of standards bodies, user groups, and industry consortia, how the regulatory paradigm adopted in a given band affects the social and economic benefits derived from that band, the incentive structures created by various spectrum policies and the potential impact on technology and business strategies, and mechanisms to enforce technical and non-technical requirements derived from spectrum policy.

Motivated on the above considerations, some of the spectrum policy research topics under consideration by the community include:

- High-level policy and legal frameworks, for example property rights vs. spectrum commons
- Policy parameters which promote spectrum sharing in terms of primary-secondary services or new cognitive radio based unlicensed bands
- Use of dynamic auctions for spectrum allocation – spectrum clearinghouse, etc.
- Distributed market mechanisms with incentives for sharing of spectrum
- Game theoretic analysis of spectrum markets in terms of scale, convergence, etc.
- How does one express regulatory and operational policies? How are policies securely updated?
- What method does one use to interpret policies? How are policies affected by different market models, e.g., property based, unlicensed, or brokered?
- Emergent behavior of large-scale spectrum markets

Moving away from a simple command-and-control model for spectrum allocation and assignment (the current model) and adopting a dynamic spectrum management model represents a tremendous change in how we use spectrum. With this change comes increased complexity, in that CR networks consist of many components, all of which can adapt in potentially extreme ways. CR networks are also not self-contained systems, but they interact in many ways with their operating environment, and as a result, their behavior depends on many external factors, including the presence of other wireless devices, user behavior, and traffic load. Faulty behavior can have disastrous consequences, e.g., poor adaptation decisions on a single wireless device can disrupt safety critical wireless communication. Such concerns have created legitimate regulatory and market resistance against the adoption of dynamic spectrum access. However, this resistance mainly stems from the uncertainty that such complex systems create. For example, it is unknown what emergent behaviors might arise as this new technology interacts with legacy radios or with other (dissimilar) DSA systems, and whether these behaviors may inadvertently, or through malicious manipulation, lead to communication failures in critical systems (e.g., aviation, public safety or defense). Core to this research is the need to explore the security, policy and operational concerns and remedies associated with DSA deployment in real-world settings. Without large-scale testbeds we will be unable to examine the technical questions surrounding this uncertainty, the consequence of which is the delay in adoption of CR networks.

3.2 Spectrum Sensing Algorithms

Spectrum sensing is a key enabling technology for a broad class of cognitive radio systems involving spectrum agility. When control protocol support is not available to help detect incumbent users (for example with legacy systems, or in primary-secondary spectrum sharing scenarios including the 700 MHz "white space" band which is the subject of recent FCC rule making), each radio must sense the surrounding spectral environment to learn about incumbents or interferers, from which it determines which frequency bands to use and what physical layer radio parameters to use. Effective spectrum sensing technology is thus critical for adherence to FCC coexistence rules based on interference.

Spectrum sensing is a challenging problem in signal processing and estimation in view of the complexity of observed spectrum signatures from multiple devices, along with noise and channel impairments. A review of spectrum sensing methods is given in [10] and it remains an important area of investigation by the wireless research community. Methods under consideration include:

- Simple energy detectors which are independent of known signal properties
- Matched filter detection of known signals such as 802.11x, Bluetooth or cellular
- Cyclo-stationary detectors which employ second-order signal structure for improved detection
- Collaborative (networked) sensing by multiple radios in which multiple spatial observations are combined to form an improved signal estimate

Each of these methods needs to be studied in terms of performance (both static and dynamic), complexity, implementability, and real-world prototyping experience on available cognitive radio platforms. For example, a recent study of cooperative sensing algorithms applied to a shared unlicensed band environment with overlapping 802.11b and Bluetooth signals showed that significant performance gains can be achieved with collaborative networked methods [38]. As the next step, it is important to evaluate these sensing methods in real-world environments. Researchers on this topic need large scale open CR network deployments with flexible radios, multiple types of services and real-end users in order to further evaluate and compare the performance of different sensing technologies. This research area has a great deal of industry interest because of the immediate opportunity presented by the FCC white space ruling.

3.3 Cognitive Radio Architecture and Software Abstractions

As mentioned earlier, a key challenge in the field is that of bringing radio technology into the digital age. Emerging SDR/cognitive radio platforms are inherently programmable and are expected to usher in a new era of flexible wireless networks and systems with high-level API's for control and management of radio resources.

Modern programmers unknowingly manipulate transistors and electricity constantly, but few of them have, or need, an understanding of Kirchoff's current laws, Boolean logic reduction or band-gap materials. Rather, they have complete indifference to the physical systems underling the abstractions that they directly manipulate, such as bits, memory and instructions because there are rich abstraction layers that isolate the "details" of computation. Currently, there is no such abstraction for the physical radio layer, and providing a coherent and understandable set of abstractions is a key challenge to better exploiting wireless communications. Likewise, the rapid innovation in VLSI systems owed much to the development of the "Mead & Conway" approach, by which a generation of computer scientists and engineers learned to turn silicon into computation.

The current construction of "software defined radios" involves tools and domains spanning circuit design, hardware design languages, complex real time software and computational intensive signal processing. Current software, such as the GNU Radio software stack [26], provides simplified abstractions that allow simple radio architectures to be developed using a "stream computing" model; however, those tools are in their infancy and unsuitable for actual production use because of inefficiencies and excessively detailed designs. There are ongoing efforts at specifying a *radio definition languages* that use declarative methods that can be combined with compilers for developing efficient signal processing algorithms and efficient hardware-software systems to capture the physical design of radio systems.

Some of the open research questions in this field can be summarized as:

- What language should be used to describe radio module capabilities? What radio interface should be presented to the application? How does one derive a common application interface from a specific module description?
- What radio control parameters must be exposed and what are the minimum shared interfaces needed to allow interoperability in a heterogeneous environment?
- How does one quantify mission requirements? How does one describe the capabilities of radio software modules? What techniques effectively translate from mission requirements to a radio configuration?
- How would the radio subsystem definition language and methodology integrate into broader programming models used in the computer science field? What high-level abstractions of the radio are appropriate for general-purpose programming as we anticipate dramatic increases in the number of computing devices that incorporate one or more digital radios?

In the last few years, there has been significant progress in the development of cognitive radios and a number of groups have developed platforms that are currently being used by the research community for experimentation. This research has significantly improved our understanding of cognitive radios architectures and their tradeoffs, and it has also resulted in initial proposals for an abstraction layer for use by higher layer software. This is however only an initial step and further progress is hindered by the lack of realistic CRN testbeds. Existing CRN testbeds tend to be small (typically a handful of radios) and homogeneous, lack full protocol stacks and applications, and are deployed in atypical environments (labs). These testbeds are not adequate for further refining requirements and for testing an evaluation of both cognitive radio abstractions and implementations. Large scale CRN testbeds are needed to continue and speed up progress in this area.

3.4 Cooperative Wireless Communications

Cooperative communication techniques with cognitive radios hold the promise of promoting efficient spectrum sharing by using approaches such as collaborative signal processing, cooperative coding, relaying and forwarding. Recent theoretical and experimental studies on cooperative communications [13, 14, 15] have shown that significant system capacity and spectrum efficiency improvements can be achieved through cooperative methods such as network coding, network MIMO, cooperative PHY diversity, cooperative MAC forwarding, and so on. Taken together, these techniques have the potential of achieving ~10 bps/Hz or higher, as compared with today's typical value of ~2-4 bps/Hz for widely used wireless systems such as WiFi and cellular. The benefit of cooperative communications can also be expressed in terms of range extension, power savings or availability/robustness, all desirable characteristics of future wireless systems.

While cooperative wireless communication is promising, there is still significant uncertainty about the practicality due to high control overhead and implementation complexity. Networks of cognitive radio platforms with full programmability and multiple operating modes offer the prospect of prototype implementations of cooperative communication methods which can then be evaluated for mass-market usage scenarios. Some of the research issues which arise are:

- Fundamental cooperation mechanisms at physical, link and network layers
- Evaluation of control requirements in terms of latency and information transfer between cooperating nodes
- Practical protocol designs to support methods such as network coding, network MIMO and cooperative relay
- Introduction of incentive mechanisms to enable distributed collaboration, using methodologies such as coalitional game theory
- Prototyping and real-world experimentation with novel high-capacity wireless systems using cooperative methods

Overall, this is a very promising research direction which is now being pursued both in academia and industry to address the need for scaling wireless system capacity and spectral efficiency. As cognitive radio platforms become available, it becomes practical to experimentally explore a wide range of innovative ideas for cooperation. Several contributors to the workshop felt that this would be an important area for NSF-funded research going forward and it is already reflected in ongoing CCF and CNS projects. It is however critical that this research can be tested and evaluated within the context of actual deployed CRNs. This is important not only to be able to evaluate different control protocols for cooperative communication and their impact on performance, but also to support research in how cooperative communication can best by integrated with higher layer protocols.

3.5 Dynamic Spectrum Access Technology and Algorithms

Dynamic spectrum access, as discussed earlier in Section 2.2, has motivated a significant amount of research activity on DSA technology and related algorithms. The simplest DSA methods proposed involve autonomous observation of radio spectrum by an agile radio receiver (typically a “secondary” device), which then selects (and continually adapts) the selected frequency band to avoid interference. This type of DSA method has been proposed for high-speed data networks covered by the IEEE 802.22 standard which uses TV white space as permitted by the FCC.

While “agile/random-access” DSA methods work reasonably well in sparse environments, hidden transmitter or receiver problems arise in dense deployments limiting the achievable spectrum efficiency. This problem is further exacerbated by the emergence of a variety of radio standards and increasing density of wireless devices. More advanced schemes based on control support either from centralized spectrum servers [16] or from a distributed common spectrum coordination channel [17,28] have also been proposed, and some of these are in early stages of deployment and investigation. Initial results indicate that system performance improves considerably when systematic coordination techniques are used in place of random-access agility. However, there is much more work to be done on Internet-scale deployment of spectrum services and/or spectrum coordination protocols that enable improved coordination. Some of the technical challenges on this topic are:

- Evaluation of reactive/agile DSA methods and related adaptation algorithms
- Specification of spectrum server data base and protocol interfaces and evaluation of performance in dense radio environments
- Specification of distributed spectrum coordination protocol across multiple radio standards, and evaluation in dense radio environments
- Algorithms for rate/power/frequency adaptation for all of the above scenarios

Research in DSA methods is challenging because of the complexity of radio propagation in a DSA context and the main goal of the research is to reduce uncertain in deployed systems, so the risk of interfering with incumbent users is reduced to an acceptable and quantifiable level. Large-scale deployments in real world environments are essential to meeting this goal. Simulation and small scale lab deployments will not be sufficient to convincingly test the technology.

3.6 Protocol Architectures for Cognitive Networks

Adaptive *networks* of cognitive radios represent an important research challenge for both the wireless and networking communities. The extreme flexibility of cognitive radios has significant implications for the design of network algorithms and protocols at both local/access network and global internetworking levels. In particular, support for cross-layer algorithms that adapt to changes in physical link quality, radio interference, radio node density, network topology or traffic demand may be expected to require an advanced control and management framework with support for cross-layer information and inter-node collaboration. At the wireless local-area network level, an important technical challenge is that of distributing and managing this inter-node and cross-layer information and then using this control information to design stable adaptive networking algorithms that are not overly complex. At the global internetworking level, clusters of cognitive radios represent a new category of access network that needs to be interfaced efficiently with the wired network infrastructure both in terms of control and data. End-to-end architecture issues of importance include naming and addressing consistent with the needs of self-organizing network clusters, as well as the definition of sufficiently aggregated control and management interfaces between cognitive radio networks and the global Internet.

A key issue in the design of cognitive network protocols is the definition of a control protocol which enables cognitive radio nodes to exchange information needed for frequency coordination, radio PHY parameter selection, medium access control method selection, network configuration and routing [18]. For example, collaborative PHY mechanisms such as network coding require control mechanisms to identify participating nodes, specify path diversity routes and eventually indicate (or download) applicable forward error correction algorithms. Similarly, for flexibility at the MAC layer, the control protocol should be able to distribute status necessary to infer current network topology and congestion conditions, together with the ability to coordinate changes in MAC functionality between a selected group of radio nodes [21]. At the network layer, radio nodes should be able to organize into voluntary ad hoc network clusters that agree to forward packets between themselves – this requires control protocol support for neighbor discovery, address assignment and routing table exchange. Cross-layer adaptation algorithms also require exchange of PHY and MAC level status information between nodes which participate in an ad hoc network cluster.

Some of the research questions being worked on in this area are:

- Concepts for cognitive network protocol architectures and evaluation of performance and control overheads. What type of control protocol best serves the needs of cognitive networks?
- How to support cross-layer optimization across all the protocol layers including PHY, MAC and network; does this require new protocol features beyond those available in existing standards?
- When should radios join existing networks and when should they compete? What are the incentives for collaboration between peers?
- What types of cognitive algorithms should be used for selection of operating mode and parameters? How must radio and network parameters be adapted dynamically to respond to mobility, changes in density, performance objectives, and so on?
- What kind of control procedures are needed to ensure system stability with distributed dynamic adaptation across multiple autonomous radio devices?
- How do the control and management planes of a cognitive network interface with the global Internet?

A number of research groups have proposed and prototyped control plane protocols, for example the collaborative CogNet [18] project being carried out at Rutgers/CMU/Kansas. The CogNet architecture is based on the concept of a logical "Global Control Plane" which provides a uniform and extensible protocol for control communication between radio nodes. Other groups, for example UCSD [19] and VA Tech [37], have also been working on alternative cognitive network protocol designs and prototypes intended to support adaptation and cognition. However, so far, evaluation has been limited to relatively small scale lab testbeds that lack the scale, complexity, and heterogeneity of future deployed CR networks.

3.7 Cognitive Algorithms for Adaptation and Resource Management

Existing link-layer designs are often burdened with design tradeoffs and backward compatibility issues. In addition, they are often designed to accommodate worst-case scenarios and incur significant overhead under normal operating conditions. For example, in the 802.11 protocol, headers are transmitted at lower rates to accommodate older nodes and nodes that are further from the transmitter. In practice, this severely limits the delivered throughput of 802.11's higher speed modes of operation. In addition, mechanisms such as RTS-CTS, which may provide benefit in some settings, are often disabled due to the performance impact in typical conditions. Protocols such as 802.11 must also choose parameters such as carrier sense thresholds to handle arbitrary topologies of communicating nodes. However, in practice, most network deployments ensure that communicating nodes are nearby (e.g., laptops typically connect to the closest access point or base station). In such settings, these configuration parameters are far too conservative and adversely affect performance. Similarly, link-layers must specify an appropriate MAC protocol. For example, many existing systems choose CSMA, FDMA, TDMA or some hybrid of these. Unfortunately, CSMA, FDMA, TDMA and hybrid protocols each have tradeoffs that make them best for particular traffic demands and link-layers are unable to adapt their choice to the current traffic needs.

Similar considerations apply to network layer protocols such as routing. The first generation of multi-hop wireless networks (such as ad hoc and mesh) suffered from serious performance limitations due to unintended interactions between protocol layers. For example, use of shortest-path routing at the network layer could have negative consequences for MAC congestions at the link layer. Cognitive networks will incorporate cross-layer awareness using protocol mechanisms discussed above in Section 3.6, and should be able to apply cognitive algorithms to improve network performance significantly. This is an area of research that involves a mix of wireless, network and machine learning/AI expertise and is thus an interesting academic research area with potentially attractive outcomes. Some of the topics being worked on in this area are:

- Algorithms for dynamic adaptation of protocol components such as MAC and routing
- Use of cross-layer information in wireless networks
- Robust decentralized algorithms for adaptation and mode switching
- Use of machine learning and artificial intelligence tools for network control
- Understanding the stability and emergent behavior of decentralized adaptive networks

Most of these research topics involve a mix of theory and experimentation in real-world environments. Initial research typically uses a mix of controlled testbeds and small-scale open testbeds. However, adaptation algorithms and protocols must also be evaluated at scale, both to understand the stability and emergent behavior, and to study interactions with adaptive at higher (e.g., application and user behavior) and lower (e.g., physical) layers in the system.

3.8 Network Security

Cognitive radios introduce an important new dimension into the security of wireless networks [43]. One of the advantages of conventional radio technology is the predictability of the signals emitted by wireless devices, which are typically type approved by the FCC. As programmability extends to the radio, it becomes possible to create a wide range of authorized and unauthorized waveforms with a low-cost consumer device. It would then be relatively easy to create denial-of-service attacks that can affect critical applications such as traffic control or healthcare. Future FCC regulations need to be aware of this potential and work with industry to develop trusted hardware architectures, monitoring frameworks or other solutions to the security problem. Some of the issues being worked on in this area are:

- What types of denial-of-service and other security attacks are made possible by emerging cognitive radio technology?
- Software weaknesses are known to be a major security problem in the Internet today – what are the implications of increasingly software-based radio implementations?
- How does one assure that CRs operate as intended and designed? Is there a trusted cognitive radio architecture which can address some of these security concerns?
- What authentication mechanisms are needed to support cooperative cognitive networks? Are reputation-based schemes useful supplements to conventional PKI authentication protocols?

At the same time, cognitive radios offer important new capabilities to defend against intrusions or denial of service attacks. The spectrum sensing and SDR capability of the radio make it feasible to employ recent developments in wireless security in which physical layer properties (such as RF signatures) are used for authentication or secure communication [20]. Also, spectrum scanning and agility associated with cognitive radios enable networks to move away from frequency channels experiencing denial-of-service attack. Location is another important feature of a wireless network, and information on geographic position can also be used to defend against certain types of attacks on cognitive networks. Research questions being addressed by the community include:

- Identification of physical layer security enhancements for wireless networks, and evaluation of performance in realistic environments
- Evaluation of denial-of-service attack scenarios and methods for defense
- Use of geo-location for improved wireless network security
- Cooperative methods for detecting and isolating intruders

While initial results are promising, evaluation has been limited to lab environments, and it is not clear to what degree these techniques will be practical in real world deployments, or will scale to high density environments. Larger scale testing in CRNs is needed. Since CRNs are still in their infancy, there is an opportunity (if not a responsibility) to make security part of their architecture from day one. This will require realistic evaluation of new techniques as they are developed.

3.9 Cognitive Networks and the Internet

The research questions and answers essential to building cognitive radio networks are, in some sense, extreme problems of wired networks. For example, both wired and wireless networks need to deal with links going up and down. However, in the wireless network, the frequency of link status changes is much higher than in today's wired network. So, wireless network architectures must pay closer attention to link status changes and react faster to these changes. Research in CR networks will carry over into wired network. Some characteristics of cognitive radio networks that are applicable to larger, end-to-end network are:

- Operating environment sensing – Cognitive radios measure and react to the environment they are operating in. The radio environment is multi-dimensional; including cooperative and non-cooperative emitters turning on and off, CRs adapting to their local changes, and traffic loads; and rapidly varying. CRs must rapidly adapt to this changing environment and communicate their changing operation settings to other wireless devices in the network. The mechanisms and techniques to sense, adapt, and communicate operation state are necessary in CR networks and applicable to networks in general.

- Robust communication services with unreliable links – The radio links, by their very nature, have intermittent outages. A link outage may result from the temporary location of the receiver, transmitter and other objects in the environment. CRs, by their very design, must deal with these very short-term link outages, and do so through a variety of techniques. It is through this large set of techniques and mechanisms that wireless networks implement a robust and reliable communications service with unreliable links. The techniques and design patterns used in wireless architectures are applicable to the larger network architecture.
- Operational state languages – CRNs, as they adapt, must communicate their observations and operation state to other CRNs in the network. A few "languages" will be needed to describe observations and operation state. This information is likely to be much richer than common link status information. For example, one radio might send a list of all emitters it has recently sensed to other CRNs in the network. The entry for each emitter might include a frequency range, time, and spatial location, and signal format (e.g., spread spectrum or narrow-band FM). The language used to describe observations and operation state will be much richer than conventional node or link state information. The language(s) and protocols necessary for CRN networks should influence general network architectures.
- Distributed Resource Management – The radio spectrum is a distributed resource. Use of the spectrum in one location affects the availability of that spectrum in other network locations. Allocation of the radio spectrum resource must be carried out in a cooperative manner and balanced between (quick) local decisions and (optimal) global allocation. The algorithms developed to allocate the distributed radio spectrum and mobile network resources based on traffic loads and operating environment are applicable to the GENI infrastructure – and will require demanding new services within the GENI network.

These examples show how techniques and mechanisms necessary to CR networks will have an influence on the architecture, design and implementations of networks in general.

4 Towards Large-Scale Deployment

As described in the previous section, a lot of progress has been made in developing the hardware, algorithms and protocols that are needed for DSA capable cognitive networks. Yet, we are very far away from seeing large-scale deployments of CRNs. One of the reasons is that the research to date has focused on developing components of CRNs, rather than complete CRNs. Moreover, a lot of the evaluation of the research has been based on simulation, which often oversimplifies many aspects of the real world.

CRNs are very complex systems and while developing all the components is important, a major challenge is figuring out how they fit together and work together under realistic conditions. In other words, we need to evaluate the performance of complete CRNs at reasonable scale and study emergent behavior in large-scale networks. Without this level of evaluation, it will not be possible to justify the necessary spectrum policy changes or to convince industry to make the necessary investments.

4.1 Broader Evaluation

Cognitive networks are very complex systems that include many components that are developed by widely different communities. Both the scope and the interdisciplinary nature of cognitive networks create unique challenges for the evaluation of cognitive networking research. For example:

- **System wide**: Testing individual components is not enough – system level testing, i.e., involving all components integrated in a functional network, is essential to validate cognitive networking as a usable technology.

- **Interdisciplinary**: Researchers from different communities (communications, networking, policy, …) will want to evaluate their work both in isolation and in an integrated system context.
- **Scale**: The scalability of the solutions needs to be evaluated.
- **Safety**: Experiments, including failed experiments, should not affect/harm other wireless users.
- **Realism**: The behavior and performance of a cognitive network will depend critically on many external factors such as traffic loads, user behavior and levels of interference. The CN system needs to be evaluated in ways that reflects realistic environments. One consideration that deployment environments can be very diverse, e.g., rural areas versus downtown DC.
- **Rigor**: The evaluation needs to be very rigorous so the results are convincing. This is especially the case if results are needed to drive changes in policy in the DSA domain.

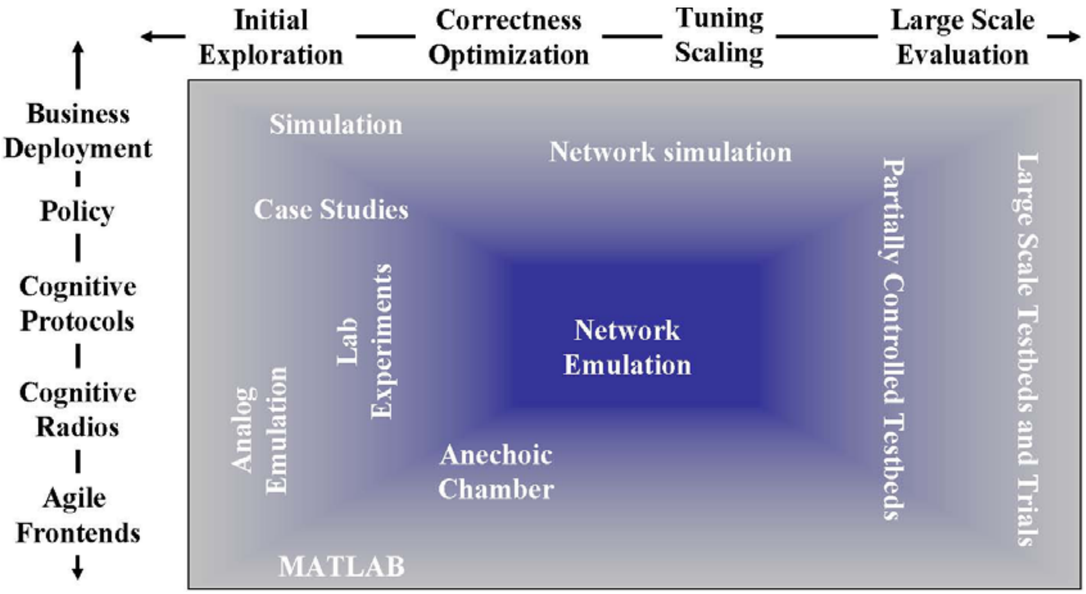


Figure 2: Evaluation Methodologies for Cognitive Networking research

Of course, no single methodology will be able to meet all these evaluation criteria and the broader cognitive networking community has developed and used a number of different methodologies. Figure 2 provides a sampling. The evaluation requirements depend both on the specific technology that is being evaluated and at the stage in the lifecycle of the project, so we placed the techniques in a two-dimensional space. In the early stages of the project, different types of simulation, modeling, formal methods, and lab experiments are used to evaluate different components. Later, in the project emulation environments that can be used to recreate realistic test environments for components prototypes and to evaluate partial integration. Finally, testbeds that can be used to evaluate partially or fully integrated prototypes are needed, followed by large-scale trials.

The degree of maturity of the evaluation techniques shown in Figure 2 is highly variable. Broadly speaking, the techniques on the left are fairly well understood and, while not perfect, there is a fairly good consensus within the various communities of the value of different evaluation techniques. Platforms for evaluation in the middle and right of the picture, e.g., for partial and full system testing, are not as advanced. Such evaluation needs to consider several system wide metrics: performance, stability, efficiency, reliability, etc. While there are analytical techniques to evaluate certain aspects of complex systems such as a cognitive network, these techniques must make many assumptions to make the analysis feasible. The behavior of cognitive radios involves considerable interaction between the radios, and their users and operating environment. This interaction is very difficult to capture in analytical models or simulations. As a result, these techniques must be complemented with experiments using actual prototypes operating under realistic conditions.

A valuable aspect of deploying experimental networks is that they enable the implementation, assessment and comparison of different solutions for the components in the system, and a careful study of how each component interacts with and is affected by the choices made in the rest of the system. For example, there are a number of important research questions with respect to higher layer services and functionality including; economic, policy and cooperation models. Large scale experimentation could examine cooperation and incentives for spectrum usage, secondary spectrum markets, efficient models of spectrum usage and policy models that might enable or enhance efficient spectrum usage. Without large developments of operational systems, it is difficult to accurately assess how such models will behave in networks that include many adaptive protocols, applications and users - simulation is simply insufficient. What regulatory models should policy makers implement to enable the growth of dynamic spectrum access? Are there feasible models for primary cooperating (even minimally) with a secondary and, if so, how this should be done? How might different models of cooperation impact spectrum usage, network performance and security of these CR systems? These are important question that can only be convincingly addressed using system wide evaluation. Similarly, many challenges exist at the lower layers of the system, including efficiently measuring interference and developing methods for mitigating this interference is critical. Dynamic models of propagation and interference mitigation is a complex and interesting control problem, but the performance of specific solutions depends critically on the deployment environment and the adaptive behavior of the higher layer components of the system.

Recently, a number of different wireless testbeds have been developed offering different degrees of experimental control and these testbeds are becoming increasingly more sophisticated in part as a result of efforts such as GENI. Cognitive wireless networks however introduce novel testbed requirements. First, cognitive networking research has a policy component that is largely missing in mainstream wireless networking research. Second, the spectrum agility needed in DSA networks adds a new research dimension and also creates new challenges for testbeds. Finally, cognitive networks have many more degrees of freedom, which translate in the need for more extensive control over experiments.

4.2 Testbed Requirements

Evaluation of cognitive wireless networks requires two types of testbeds:

Controlled testbeds that can be used for relatively early testing of prototypes of partially or fully integrated networks. Key requirements are flexibility (i.e., being able to run very diverse experiments and involving heterogeneous platforms), high degree of control (i.e., ability to create very diverse scenarios for testing), isolation, repeatability (so results can be validated and compared) and safety (i.e., errors in various network components will not cause any harm). Controlled cognitive testbeds can be based on a number of different technologies, including signal-propagation emulation, large anechoic chambers or testbeds in remote, isolated regions where ample spectrum is available. The scale of controlled testbeds can vary from tens to possibly a hundred nodes. Two examples of existing radio testbeds with cognitive networking capabilities are the CMU emulator [22] and the ORBIT radio grid testbed at Rutgers [24] – these are briefly described in Appendix A.

Open testbeds that can support larger scale experiments in fully realistic environments. The key difference with controlled testbeds is that being immersed in the real world (“open”), the signal propagation environment will include the effects of real world objects, mobile objects and people, and possibly interference from a variety of RF sources. Key requirements include heterogeneity (e.g., diverse devices and applications, mobile and stationary hosts, diverse device densities, etc.), use of a reasonably rich spectrum (involving licensed and unlicensed), and programmability at all levels of the system. Since any testbed will be tied to a particular physical environment, a small number of open testbeds in diverse contexts would be made available, e.g., rural, inner city, etc. targeting different classes of applications. Ideally, some of the testbed would involve real users to achieve a high degree of realism, since traffic load mobility, two key inputs to cognitive network behavior, depend in part on user behavior. Alternatively, realistic emulated traffic loads can be used. Open testbeds should generally be an order of magnitude larger than controlled testbeds to allow realistic and challenging experiments. Some examples of open real-world wireless networking testbeds are the “DieselNet” testbed at UMass, the outdoor ORBIT testbed at Rutgers, the Homenet residential testbed at CMU, and the CitySense network at Harvard. However, these existing wireless testbeds are based on available radio technologies such as WiFi and WiMax and do not yet have the cognitive radio capabilities being discussed at this workshop.

There are many challenges involved in building both controlled testbeds (e.g., isolation, control, etc.) and open testbeds (e.g., high node and traffic density, stability, etc.). However, the community has gained significant knowledge in building and operating such testbeds, as witnessed by the many wireless testbeds currently available to outside users over the Internet. Our understanding and experiencing in building, managing, and sharing testbeds is likely to continue, as a result of the BBN-led GENI effort. The testbeds must also be adequately instrumented so that experiments can be monitored. This is important so users can understand the behavior of the network, diagnose problems and improve performance. It is crucial that the spectrum sensing infrastructure be robust, extensive and sufficiently sensitive in a CRN testbed to ensure the validity of the sense and detect algorithms and to quantify the over all success of the DSA systems.

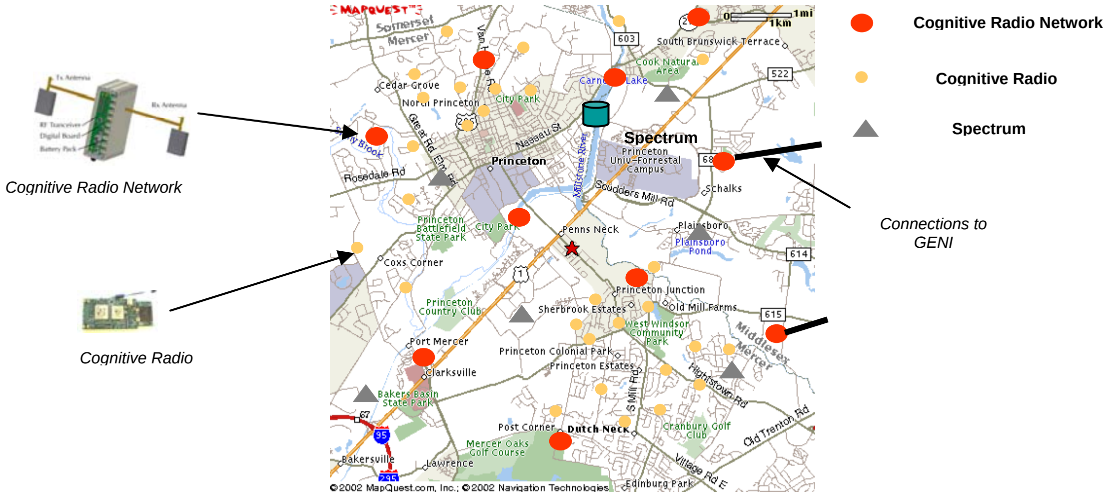


Figure 3: Real-world cognitive radio testbed deployment plan (reproduced from [36])

Figure 3 shows an outdoor deployment scenario for cognitive radio evaluation based on deployment of multiple cognitive radio networks in a target geographic area. This plan was originally developed for GENI, but has been deferred to a later stage of the project pending increased availability of the technology. The planned CRN deployment would include high-power base stations or access points using CR technology, CR mobile devices (typically user laptops with an external module, or a vehicular communications node), as well as spectrum monitoring devices needed for evaluation.

4.3 Cognitive Radio Platforms

Multiple classes of platforms will be needed to populate the testbeds. These include:

- Base stations: more powerful nodes with no power constraints
- Client nodes: typically less capable, more compact and lower cost
- Mobile platforms: more challenging clients since there are size, weight and power constraints. Some of these challenges may be reduced by using cars for deployment.
- Wide band spectrum sensors

- Various RF sources of interferences or different types of users in specific spectrum bands.

The research community has developed a variety of software radio platforms that can be used as the basis for cognitive radios. These include USRP 2, WARP, KU Radio, DARPA WNaN, WiNC2R, etc. Appendix B presents more details on some of the platforms. What platform to pick requires further study and it is unlikely that a single platform will meet all our needs. Here are some factors to consider during the platform selection:

- Platform flexibility: this covers a broad set of issues including the ability to implement diverse physical layers, support for diverse front ends (e.g., covering various spectrum bands including very wide band, very sensitive spectrum sensing (-115dBm), different quality/cost tradeoffs), and access to programming tools. Note that a number of suitable commercial front ends are available (e.g., from M/A COM WNaN radio), so it would be attractive to be able to use those.
- Software availability: Developing software for software radio platforms is expensive and time consuming, so preference should be given to platforms that come with a broad base of stable (and preferably open-source) software. In this context, software includes the code for all components of the system, including FPGAs, embedded cores, CPUs, and the host. Ideally, a large fraction can be shared across multiple platforms, both to reduce cost and threshold of entry for new groups. While developing architectures and APIs that support software portability are part of the research agenda, there needs to be credible path that this will be feasible for the selected platforms. The project should not only consider the initial availability or development of the software, but also the effort needed for upgrading and maintaining the software over time. In that sense, availability of open source software (as with the GNU Radio project [26]) is considered critical to the success of a community testbed effort.
- Physical properties of the device: This covers a broad range of issues including packaging deployment in various environments, ability to withstand the element, ability to radiation exposure, high degree of isolation from vital equipment operating in nearby bands, use spectrum sensor that kills the set up if it goes outside of operating range, etc.

It is of course possible to build a new platform that is better than any of the available platforms. However, this approach would significant increase risk and would delay testbed deployment.

4.4 Testbed Deployment and Management

The deployment of testbeds in outdoor environments (e.g., open testbeds or partially controlled testbeds in isolated areas) is very challenging. It may involve collocating equipment with commercial providers (e.g., on cell towers), right of ways issue, and power and network access in various locations. Ideally, these tasks would be handled by partner companies that have experience in this area. One example is Open Range Communication.

Another challenge is the management of the testbed infrastructure and support for experiment control. These issues are currently being addressed by the GENI effort and it would make sense to leverage that work, for example by collaborating with one of the control frameworks that were established as part of the Spiral 1 development effort headed by BBN. Frameworks such as ProtoGeni already provide support for many functions such as node management, experiment control, federation, etc. in the context of heterogeneous testbeds. Note that GENI is currently focusing on integrating existing testbeds, rather than building new ones, so the focus of any CRN testbed effort would be complementary.

While many aspects of CRN technology can be explored in the unlicensed spectrum, many aspects of DSA research can benefit from access to licensed spectrum through experimental licenses. This may be necessary for a number of reasons. First, since signal propagation properties depend on the frequency, it is important to explore different parts of the frequency spectrum. Second, some experiments may violate FCC rules for the available unlicensed bands. Finally, the existence of other unlicensed traffic may be disruptive to the experiment. The FCC does grant experimental licenses, but these can be hard to get for bands with reasonable bandwidth. One possibility would be to establish one or more open testbeds in sparsely populated regions, such as rural areas or the Tribal Nations, since it may be easier to obtain experimental licenses. Such testbeds also offer unique opportunities for outreach, as discussed below.

Another issue is the sustainability of the testbeds past the end of the program. Sustainability should be a goal for both the testbeds and the outreach activities that are associated with them. Sustainability raises a number of issues:

- The equipment must be reliable and supported by an organization that is able to provide the necessary maintenance and customer service.
- At least part of the infrastructure should use a standard commercial protocol for which upgrades and replacement equipment will continue to be available, and which can be commercially maintained past the lifetime of the testbed. One possibility would be to use a WiMax infrastructure both as the control plane for the CRN testbed and a reliable network that can be used for outreach activities.
- Building on an existing management framework would significantly help the sustainability of the testbed. For example, the CRN testbed or testbeds could federate with other GENI testbeds and could thus become part of the GENI effort.

5 Research Program Organization

The breadth of research questions and technologies involved in building CRN systems calls for considering innovative approaches to organizing a CRN research program. There are four aspects to consider when setting up a CRN research program:

1. CRN research and development requires a multidisciplinary approach involving researchers in the areas of radio frequency circuit design, signal processing, networking, adaptive systems and learning, spectrum policy, economics, and social sciences.
2. CRN research requires a structure that insures wide participation in developing CR technologies.
3. CRN research must be built on a foundation of field measurements (testbeds) and repeatable experiments.
4. CRN research must be connected with emerging applications and radio communications needs.

Point (1) argues for a few (2-3), significant efforts to organize and maintain solid engineering teams to address the breadth of CRN technologies. These efforts might involve single or multiple institutions, but should be funded at a level to support locally developed technologies as well as the ability to integrate technologies from other research groups. These efforts should be able to widely disseminate CR experimental platforms to others. Point (2) argues for a collaborative effort to collect and disseminate information and CRN measurements and models to a wide range of institutions. Many research groups can contribute to CRN research but do not have the infrastructure to begin from scratch. Organizing a cooperative, collaborative effort is important.

CRN research must be grounded in the physical world. Radios work in the physical world, not in models. A CRN research program must develop the tools and techniques to easily move information from field experiments (testbeds) to abstract models and move questions from the models to experiments in the field. A range of capabilities is required. First, we need experimental testbeds to gather physical world experience. We cannot improve our science without measurements in the real world. Second, we need facilities for controlled experiments. We cannot move the technology forward if there are too many unknowns in an experiment. We must be able to repeat experiments. Third, we need techniques to abstract field experiment measurements into simpler models. This enables us to consider larger CRN systems before extensive deployment. At the same time, we need to learn how to extract questions from our models to design new and worthwhile field experiments. We see this as a continuum from simulation models, to emulation, to controlled laboratory experiments, to field experiments.

Point (4) argues for grounding CRN research in current or foreseeable user needs. A balance is required here. We must understand the emerging needs and incorporate those needs into the motivation for our CRN research. However, we do not attempt to use a CR networking research program to solve a specific application requirement.

There are three possible research structures:

1. The first is the standard NSF program. A research program is announced. Investigators submit proposals. The best are selected by a review panel and funded. The problem with this approach is that without significant NSF Program Director involvement over the long term, there is little coordination across the funded research efforts.
2. A second approach, used in the GigaBit testbeds and, to some extent, in the current GENI GPO, is to issue a large grant to a single institution, in the case of the GigaBit testbeds it was CNRI and in GENI it is BBN. The outside institution solicits proposals, reviews them and issues grants/contracts. This can lead to a coordinated endeavor. A task of the coordinating entity is to ensure collaboration among funded investigators and ensure collection and dissemination of work.
3. A third approach would be one or a small number of large collaborative grants supporting a consortium of university partners to move this endeavor forward in a coordinated fashion.

Given that one of the major research challenges is how to integrate the many CRN components into a larger, stable, and deployable system, the panel felt that the 2nd and 3rd approaches were worth considering, and that there are important lessons to be learnt from the Gigabit Testbeds and GENI project structure. However, the 1st approach is also feasible, if accompanied by mechanisms to coordinate the selected projects, as is done in the recent Cyber-Physical Systems program (NSF 08-611).

Putting a program together is however a significant and possibly lengthy process and the panel felt that there is an opportunity for an immediate, focused effort that would have a significant impact on the CRN community. The lack of shared CRN testbeds is a serious impediment to continued research progress in the field. It leads to heavy reliance on simulation or small scale experiments in lab environments that are non-repeatable and often not realistic. Given our improved understanding on how to deploy and manage shared wireless testbed, there is an opportunity for a focused research effort in the area of CR networking testbeds, including testbeds that support controlled, partially controlled, and in-the-wild testbeds. This testbed effort should be coupled with a development of a shared community infrastructure for CR networks that can be used by other researchers for their experiments. The results of such a focused effort would of great value to the CRN research community and it would also provide a solid starting point for, accelerate, and reduce the risk of any future program in the CRN area. Note that because of the unique features of CR networks, the development of CRN testbeds requires a research effort – it is not an infrastructure project.

6 Broader Impacts in Education and Public Safety Applications

By systematically examining how CRN systems would interact with each other and with legacy radio systems, CRN research will remove the uncertainty surround dynamic spectrum access. The results will shed light on areas of true concern and dispel the false concerns that have been made by the opponents of this technology. The research will provide a method for assessing technical criteria proposed in the regulation and management of spectrum. Rather than relying on simulation or extension of emulated results, these testbeds will be able to provide a means for more accurately assessing the impact of different radio network deployments and the usage rules that should subsequently be employed. The experimental results will enable the adoption of cognitive radio networks by demonstrating how and where the technology can be deployed. As a result, this research will help usher more efficient use of the radio spectrum and encourage more dynamic and intelligent use of network resources. Lastly, this effort will extend the current scientific understanding of complex dynamic networked systems and therefore provide insight beyond radio systems to influence a better understanding of wired network dynamic design.

Cognitive networks and the resulting significant improvements in spectrum efficiency will have significant broader impacts on society by enable further growth in wireless applications and services. Domains that are particularly noteworthy are 1) enabling better communications for public safety and homeland security, 2) provisioning Internet access for underserved areas, 3) providing a robust communications system for Tribal Nations, and 4) demonstrate viable uses of CRN technology that can lead to deployments. Finally, a CRN research effort will involve a large number of graduate and undergraduate students building and evaluating large-scale network systems, a skill set that is in high demand in industry. We anticipate that the research conducted through this testbed should result in a substantial number of MS and PhD theses.

6.1 Public safety scenario and uses/benefits of CR technology

The public safety community is in dire need of additional spectrum to enable broadband applications to its officers. Most police, fire and paramedic personnel have limited access to the modern communications services and applications necessary for them to complete their missions. Much of this limitation is due to the design of the public safety radios and the associated networks. While additional spectrum bands have been allocated to public safety, these officers don't have the radio technology that can operate dynamical across this additional spectrum – this is a problem that CRN technology can address. Furthermore, there continues to be a substantial lack of interoperability among police, fire and paramedics, even though this specific interoperability problem has been explored for more than two decades. CRNs can offer public safety substantial communications improvements by enabling dynamic access to bandwidth and providing methods for interoperability.

At a recent National Institute of Justice (the research arm of the US Department of Justice) Technical Work Group meeting, cognitive radio was identified as a critical part of future public safety communications technology. The work group also identified a number of bandwidth intensive applications that public safety officers currently require, but do not generally have; this included video streaming, license plate detection and web access. The work group recognized that CR networks can both enable access to additional bandwidth and offer a path toward interoperability.

Joe Heaps, from NIJ, attended the NSF workshop (held March 2009) and indicated that public safety would benefit by having NSF support the development of a large-scale CR testbed. He indicated that progressing the understanding of how these networks would operate and assessing the benefits and concerns that could be explored in such as testbed, would be a great benefit to the public safety community.

6.2 CR Benefits for Internet Access and Education in Underserved Regions

One of the anticipated benefits of CR technology is that it will enable lower cost Internet access by reducing the substantial cost component associated with the purchase of spectrum. In a DSA based approach to spectrum management, unused spectrum could be accessed by users to enable broadband access to the Internet. By deploying smart mesh CRN systems, the network could create the backhaul necessary to reach remote rural areas. It could also be used in dense urban areas to enable efficient sharing of the scarce spectrum resource.

6.3 Use in Educational Projects in Tribal Lands

We plan to work with a Native American Tribe as part of our testbed deployment. Our goal is to create a testbed that could also serve as a production network for this community. This network should be built to serve the community in a meaningful manner and we plan to provide a mechanism to ensure continuity of the system after the experimental phase of our work is completed. We also plan to incorporate the testbed development and experimental processes with local tribal high schools and community colleges. Part of this effort will focus on the creation of an "experimental networking education consortium" where local high school students will work with their teachers and members of this proposal to explore and foster an interest in networking science and engineering. Ultimately, we hope to both provide a robust infrastructure for the tribal nation and encourage participation and interest of local youth in the fields of computer science and engineering.

Some members of the workshop have been involved with related activities to enhance communications infrastructure for Native Americans. As a result, we are very aware of the cultural implications of what we are trying to achieve and that for us to be successful we will need to work closely with tribal leaders (and experts in the field) to gain an understanding of 1) how best to approach this deployment, 2) what services this should offer to the local users, 3) how local users might participate in the experiments (e.g., interested high school students) and 4) how this infrastructure might be managed after we leave. To this end, we have begun discussions with two tribes (the Little River Band of the Ottawa Indians and the Salt River Pima-Maricopa Indian Community) but plan to engage with several tribes to ensure that we can best help provide a useful infrastructure for the tribe.

6.4 Near-term Commercial Uses of CRNs and the Role of Industry

As we have described, CR networks face market and regulatory resistance due to the substantial uncertainty that they introduce into the current model of spectrum management. However, there have been a number of regulatory changes that support the potential for CR adoption. The most significant is the recent TV White Space (TVWS) ruling, which describes a CR based approach to accessing large amounts of unused spectrum (in a particular geographic region) for building broadband access networks. Several large companies are backing this effort (e.g., Microsoft, Motorola, Google and Intel) but it is still unclear if TVWS networks will be a commercial success. One of the issues currently facing the use of this spectrum is the detection thresholds that have been assigned by the FCC. It may be that they are too conservative and thereby restrict the potential reach of TVWS devices. In the absence of large-scale testbeds, the FCC has limited ability to determine what the correct threshold should be and erring on the conservative side is a safe position to take. However, the testbed we propose could help determine where such thresholds should be set and examine the potential harm to incumbents if the levels are set too high.

This is just one example of how CRN testbeds could aid near term adoption of CRN. There are numerous other applications that warrant additional study through such testbed facilities. One of the more interesting applications of CR networks is in the application to assistive technology for the physical handicap. There is an effort currently underway to deploy personal wireless networks for enabling muscle activation in paraplegics. Through this technology it is thought that victims of crippling spinal accidents may be able to walk again through cyberphysical systems operating over wireless systems. This technology is making use of CRN technology to avoid interference and to enable high reliability of the cyber-physical system. Numerous other technologies are also considering CRN technology but there is substantial uncertainty holding back the adoption of CRN – again, this is where a testbed could help address this uncertainty.

7 Workshop conclusions

The workshop conclusions can be summarized as follows:

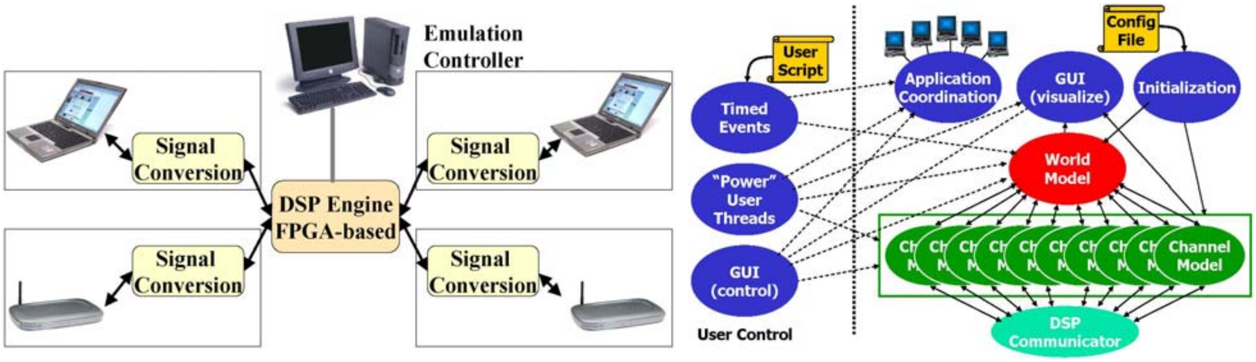
- The rapid proliferation of wireless technologies is expected to increase the demand for radio spectrum by orders of magnitude over the next decade. This problem must be addressed via technology and regulatory innovations for significant improvements in spectrum efficiency and increased robustness/performance of wireless devices.
- Emerging cognitive radio technology has been identified as a high impact disruptive technology innovation, which could provide solutions to the "radio traffic jam" problem and provide a path to scaling wireless systems for the next 25 years.
- Cognitive radio network represent a paradigm shift in both radio and networking technologies, with the potential to provide major gains in performance and spectrum efficiency. However, even as cognitive radio platforms have started to emerge, significant new research work is required to address the many technical challenges of cognitive radio networking. These include dynamic spectrum allocation (DSA) methods, spectrum sensing, cooperative communications, incentive mechanisms, cognitive network architecture and protocol design, cognitive network security, cognitive system adaptation algorithms and emergent system behavior.
- Based on an assessment of progress in the area of cognitive networks in the last five years, the workshop concluded that a major hurdle in continued progress in the field is the inability to conclusively test, evaluate, and demonstrate the cognitive networking technology, at scale and in real-world deployment scenarios. This calls for the development of a set of cognitive networking testbeds that can be used to evaluate cognitive networks at various stages of their development.
- The workshop participants urge NSF to consider creation of a new collaborative research project or research program to address the CR networking opportunities identified here. We specifically advocate a two phase effort. Besides a long-term, interdisciplinary effort that tackles the problem of how to build and deploy large-scale CR networks that meet the future needs or our society, we believe there is a need for an immediate research effort in the area of CR <u>networking</u> testbeds and shared infrastructure. Such an effort would be of immediate benefit to the community and provide an excellent starting for a broader CRN research program.

Appendix A: Overview of Wireless Testbeds

We present two examples of controlled wireless testbeds.

A.1 CMU wireless network emulator

Signal propagation emulation [22] makes it possible to conduct network experiments using real wireless devices running in real-time in a controlled environment. The operation of the emulator testbed is illustrated in Figure 4(a). A number of wireless devices are connected to the emulator through a cable attached to the antenna port of their wireless network cards. On transmit, the RF signal from a given device is passed into the signal conversion module where it is shifted to a lower frequency, digitized, and then forwarded in digital form into a central DSP Engine that is built around an FPGA. The DSP Engine models the effects of signal propagation (e.g., large-scale attenuation, multi-path, and small-scale fading) on each signal path. Finally, for each device, the DSP combines the processed input signals from all the other devices and sends it to the signal conversion module. It converts the digital signal back into an RF signal and sends it to the wireless card through the antenna port.



(a) Architecture **(b) Software**

Fig 4. CMU wireless network emulator

The emulator simultaneously offers a high degree of realism and control. Devices are shielded from each other (boxes in Figure 4(a)) so no communication occurs over the air. Since devices only communicate through the emulator, we have full control over the signal propagation environment. The only simulated element is the propagation of signals between hosts. Channels are modeled at the signal level but the wireless hardware, signal generation and reception, and software on the end hosts are all real.

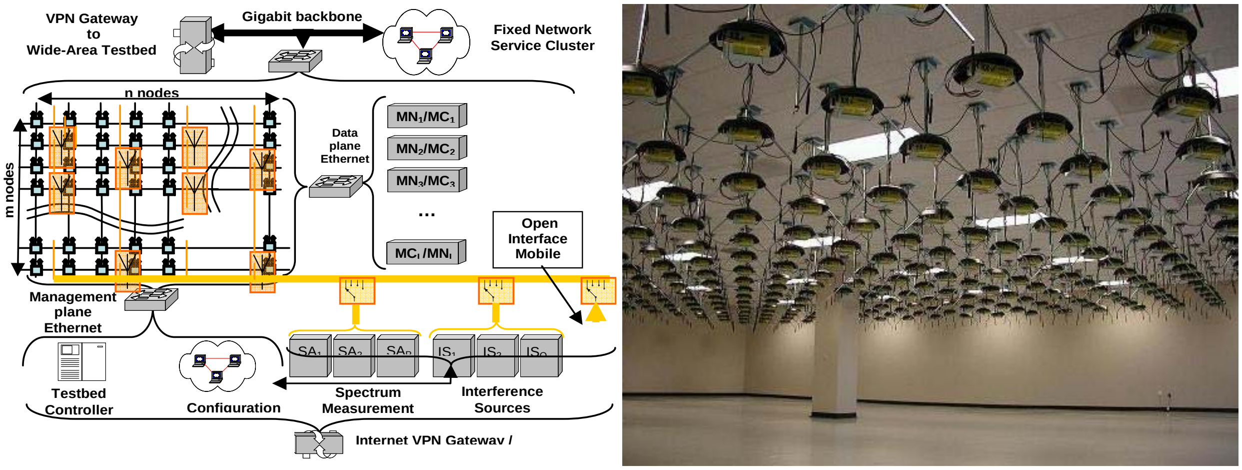
Emulation is controlled by an Emulation Controller executing on the Emulation Control PC. The Emulation Controller models the emulated physical environment including the movement of the wireless devices (World Model in Figure 10(b)). It also coordinates the movement of devices with the modeling of the signal propagation in the FPGAs by modifying its parameters in real time (Channel Models). To use the system, user log into the Emulator Control PC over the Internet. Users can specify and control wireless experiments in three different ways: an interactive GUI, simple scripts, or programmatic control using Java [23] (left side of Figure 4(b)).

The emulator supports the full 2.4 GHz ISM band and has 15 nodes. The nodes are laptops with 802.11b interfaces based on the Atheros chipset and some nodes also have software radios (USRP) or Bluetooth. The wireless emulator testbed has been available to external users since Spring 2007 and it has been used by many research projects both at CMU and elsewhere. It has also been used for assignments and projects in both graduate and undergraduate courses at CMU and elsewhere. The wireless emulator testbed is part of the GENI Spiral 1 development project under the ProtoGeni control framework. More information on the wireless emulator testbed can be found at on the emulator web page: http://www.cs.cmu.edu/~emulator.

The wireless emulator is a natural testbed for supporting research in CRNs. RF signals are shifted to an intermediate frequency before they are digitized, so by using different local oscillator frequencies we can easily support different frequency bands. We can also adapt the signal propagation models used in the emulator to match the frequency band being used. Moreover, since the emulator is digital and all analog components are in RF shielded boxes, we do not need to be concerned about interference with production networks. Finally, very diverse scenarios can be emulated on a single platform.

A.2 ORBIT Testbed

The 400-node ORBIT radio grid testbed at WINLAB, Rutgers University is shown in Figure 5 below. The testbed provides 400 programmable radio nodes for at-scale and reproducible emulation of next-generation wireless network protocols and applications. The ORBIT radio grid can be accessed by experimenters via an Internet portal, which provides a variety of services to assist users with setting up a network topology, programming the radio nodes, executing the experimental code, and collecting measurements. The testbed also supports end-to-end wired and wireless experiments using a combination of ORBIT and PlanetLab nodes under the same experimental execution framework. Upgrade of the testbed with GNU/URSP2 radios to support programmability at the radio PHY and MAC layers is currently in progress, with the objective of support emerging cognitive radio networking experiments. The radio grid is also supplemented by a number of outdoor and vehicular nodes deployed on or around the Rutgers campus, to be used for real-world validation of results or for application trials.



(a) ORBIT radio grid architecture **(b) ORBIT radio grid at RU tech center building**

Figure 5: ORBIT radio grid

The ORBIT testbed is centered around the “radio grid emulator” which provides facilities for reproducible networking experiments with large numbers (~100’s) of wireless nodes. The testbed also includes an outdoor “field trial system” intended to support real-world evaluation for protocols validated on the emulator, and for application development involving mobile end-users. Construction of the 5000 sq-ft, 400-node ORBIT radio grid facility at the WINLAB Tech Center II building in North Brunswick, NJ was completed in mid-2005, leading to the first community release of testbed services in Oct 2005. Since then, the ORBIT testbed has been made available on a 24/7 basis to an increasingly large number of research users worldwide. The total number of registered users is currently about 250, with a total of over ~12,000 experiments completed on the radio grid facility to date. The service interface on the www.orbit-lab.org website has been upgraded over the past year to support a number of new features including access to several sandbox units, GNU radios, noise generators for topology control and improved experiment scheduling. Some examples of specific research projects carried out on ORBIT are dynamic spectrum access (DSA) protocols and algorithms, mobile ad hoc networks (MANET) for tactical applications, mesh network protocols used for municipal WiFi access, DTN (delay tolerant networks), media streaming over wireless networks, mobile content delivery and wireless network security. The testbed has also been used for future Internet architecture experiments involving new protocols for both wired and wireless network subsystems. More information about ORBIT can be found on the Orbit web site: www.orbit-lab.org.

Appendix B: Cognitive Radio Technology and Experimental Platforms

We briefly review the concept of a cognitive radio and describe a number of cognitive radio platforms currently available, including: WARP, DARPA WNaN, USRP/USRP2 GNU radio, WiNC2R software radio, and KU radio.

B.1 What is a Cognitive Radio?

The idea of a cognitive radio extends the concepts of a hardware radio and a software defined radio (SDR) from a simple, single function device to a radio that is senses and reacts to its operating environment.

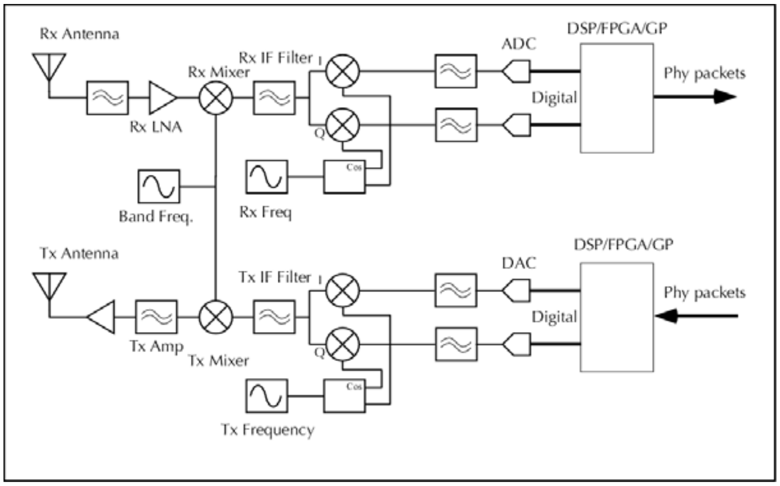


Figure 6: Block diagram of a Typical Software Defined Radio.

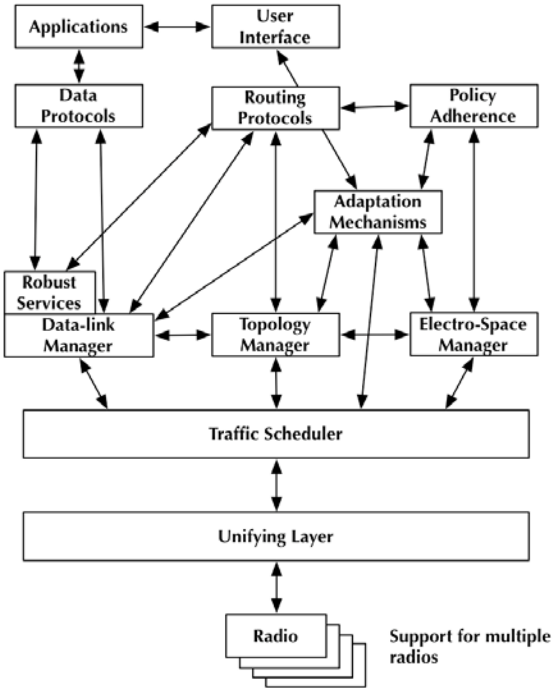


Figure 7: CR Software

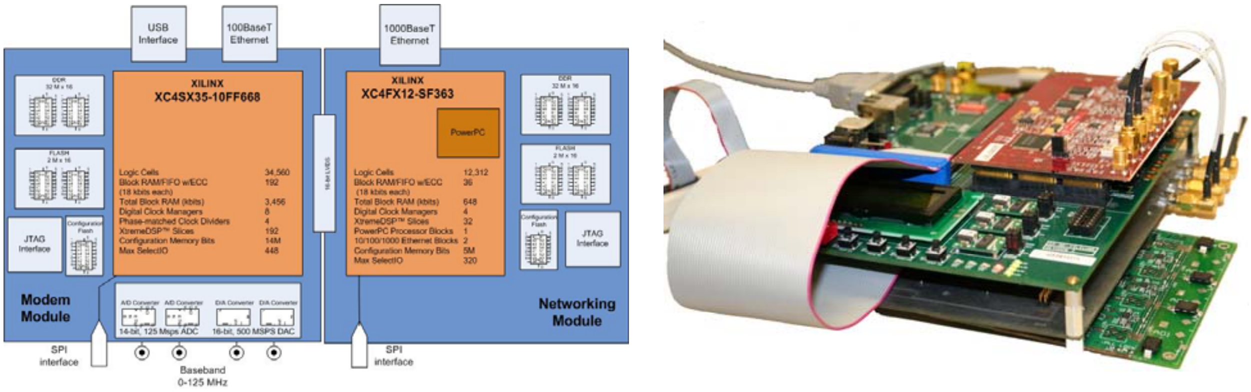
For several decades [25], engineers worked toward moving radio functions from analog, hardware based technologies to software based technologies. The key motivations for pursuing this transition are to increase flexibility, e.g., changes to radio functionality are software changes rather than hardware changes, and increased capabilities. A block diagram of a typical SDR is shown in Figure 6; analog circuits are on the left and digital processing is on the right.

Figure 7 illustrates a possible functional organization of CR software. At the lowest levels are “device drivers” and “hardware resource schedulers” that allow the majority of CR software to operate on multiple radio platforms and prioritize access to the radio hardware. There may be multiple radio channels in the radio platform. The ElectroSpace Manager is a distributed radio resource manger. It keeps track of frequencies in use and negotiates with nearby radios for access to or release of radio spectrum resources. Radios have the unique capability to establish new links or tear-down old links based on traffic demands.

The Topology Manger determines when and how to take these actions. As links between radios change, network routing must be updated and the Routing Protocols function takes care of this. We expect radios will exchange information on the performance of established links. As link conditions change, radios will adapt to the new situation. The Adaptive Mechanisms function handles this aspect of a CR. Finally, CRs adhere to policy based on regulation, location, current environment, and operating limitations. The Policy Adherence function implements the “rules of operation.” This illustrates only one of many approaches to implementing a CR.

B.3 WiNC2R Cognitive Radio Board

WINLAB has developed a prototype “network centric” cognitive radio board (called “WiNC2R”) [27]. The project was funded by NSF as part of the ProWIN program (~2004-07). The WiNC2R is a flexible and high-performance cognitive radio board capable of operating at ~10-50 Mbps depending on the complexity of PHY and MAC used, and is also equipped with a tri-band radio front end suitable for operation at 700 MHz, 2.4 GHz and 5 GHz bands (Figure 8). The prototype board was completed in 2007, and is now being used as an experimental platform for evaluating FPGA acceleration architectures and hardware-software performance trade-offs. The platform is also being used to investigate hardware level virtualization of radio devices.



(a) Baseband diagram **(b) RF module diagram**

Figure 8: Prototype hardware implementation of WiNC2R board

Modem Module: The modem module performs the baseband PHY functions, where baseband signals are modulated and demodulated according to the wireless protocol requirements. Hardware accelerators for simplified 802.11b DSSS and generalized 802.11a OFDM PHYs implementation are under development. The modem module provides two analog input and two analog output channels as interfaces to the RF module. Each pair of analog signals translates to a pair of I/Q data streams. The incoming analog signals are first low-pass filtered, sampled at a rate of 125MSPS, and then converted to a dual 14-bit data stream. This digitized version of the analog signal is further processed by the modem FPGA. At the outgoing signal path, two 16-bit, 500MSPS, 2x-8x interpolating dual-channel DACs generate the analog equivalents to the 16-bit I/Q data pair. The RF module frequency selection, Rx/Tx switching, and power settings are controlled through the provided SPI interface. These settings are configurable from the modem FPGA.

Physical layer baseband processing uses a Xilinx Virtex-4 SX series FPGA, e.g., XC4SX35, which is geared towards high-performance digital signal processing applications. For designs which require a moderate embedded processor, one or more soft-core 32-bit processor can be instantiated. Wireless PHY control and supervisory functions are implemented in software targeted for the soft core 32-bit processor. Additional 32Mx16 (512Mbits) DDR RAMs and 2Mx16 (32Mbits) flash memory are available off-chip, along with the configuration flash memory. For off-board communications, the modem module provides the following options: USB interface, 100BaseT Ethernet and RS232 port. Data transfer between PHY, MAC and higher layers occurs through a 16-bit high-speed LVDS bus.

Networking Module: The networking module is implemented as a daughter board that can be plugged into the baseband modem module. Packet and network protocol processing are performed using a Xilinx 4FX12 FPGA. The FX series FPGA with a hard core Power PC was considered, but since we are incorporating a host processor it was deemed that the trade-off of more logic resources is more important than hard core Power PC(s). The baseband FPGA will be configured for instantiating two Gigabit Ethernet MAC soft-core(s) enable dynamic switching between virtual ports. This has a minimal impact on logic resources using only ~3% of available gates. The following two examples illustrate how we may scale the available resources used in typical designs: a 5-bit width with a 126 traceable length Viterbi decoder uses only ~1500 slices plus 4 BRAM(s) (Block RAM), and a single 16 bit 8192 point FFT impacts ~4% logic resources, 7% of BRAM, and 19% of XtremeDSPTM slices. To supplement the memory resources of the BRAM(s) of the baseband FPGA with 6.048Mbits, we have chosen the 8Mx36 (288Mbit) RLDRAM II (reduced latency DRAM) operating at 200MHz (400MHz data rate). This Virtex-4 family supports partial reconfiguration in real-time with two methods. Parameters are adjusted locally with a soft-core (8-bit) microcontroller/ (32-bit) microprocessor.

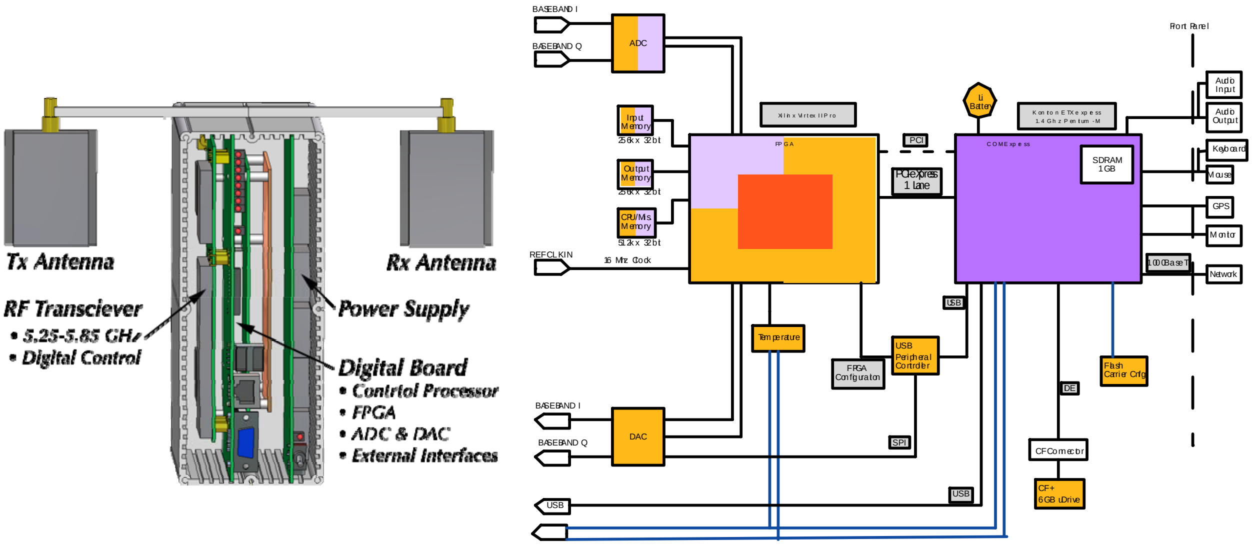
RF front-end: The RF front-end board is designed around a Maxim, Inc. MAX2829ETN+D radio transceiver chip capable of operating in one of three ISM frequency bands, namely 2400-2500 MHz , 4900-5300 MHz, 5400-5875 MHz. The module is controlled via SPI serial bus by the baseband module. The module has four integrated dual mode 2.4 – 2.5 GHz and 4.9 – 6.0 GHz SMD dipoles with peak gains of 2dBi and 3 dBi respectively. Antenna switching is possible for diversity gain. It is also possible to switch all Tx and Rx signals into a single antenna.

B.4 KU Agile Radio

The KUAR is a software-defined radio (SDR) specifically designed to address the needs of wireless networking, communication systems, and radio frequency (RF) research. It features a modular design consisting of a separate power supply, a digital processing board and a RF transceiver. The current version of the radio operates in the 5 – 6 GHz band and is capable of implementing numerous modulation algorithms, media access protocols, and adaptation mechanisms. As shown in Figure 9(a), the KUAR consists of five major sub-systems on three printed circuit boards: (i) a power supply, (ii) a control processor (CP), (iii) a digital board (DB) with a programmable signal processor (FPGA), analog-to-digital (A/D) and digital-to-analog (D/A) converters, (iv) an RF transceiver, and (v) antennas. With the exception of the antennas, the sub-systems are contained within a shielded box approximately 7 inches tall, 3 inches wide, and 6 inches deep, or roughly the size of a good dictionary.

A modular design was chosen so that sections of the KUAR platform can interoperate with other third party prototypes for purposes of experimentation and testing. For example, the KUAR CP and DB could be connected to other RF transmitters or receivers, to allow investigation of other frequency ranges or channel parameters. Alternatively, the KUAR active antennas and RF transceiver could be used with existing signal processing systems. The KUAR supports the GNU Radio [26] software system on the CP.

The Digital Board contains the CP, an FPGA, A/D and D/A converters, and external interfaces (Figure 9(b)). The organization of these components is shown in Figure B-8. The CP is an embedded PC operating at 1.4 GHz with 1 GB SDRAM and 6 GB micro-disk built on the COMExpress form factor. The CP uses PCI to interface with the FPGA. External interfaces include USB 2.0, VGA PCI Express connections, and Gigabit Ethernet. The default operating system on the CP is Linux, however other operating systems could be employed. Linux provides common networking services and applications while Ethernet enables the radios to easily connect into existing laboratory networks or be used in standalone configurations. The processing power of the CP and FPGA enable experiments requiring rapid operational changes based on current RF environment measurements, quick changes of radio configuration, and significant signal processing.



(a) KUAR Radio **(b) KUAR Digital Board**

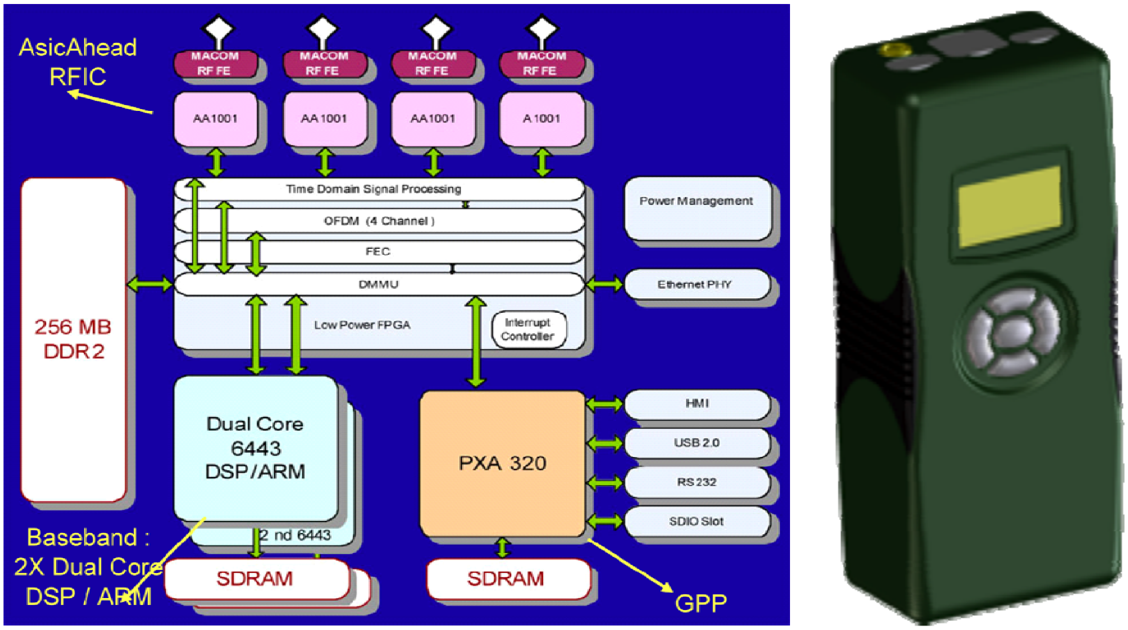
Figure 9: The Kansas University Agile Radio

The primary sub-system for signal processing operations is the FPGA. The KUAR uses a Xilinx Virtex II Pro P30 FPGA, which has 30,816 logic cells, two PowerPC 405 cores, and operates up to 350 MHz. The FPGA is directly connected to quadrature A/D and D/A converters, 4 MB of SRAM, and the CP. The KUAR provides significant flexibility in locating signal processing functions in hardware logic, the embedded PowerPC processors or the CP, depending on the signal processing demands and experimental goals. The received quadrature signal is sampled at up to 105 Msamples/sec with 14-bit resolution and the transmitted quadrature signal is converted at up to 160 Msamples/sec with 16-bit resolution.

The RF transceiver implements independent transmit and receive frequencies, digitally controlled transmit power outputs, and receive gain levels. The RF transceiver uses standard RF connectors to allow the use of a variety of antenna types and configurations. Digital control of transmitter output power, receiver attenuation, and demodulator amplifier gain is useful for fading channel experiments and also allows automatic or programmed control. The RF transceiver covers the frequency range of 5.25 - 5.85 GHz within the 5 GHz UNII band. The receiver sensitivity with active antennas is -100 dBm and the transmit power with active antennas is up to +25 dBm.

An 8-bit microcontroller unit (MCU) is used to interface the CP to the programmable components of the RF transceiver. The MCU translates commands from the CP to component control signals and returns status information from the RF transceiver to the CP.

Three basic configurations of broadband 5 GHz directional planar antennas have been developed for the KUAR system – (i) basic passive, (ii) active receive (Rx), and (iii) active transmit (Tx). The passive antennas are intended for use in indoor or short range outdoor environments, while the active versions utilize integrated RF amplification and filtering to provide longer range outdoor performance.



(a) Functional Organization **(b) Illustration**

Figure 10: The DARPA WNaN Radio

B.5 DARPA Wireless Network After Next (WNAN) Radio

Defense Advanced research Projects Agency (DARPA) is in the process of developing and experimenting with the Wireless Network After Next (WNaN) Cognitive Radio (Figure 10). This device was purpose-built to leverage the state of the art in cognitive radio and networking technology [39] through reliance of cognitive adaptation, rather than intrinsic performance of the hardware. The frequency coverage of 900 MHz to 6 GHz was selected to provide a wide range of propagation environments in bands that offer opportunities for Dynamic Spectrum Access (DSA). Each handheld unit includes four independent transceivers that can be selectively grouped to form MIMO channels, or can be operated independently to create dense link connectivity by simultaneously maintaining membership and participation in multiple networks, or as sensors to support environmental assessment, such as needed for DSA. The integration of dynamic formation of networks via DSA, and the ability to operate multiple networks on each device is intended to address scaling issues of large Mobile Ad-Hoc Networks (MANET) networks. Table 1 lists the hardware performance objectives (taken from [40]).

Table 1: WNaN Performance Characteristics

Frequency Range	900 MHz to 6 GHz Continuous
RF Power	1 Watt/ Transceiver, 4 Watts Total
Date Rate	16KBPS to 10 MBPS
Filter Q	Q > 150
	OFDM, QPSK, BPSK, QAM
MIMO	2x2, 3x3, 4x4
Chance of RF Overload	< 0.01% in Dense Environments
Cost	Under $500 in Quantity

One of the fundamental objectives of the WNaN program was to reduce the cost of the transceivers to the point where a sophisticated, multi-transceiver cognitive radio can achieve a cost point below that of conventional technology. The principle was that the adaptation inherent in cognitive operation can enable the performance requirements of the transceivers to be reduced; with particular emphasis on the analog segments that are not influenced by the progression of digital electronic technology. Of particular interest were the ability to reduce the front-end linearity and Spur Free Dynamic Range (SFDR), which it is believed cognitive adaptation can address at lower device cost [41], [42]. For this reason the pre-selector and notch filters within WNaN are reasonably high performance in order to provide the DSA cognitive adaptation as many frequency alternatives as possible. The assumed RF model for the WNaN, and likely follow-on radios is a single commercial integrated Radio Frequency Integrated Circuit (RFIC), which places a premium on adapting around the inherent limitations of the constrained RF performance.

B.6 USRP and GNU Radio

The Universal Software Radio Peripheral (USRP) is a low cost, high speed USB 2.0 peripheral, specifically designed to enable the construction of software radios. The USRP provides the minimal hardware required to make software radios a reality. The USRP solves the problem of interfacing the signal processing software with the RF spectrum by providing a set of RF daughter boards to perform analog RF up and down conversion, 1 million gates of FPGA, typically used to convert to and from complex baseband, 4 high speed A/Ds (64 MS/sec 12-bit), 4 high speed D/As (128MS/sec 14-bit) and a USB 2.0 controller chip. This hardware, along with the GNU Radio software, allows the USRP to convert an 8MHz section of RF spectrum to and from complex baseband and transfer it across the USB at up to 8MS/sec complex. Everything is configurable by the user. The FPGA and USB controller chip firmware are loaded over USB. The USRP2 (Figure 11) supports bit-rates in the range ~10 Mbps+ depending on PHY processing requirements and improved FPGA support.

Figure 11: USRP2 board

The GNU software architecture [26] is based on connecting reconfigurable processing blocks into a graph that describes the data flow of the target radio system. Each of the signal processing blocks have a set of input and output streams (ports) with specified type. Based on the blocks being processed, the output stream is generated at a rate that can be either the identical fixed ratio or variable with respect to input stream rate. The primitive signal processing blocks are implemented in C++. Both topology and individual block parameters can be modified "on the fly" during the graph execution by the dynamic scheduler. All graph construction, policy decisions and non-performance critical operations as well as runtime system manipulations are performed in Python. The library of signal processing blocks includes filters, modulators, demodulators, forward error correction, etc. GNU Radio is being extended to support MAC protocols, besides physical layer processing [32,33,34,35]. USRP 2 and GNU radio are used to develop a software base for CR networks, called *CogNet* [18].

B.7 Rice WARP

As depicted in Figure 12, the Rice WARP board contains a Xilinx Virtex-II Pro FPGA which contains a PowerPC core, supports up to three gigabit Ethernet interfaces for fast I/O, and allows the addition of up to 4 daughtercard interfaces. The interfaces include: an analog card interface, which contains a dual 14-bit 65 MSPS ADC and a dual 16-bit 125 MSPS DAC [29] and an RF interface, which allows transmit and receive at 2400-2500MHz and 4900-5875MHz, the RF daughtercard contains the same ADC DAC interface mentioned previously. There is also a video daughtercard interface. A more recent version of the board uses a Virtex-4 FPGA offering more slices, a higher clock rate and support for up to 2 GByte of memory.

While users' can purchase the WARP board from a third party vendor [30] the WARP board is an open source platform which allows users' to incorporate their own daughter boards, whether to expand RF, computing, or other functionalities of the platform. The Rice WARP website provides a free FPGA based OFDM implementation for the Virtex-II Pro FPGA in addition to providing a CSMA MAC implementation available for download and development as part of a user's application [31].

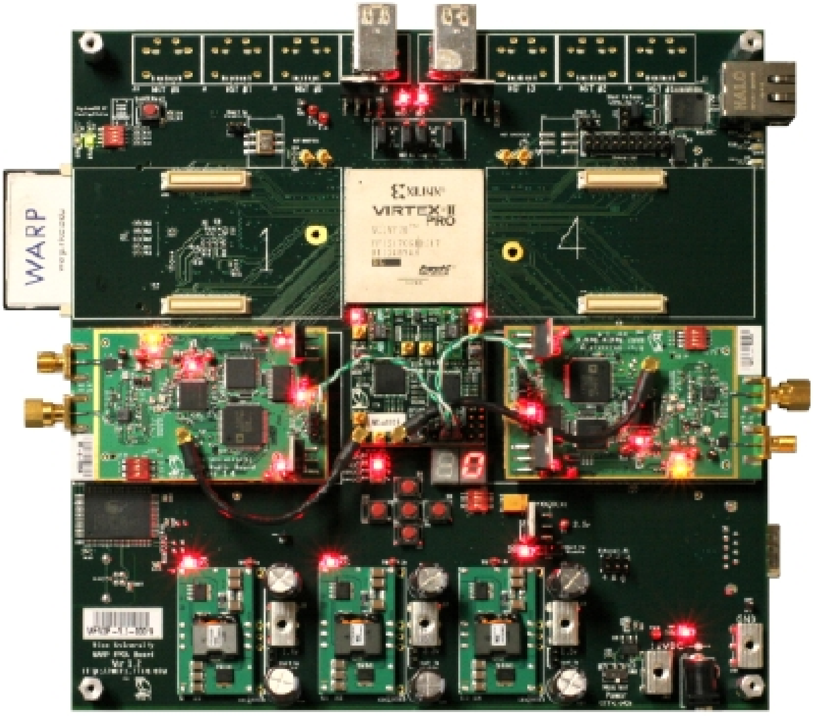


Figure 12: The Rice WARP Board

References

[1] Wireless 2025: The Future of Mobile, Telephony Online, http://telephonyonline.com/, April 2009.

[2] IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN) at http://www.ieee-dyspan.org.

[3] See FCC Spectrum Policy Task Force's reports at http://www.fcc.gov/sptf/reports.html.

[4] NTIA Testbed, http://www.ntia.doc.gov/ntiahome/frnotices/2006/spectrumshare/comments.htm

[5] DARPA next generation (XG) program - http://www.darpa.mil/sto/smallunitops/xg.html

[6] NeXt generation/dynamic spectrum access/cognitive radio wireless networks: a survey, IF Akyildiz, WY Lee, MC Vuran, S Mohanty - Computer Networks, 2006 – Elsevier

[7a] Center for Strategic and International Studies, Spectrum Management for the 21ST Century, Washington, D.C., September 2003.

[7b] Defense Science Board, "Coping with Change: Managing: RF Spectrum to Meet DoD Needs," December 2000.

[7c] Defense Science Board, "Wideband Radio Frequency Modulation: Dynamic Access to Mobile Information Networks," July 2003.

[7d] Federal Communications Commission, "Spectrum Policy Task Force," ET Docket No. 02-135, November 2002.

[7e] Report of the Spectrum Efficiency Working Group, Federal Communications Commission Spectrum Policy Task Force, November 15, 2002.

[7f] General Accounting Office, "Defense Spectrum Management: More Analysis Needed to Support Spectrum Use Decisions for the 1755-1850 MHz Band," Report GAO-01-795, August 2001.

[7g] General Accounting Office, "Telecommunications: Better Coordination and Enhanced Accountability Needed to Improve Spectrum Management," Report GAO-02-906, September 2002.

[7h] General Accounting Office, "Comprehensive Review of U.S. Spectrum management with Broad Stakeholder Involvement Is Needed," Report GAO-03-277, January 2003.

[8] World Radiocommunications Conferences (WRC) at http://www.itu.int/ITU-R/index.asp?category=conferences&rlink=wrc&lang=en.

[9] J. M. Peha, “Sharing Spectrum Through Spectrum Policy Reform and Cognitive Radio,” Proceedings of the IEEE, April 2009.

[10] D. Cabric, Cognitive radios: System design perspective, Ph.D. dissertation, Univ. of California, Berkeley, Nov 2007.

[11] Peter Koch and Ramjee Prasad, The Universal Handset, IEEE Spectrum, April 2009.

[12] “In the Matter of Unlicensed Operation in the TV Broadcast Bands”, ET Docket No. 04-186, US Federal Communications Commission, Nov 12, 2008 .

[13] M Janani, A Hedayat, TE Hunter, A Nosratinia, Coded cooperation in wireless communications: space-time transmission and iterative decoding, IEEE Transactions on Signal Processing, 2004,

[14] Karakayali, GJ Foschini, RA Valenzuela, RD Yates, On the maximum common rate achievable in a coordinated network, Proceedings of IEEE International Conference on Comm, 2006,

[15] S Katti, H Rahul, W Hu, D Katabi, M Médard, J. Crowcroft, XORs in the air: practical wireless network coding, IEEE/ACM Transactions on Networking (TON), 2008

[16] M.M. Buddhikot, K. Ryan, Spectrum management in coordinated dynamic spectrum access based cellular networks, in: Proc. IEEE DySPAN 2005, November 2005, pp. 299-307.

[17] D. Raychaudhuri and X. Jing. A spectrum etiquette protocol for efficient coordination of radio devices in unlicensed bands. *In Proc. PIMRC 2003*, Beijing, China, September, 2003.

[18] D. Raychaudhuri, N. B. Mandayam, J. B. Evans, B. J. Ewy, S. Seshan, P. Steenkiste. *CogNet* - An Architectural Foundation for Experimental Cognitive Radio Networks within the Future Internet. *In Proc. of MobiArch'06*, Dec. 2006.

[19] B. S. Manoj, Ramesh R. Rao, and Michele Zorzi, Architectures and Protocols for Next Generation Cognitive Networking, Cognitive Wireless Networks, 271–284. F.H.P. Fitzek and M.D. Katz (eds.), 2007 Springer.

[20] Suhas Mathur, Wade Trappe, Narayan B. Mandayam, Chunxuan Ye, Alex Reznik: Radio-telepathy: extracting a secret key from an unauthenticated wireless channel. MOBICOM 2008: 128-139

[21] George Nychis, Srinivasan Seshan, Peter Steenkiste, Thibaud Hottelier, Zhuocheng Yang, Enabling MAC Protocol Implementations on Software-defined Radios, The 6th USENIX Symposium on Networked Systems Design and Implementation (NSDI '09), Boston, April 2009.

[22] Glenn Judd and Peter Steenkiste, Using Emulation to Understand and Improve Wireless Networks and Applications, 2nd Symposium on Networked Systems Design and Implementation (NSDI), Usenix and ACM, Boston, May 2-4, 2005.

[23] Glenn Judd and Peter Steenkiste, A Software Architecture for Physical Layer Wireless Network Emulation, The First ACM International Workshop on Wireless Network Testbeds, Experimental evaluation and CHaracterization (WiNTECH 2006), held in conjunction with ACM MobiCom 2006, September 2006, Los Angeles.

[24] D. Raychaudhuri, I. Seskar, M. Ott, S. Ganu, K. Ramachandran, H. Kremo, R. Siracusa, H. Liu, and M. Singh, A Large-scale Testbed for Reproducible Ad hoc Protocol Evaluations, Proceedings of the Wireless Communications and Networking Conference (WCNC'05), March 2005.

[25] Raymond J. Lackey and Donal W. Upmal. Speakeasy: The military software radio. IEEE Communications Magazine, 33(5):56–61, May 1995.

[26] GNU Radio Project, http://www.gnu.org/software/gnuradio

[27] Z. Miljanic, I. Seskar, K. Le and D. Raychaudhuri, "The WINLAB Network Centric Cognitive Radio Platform – WiNC2R", *Proc. CrownComm 2007.*

[28] X. Jing and D. Raychaudhuri, "Global Control Plane Architecture for Cognitive Radio Networks," *IEEE CogNet'07 Workshop (with IEEE ICC)*, June 2007.

[29] P. Murphy, A. Sabharwal, and B. Aazhang, "Design of WARP: A Wireless Open-Access Research Platform," in *European Signal Processing Conference* Florence, Italy, 2006.

[30] Mango Comm. 2009. http://www.mangocomm.com/

[31] WARP: Wireless Open Access Research Platform. 2009. http://warp.rice.edu/

[32] Rahul Dhar, Gesly George, Amit Malani, and Peter Steenkiste. Supporting Integrated MAC and PHY Software Development for the USRP SDR. IEEE Workshop on Networking Technologies for Software Defined Radio (SDR) Networks, held in conjunction with IEEE SECON 2006, Sept. 2006, Reston.

[33] http://gnuradio.org/trac/wiki/InBandSignaling

[34] http://gnuradio.org/trac/wiki

[35] http://acert.ir.bbn.com/downloads/adroit/gnuradio-architectural-enhancements-3.pdf

[36] Overview of Wireless, Mobile and Sensor Networks in GENI, GENI Design Document 06-14, Wireless Working Group, September 2006.

[37] Virginia Tech to smarten up cognitive radio, EE Times, http://www.eetimes.com/news/latest/showArticle.jhtml?articleID=171000063

[38] Xiangpeng Jing, Shanmuga Anandaraman, Mesut Ali Ergin, Ivan Seskar, and Dipankar Raychaudhuri. Distributed Coordination Schemes for Multi-Radio Co-existence in Dense Spectrum Environments: An Experimental Study on the ORBIT Testbed. In *Proceedings of the 3rd IEEE International Symposia on Dynamic Spectrum Access Networks (IEEE DySPAN 2008)*, pages 156-166, October 2008.

[39] P. Marshall, “Extending the Reach of Cognitive Radio,” Proceedings of the IEEE, April 2009, vol. 97, No. 4, pp612-625.

[40] P. Marshall, “Progress towards Affordable, Dense, and Content Focused Tactical Edge Networks, 2008 IEEE Military Communications Conference, San Diego, CA. 2008.

[41] P. Marshall, “Cognitive Radio as a Mechanism to Manage Front-End Linearity and Dynamic Range”, IEEE Communications Magazine, March 2009, vol. 47, No. 3, pp81-87.

[42] P. Marshall, “Dynamic Spectrum Management of Front End Linearity and Dynamic Range,” 3rd IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, Chicago, IL. 2008.

[43] D. Sicker and R. Dhillon, “Security of Cognitive Radio Networks”, University of Colorado Technical Report, http://www.cs.colorado.edu/department/publications/reports/2009.html.