A PUBLIC SAFETY COGNITIVE RADIO NODE

Bin Le (bin.le@crtwireless.com, Cognitive Radio Technologies, Lynchburg, VA),
Francisco A. G. Rodriguez, Qinqin Chen, Bin Philip Li, Feng Ge, Mustafa ElNainay,
Thomas W. Rondeau, and Charles W. Bostian (Center for Wireless Telecommunications,
Virginia Tech, Blacksburg, VA)

ABSTRACT

This paper gives a complete map of building a cognitive radio. It goes through architecture definition, functional block building, system integration, and finally to a fully-functional CR node prototype that can be directly packaged for application use.

In our CR solution, a platform independent CR system architecture is defined with a software algorithm package called a cognitive engine (CE) with a general radio interface. Within the CE different functional modules are defined to realize cognitive capabilities including awareness, reasoning, solution making and optimization, and adaptive radio control. Based on this general CR solution, we present an application specific CR node prototype for public safety communication interoperability.

1. INTRODUCTION

Cognitive radio (CR) technology introduces a revolutionary wireless communication mechanism in terminals and network segments, so that they are able to learn their environment and adapt intelligently to the most appropriate way of providing the service for the user's exact need. By supporting multi-band, mode-mode cognitive applications, CR provides an interactive way of managing the spectrum that harmonizes technology, market and regulation.

We define a cognitive radio as an intelligent communication device that is aware of its environment and application needs, and can reconfigure itself to optimize quality of service [1]. Following this definition, we provide a complete CR node solution with an intelligent layer of awareness, reasoning and learning necessary to optimize performance under dynamic and unpredictable situations. Such an intelligent layer is realized by a software system called a cognitive engine (CE). The CE can be applied to different reconfigurable radio platforms via its general radio interface. The CE embeds a two-loop cognition cycle as its learning core. The cognition cycle integrates radio environment sensing and recognition, case-based reasoning and solution making, and evolutionary solution improving. Radio knowledge is defined and the knowledge database is implemented to support the reinforcement learning through the cognition cycle.

To be generally applicable for various applications, the CR solution emphasizes platform independent system architecture, and the CE has an algorithm framework that is open-structure and modular, which can be easily reconfigured for the target problem.

Based on this general CR node structure, a fully-functional public safety cognitive radio (PSCR) node is prototyped to provide the universal interoperability for public safety communications. The complete PSCR node software system has been packaged for outside organizations to build prototypes and carry on field testing.

In the following parts of this paper, Section 2 introduces the CR system architecture; Section 3 describes the CE structure and building blocks; Section 4 explains the design of radio awareness, Section 5 explains the design of reasoning, decision and optimization; Section 6 describes the platform independent radio interface; Section 7 illustrates the example PSCR node prototype.

2. COGNITIVE RADIO ARCHITECTURE

Following the CR definition above, our CR solution can be presented as the list below:

- An algorithm software package, called the cognitive engine (CE), is designed and overlaid on the radio hardware platform. The CE manages radio resources to accomplish cognitive functionalities and adapts radio operation to optimize performance. Shown in Figure 1, the CE enables a radio to provide cognitive functionalities by combining the machine learning process with radio operation.

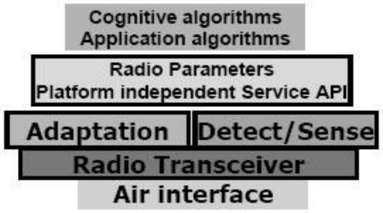

Figure 1. Cognitive radio system model

- A machine learning core is designed to enable cognitive capabilities for wireless applications. Reinforced learning and evolutionary optimization are key design principles of the learning core. A two-loop cognition cycle is embedded in the learning core, detailed in Section 3.3.
- Any radio with an appropriate level of reconfigurability can support and be controlled by the CE via a platform independent radio interface. Since CE is not platform specific, general knowledge and learning can be applied for a variety of applications' problems.
- The cognitive functionality focuses on layers 1 to 3 to achieve cross-layer optimization. The general cognition algorithms can be extended to higher layers, and configured to meet various application specific requirements.
- As a network node by nature, a CR can work individually or jointly on resource management and performance optimization. The CR learning structure consists of three steps: recognition, reasoning and adaptation, which can be flexibly implemented in either a centralized way as a fully functional CR node or be distributed across the network where different local parts of the network require different levels of intelligence and different layers of optimization [2]. Such CR node functional structure is shown in Figure 2.

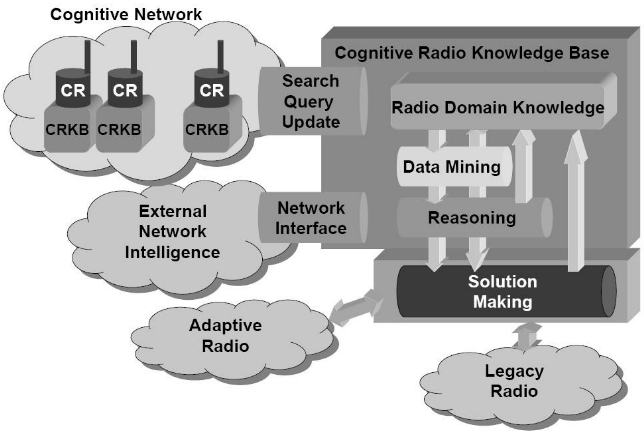

Figure 2. CR functional structure as a network node

3. CR NODE COGNITIVE ENGINE

3.1. CR Domain Knowledge Partitioning

CR research is multi-disciplinary, combining wireless communications, radio engineering, machine learning, spectrum regulations, application service, marketing, and many others. In a narrow sense of engineering background, CR technology involves three major fields, the policy domain, the radio domain, and the user domain:
- The policy domain contains regulatory information, like the frequency plan, transmit power and interference limits, that is interpreted as hierarchical-structured (tiered by priority) rule sets used as boundaries in the radio operational space. Policy domain knowledge is used to guarantee the security and legality of the CR operations.
- The user domain defines both the service access preferences and performance requirements from both the service provider and the end user. It mainly includes objectives like access availability, service type and Quality of Service (QoS). The CR needs to interpret such objectives and try to meet them by adapting its operation.
- The radio domain mainly consists of radio environment and radio platform. The corresponding external and self awareness are combined to feed machine reasoning in two forms: either to provide objectives if some radio capabilities be utilized under observed environment conditions, or else constraints if radio resource limitation becomes an issue.

3.2. Cognitive Engine Structure

By partitioning the knowledge, cognitive functionalities can be modularized. Thus the CE can be designed with an open structure, which is important to modularize specific algorithms for specific task, while still maintain a general framework, shown in Figure 3,

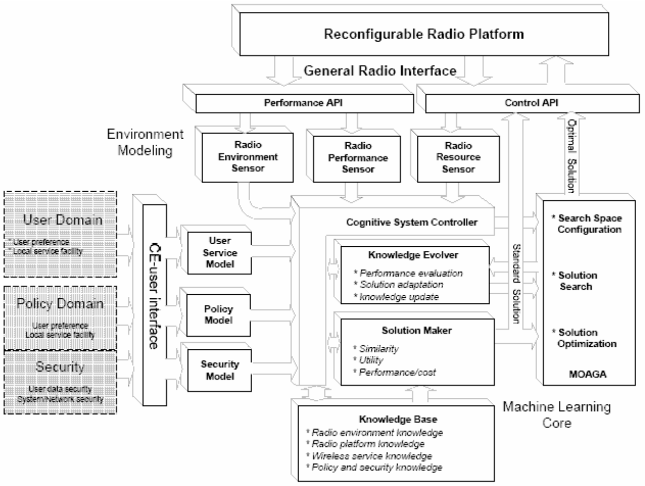

Figure 3. Cognitive engine system diagram

The CE consists of the following key sets of modules:
- Environment modeling modules handle information collection and recognition for specific domains. Radio, user and policy (including security) domains are modeled, interpreted and reported to the learning core.
- The solution maker is the kernel module that generates a viable solution according to the current input problem scenario (including the environment, user objectives, available resources, etc.) through knowledge based reasoning.
- The multi-objective adaptive genetic algorithm (MOAGA) is an evolutionary search module that works with the solution maker to further optimize or adapt solution for performance-critical or novel situations.

- The knowledge base is a database containing domain related data like situational information, performance criteria and general principles of reasoning and learning.
- The CE provides an interface between itself and each domain. For the radio domain, a platform independent radio interface is constructed with which the CE can monitor, configure and control different radio hardware without changing its own algorithm. Both user and policy domains are connected to the CE via a user interface due to the similarity in data collection and modeling.

3.3. The Cognition Cycle of the Learning Core

The design objective of machine-learning capability leads to the creation of a cognition cycle as the soul of the CE, where radio intelligence evolves through the loop of reasoning, decision making, adaptation and knowledge accumulation. Such a cognition cycle should be efficient and straightforward with clear functional definitions, but also complete enough to carry general machine learning capabilities for various wireless applications.

Shown in Figure 4, the cognition cycle has two feedback loops that realize two levels of intelligence which separates the general machine-learning core from radio platform specific operations. The outer loop consists of information recognition and behavior adaptation, which are directly coupled with domain knowledge. The inner loop is a machine-learning loop where artificial intelligence algorithms are tailored and combined for a general solution making and self-learning. Knowledge base is updated with the feedback of deployed new solution, thus the CE educates itself by evolving its knowledge from practice, which is the true power of cognition.

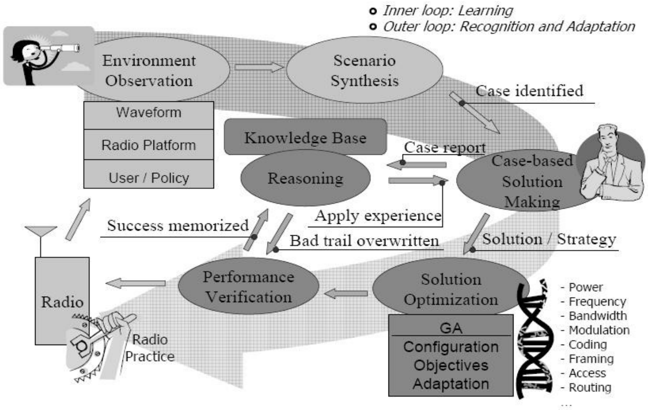

Figure 4. Cognition cycle of CR learning core

The outer loop serves the inner loop. It observes the environment and reports derived information like waveform features, interference and propagation channel characteristics, user service preferences, service policy and spectrum regulations, to the inner learning loop. It also interprets the solution from the inner loop and formulates adaptation instructions, according to the solution, to feed the radio platform for action. Such a hierarchical structure bridges general machine learning, specific application, and heterogeneous radio platforms.

Knowledge is the key in machine learning [3]. It can be divided into two categories based on sources: one is experience that includes situations, actions taken, and their consequences; the other consists of pre-set principles and non-adaptive examples. In CR system, the first type of knowledge, such as changing radio environment, is achieved from self-practice, while the second type, such as radio resources and spectrum policy, can be simply pre-loaded rather than through the long-term education.

Our CR knowledge base is implemented as a relational meta-database that consists of multiple sub-databases, such as the radio environment map (REM) [4] for environment awareness, user service knowledge for performance objectives, case base knowledge for scenario-solution association, radio resource knowledge for solution boundary, and regulation knowledge for legality and security verification [5].

4. RADIO AWARENESS

The domain knowledge partition sets the scope of CR awareness. Generally speaking, the awareness of user and policy domains involves relatively static knowledge access and interpretation, while the awareness of radio domain consisting of radio environment and radio platform, is more complicated and dynamic. For the radio domain, the CE provides a set of sensors collecting radio environment information like waveform features, interference and propagation channel conditions, transceiver performance like error rate and throughput; and radio platform resource status like power consumption and computational cost.

The radio environment knowledge is separated into two groups that lead to two awareness levels in supporting the radio domain cognition, shown in Figure 5.

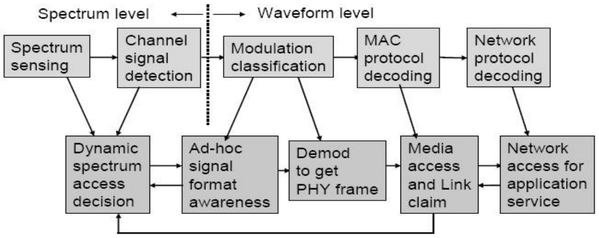

Figure 5. Radio environment awareness

The first level is the spectrum energy including the location and power of existing signals across a certain range of frequency. Such knowledge makes the CR aware of the energy occupation pattern in time at the frequency of interest, thus enabling itself to pick the right channel, the right power, and the right time of using the spectrum to avoid interference, such as dynamic channel/spectrum allocation (DCA or DSA) algorithms. Spectrum overview is obtained through frequency sweep and power spectrum density (PSD) based energy detection. The processing diagram is shown in Figure 6. Hierarchical fast Fourier transform (FFT) and time-frequency domain adaptive averaging techniques are used to achieve the best tradeoff between processing cost, accuracy and resolution [5].

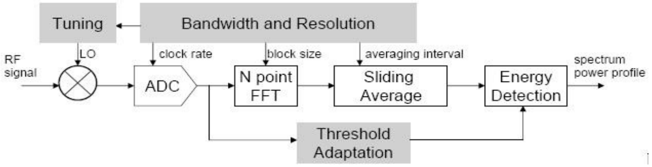

Figure 6. PSD based spectrum energy detector

The second level of knowledge includes knowing the format of the waveform at the channel of interest, and modeling the propagation channel. Such knowledge of the observed channel waveform makes the CR understand who else is out there and how to communicate. Waveform recognition is a system-level design challenge comprising a hierarchical sensing and classification procedure along with the signal processing chain from RF tuning to baseband decoding, so that different levels of waveform parameters are extracted at different stages of the receiving process [6].

For CR to recognize an incoming signal, many key signal properties, like carrier frequency, signal bandwidth, symbol rate and modulation scheme, need to be identified. The major task is to identify the incoming signal's modulation scheme to guide the carrier synchronization. The difficulty is that most modulation-sensitive information like complex phase change and signal constellation is at baseband, and therefore only available after achieving carrier phase lock [7]. Also, the absence of prior signal knowledge makes the conventional standard-specific design not suitable for the cognitive radio receiver. A new receiver structure is needed to synchronize and demodulate different signal formats, where the synchronization should have a general looping structure to track incoming signals with different modulation schemes and symbol (or baud) rates, and be reconfigurable in real time to adapt its nonlinear operation and looping bandwidth. Figure 7 shows the top-level block diagram of such a "smart" receiver. Once modulation is classified and the information bits are demodulated, the subsequent recognition on frame and packet format are largely based on straightforward table lookup.

Feature based pattern recognition approach is used for signal classification. A two-stage, adaptive modulation classification system is designed, in which the incoming signal is projected to a multi-dimensional feature space and classified by statistical pattern recognition techniques including artificial neural networks and k-nearest neighbor cluster. Modulation information is fed to adaptive carrier synchronization module to obtain phase lock. Detailed design is in [6, 8].

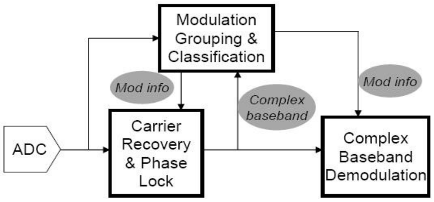

Figure 7. Waveform recognition processing chain

Propagation channel recognition is more complicated in CR because there may be little prior channel knowledge available, especially when the incoming waveform is unknown. Highly-adaptive or "blind" channel modeling techniques are needed to condition the waveform through an unfamiliar or unknown channel [9].

5. RADIO DECISION AND KNOWLEDGE

The CR learning core follows the reinforcement learning principle [10]. Reinforcement learning builds up intelligence by evolving knowledge with the experience of the practice instructed by previous available knowledge. Appropriate problem-solution association is explicitly formulated as part of the knowledge, and the performance of the practice associated to the problem is evaluated in relative metrics – there's no "optimum" solution, only a better solution or the best solution ever achieved and remembered, i.e., "optimum" is always the goal to achieve by continuing improving the current solution.

The reinforcement learning principle is the basis of case based reasoning (CBR) [11, 12] and solution making theory [11]. In CBR, the solution making relies on the past experience formulated as knowledge. The CBR emphasizes on-line performance improvement, which involves finding a balance between exploration (of untouched solution space) and exploitation (of current knowledge). The exploration vs. exploitation trade-off provides important flexibility between creativity and rationality in learning algorithm design for target applications.

Although effective with familiar problem scenarios, CBR performs poor in a new situation. When the association between the encountered problem and previous experience is difficult to generate, a more "creative" solution making mechanism is needed. An evolutionary searching method serves as the best candidate to provide creative solutions [13]. Specifically, a genetic algorithm (GA) is designed [14, 15]. With the emphasis on flexible problem space parameterization (chromosome) and performance objective encoding (fitness functions), GA can effectively provide multi-objective solution search on a complicated, unfamiliar problem space.

With the combination of CBR and GA to balance between rationality and creativity, the solution making strategy is adapted according to the encountered problem scenario. Once the solution is made, it is put into practice, and its performance in the real world is recorded as the solution's metric for future reference. Thus with its knowledge updated the CR learns from its own experience. Such a CBR-GA decision making chain is shown in Figure 8. Detailed design is available in [5].

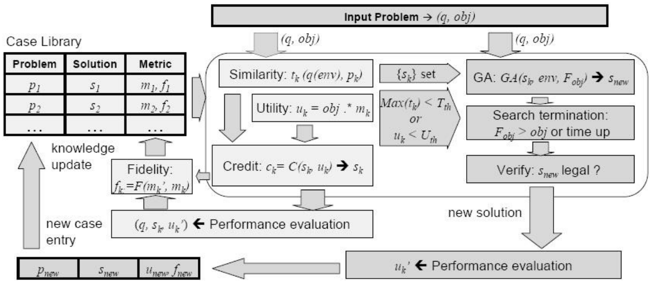

Figure 8. CBR-GA decision chain

6. RADIO PLATFORM INTERFACE

The radio interface is responsible for two tasks: (1) delivering platform knowledge to the CE to form its basic operational space, and (2) carrying configuration and control from the CE to instruct the radio's operation.

To be aware of the capabilities of the radio platform, the CE should interpret a representation of the radio, which is called the radio platform profile. Such a representation abstracts the radio's implementation details and looks solely at the communication level [16]. Thus it can be used to represent various radio platforms regardless of their hardware realization. The content (such as parameter values) in the radio profile can be coded totally device specific as far as the profiles of different radios share the same script format and data structure. The radio profile is a manually-coded script and preloaded. It avoids an additional protocol layer between radio platform and cognitive algorithms, which greatly improves system efficiency and real-time response. This preloaded platform profile helps the CE form a more confident operational space than ad-hoc querying and reasoning.

The sensed radio environment information is reported from radio to the CE using a standard parametric format, called the radio environment profile; the CE makes a decision according to obtained awareness, and passes the decision to the radio with another standard parametric format, called waveform solution profile. It is at the functionality level, thus can be applied to various radio platforms. The solution profile is interpreted at the interface down to platform specific API to configure the control the radio hardware.

With standard profile representation and supporting parsing modules, this interface serves as the bridge between application algorithms and radio hardware resources, and it largely defines the CR node overall system hierarchy. A block diagram of the interface is shown in Figure 9. A detailed design is available in [17].

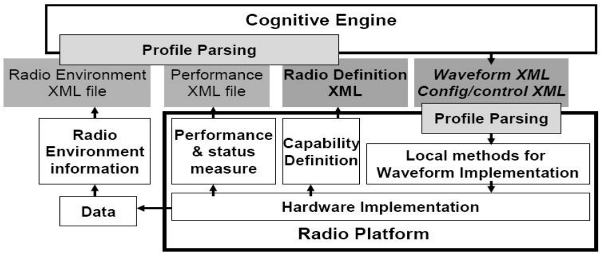

Figure 9. Platform independent radio interface

8. PSCR NODE PROTOTYPE

Today in US, more than 55,000 separate public safety (PS) agencies operations are based on disparate technologies, frequency bands and protocols. Beginning in 2005, the Center for Wireless Telecommunications (CWT) of Virginia Tech was sponsored by the National Institute of Justice (NIJ) to apply CR technology to the problem of public safety interoperability [18]. The application requirements are decomposed into three use cases to lead the design of a public safety cognitive radio (PSCR) system:

- Interoperabilty with various incompatible public safety waveforms: this is to provide the universal interoperable communication service of voice and data. The PSCR serves as a gateway to bridge incompatible waveforms, different frequency bands and networks, or serves as a multi-mode multi-band wireless terminal for the user.
- Radio environment sensing and cognitive link/network control: the PSCR needs to be able to sense the frequency band of interest, detect and identify existing PS waveforms and networks, and report to the user to enable the awareness of the radio environment.
- Flexible radio node configuration and field deployment: the PSCR system, especially the application algorithms should be easily cooperated with various radio platforms, and to be fast deployable on the field with little prior environment knowledge.

Based on the CR architecture and building blocks described in previous sections, the PSCR node is designed to fit the above three use cases. The system block diagram is shown in Figure 10. The PSCR consists of four major subsystems. Among which the kernel part is the CE that is implemented as an PS application specific version, where the solution making module is a CBR-GA chain. Because PS communications use pre-defined standards-based waveforms, customized waveforms are not always needed from a GA solution search. However, a GA is enabled to improve the link performance by adjusting parameters of these PS waveforms. Thus the GA solution improvement module can be switched on/off accordingly.

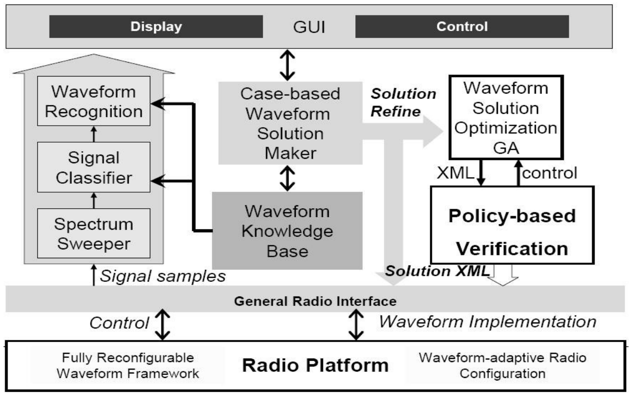

Figure 10. Platform independent radio interface

The second subsystem is the Graphical User Interface (GUI), shown in Figure 11. It provides the user with spectrum scan, ad-hoc link, and universal gateway working modes. The backend processing of the GUI integrates the central control of the CE. It also features a full Java implementation for portability. All the inter-module communication within the CE is implemented with standard TCP/Socket protocol, which supports fully distributed cognitive functionalities across the network.

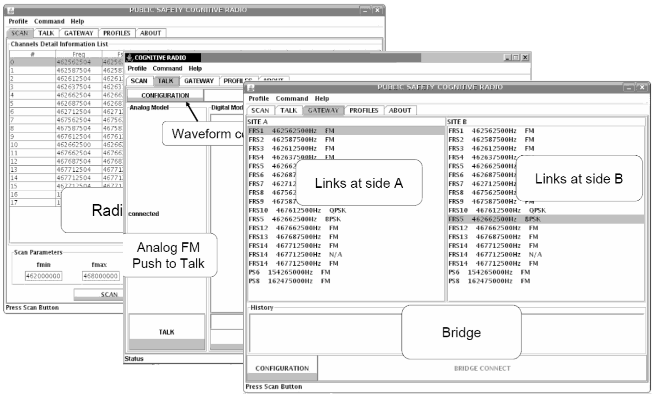

Figure 11. PSCR GUI display

A standard MySQL database is implemented for the PSCR knowledge base to support solution making. The general radio interface and a supporting software defined radio platform are also developed and integrated in the PSCR system [5]. The complete PSCR node software system is packaged as an official release with installation guide and developer manuals.

This work is supported by NIJ Award No. 2005-IJ-CX-K017 and NSF Grant No. 9983463, DGE-9987586, and CNS-0519959.

8. REFERENCES

[1] B. Le and C. W. Bostian, "Radio Domain Cognition - a System Approach in Theory and Implementation " *Virginia Tech IP Disclosure (VTIP) No. 05-077,* Oct. 31 2005.

[2] Y. Zhao, B. Le, and J. H. Reed, "Network Support - The Radio Environment MAP," *Chap. 11, Cognitive Radio Technologies, Newnes,* 2006.

[3] B. A. Fette, *Cognitive Radio Technology*: Newnes, 2006.

[4] Y. Zhao, J. Gaeddert, K. K. Bae, and J. H. Reed, "Radio environment map enabled situation-aware cognitive radio learning algorithms," in *Software Defined Radio Forum (SDRF) technical conference*, Orlando, FL, 2006.

[5] B. Le, "Building a Cognitive Radio - From Architecture Defintion to Prototype Implementation," *PhD Disseration, Electrical and Computer Engineering Dept. Virginia Tech* June 2007.

[6] B. Le, T. W. Rondeau, D. Maldonado, D. Scaperoth, and C. W. Bostian, "Siganl recognition for cognitive radios," in *Software Defined Radio Forum Tech. Conf.* Orlando, FL, 2006.

[7] J. G. Proakis, *Digital Communications*, 4 ed. New York: McGraw Hill, 2000.

[8] B. Le, T. W. Rondeau, D. Maldonado, and C. W. Bostian, "Modulation Identification Using Neural Network for Cognitive Radios," in *Software Defined Radio Forum Technical Conference*, Anaheim, CA, 2005.

[9] S. U. H. Qureshi, "Adaptive Equalization," *Proceedings of the IEEE,* vol. 73, September 1985 1985.

[10] R. S. Sutton and A. G. Barto, *Reinforcement Learning: An Introduction*: MIT Press, 1998.

[11] I. Gilboa and D. Schmeidler, *A Theory of Case-Based Decisions*. Cambridge: Cambridge University Press, 2001.

[12] J. Kolodner, *Case-Based Reasoning*. San Mateo, CA: Morgan Kaufmann Pub., 1993.

[13] F. Streichert, *Evolutionary Algorithms in Multi-Modal and Multi-Objective Environments*: Logos Verlag Berlin, 2007.

[14] D. E. Goldberg, *Genetic Algorithms in Search, Optimization, and Machine Learning*. Reading, MA: Addison-Wesley, 1989.

[15] T. W. Rondeau, B. Le, C. J. Rieser, and C. W. Bostian, "Cognitive Radios with Genetic Algorithms: Intelligent Control of Software Defined Radios," in *Software Defined Radio Forum Technical Conference*, Phoenix, AZ. , 2004, pp. C-3 - C-8.

[16] SDRF, "Hardware abstraction layer workgroup report on results of request for information," *SDRF RFI doc: SDRF-04-A-0009-V0.00,* July 17 2004.

[17] B. Le, T. W. Rondeau, and C. W. Bostian, "General radio interface between cognitive radio algorithms and software defined radio platforms," in *Software Defined Radio Forum Tech. Conf.*, Denver, CO, 2007.

[18] C. W. Bostian, "A prototype public safety cognitive radio for universal interoperability," Center for Wireless Telecommunications, Wireless at Virginia Tech 2006.