INTERNATIONAL COLLABORATION FOR A COGNITIVE RADIO TESTBED

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ABSTRACT

With the constant advances in cognitive radio technology, there is a developing need for proper testing facilities. This paper introduces efforts to bring together research and development of cognitive radio, dynamic spectrum access (DSA), and software defined radio systems to enable testing in real-world environments, and to develop applications for these emerging systems. Using licensed test spectrum available to CTVR in Ireland, we propose a flexible, extensible cognitive radio platform designed to interface with different SDR, sensing, learning, and cognitive algorithms. The testbed will accelerate research and development as well as facilitate direct comparison of systems and algorithms to advance the knowledge and science of cognitive radio.

1. INTRODUCTION

This paper discusses concepts of building a system capable of testing and experimenting with different cognitive radio and dynamic spectrum access systems. In this paper, we present a number of the technologies and policies that provide a foundation for such a system. Throughout, we hope to provide a survey of the tools and techniques already available and engage the larger SDR community in the design.

We have seen a proliferation of research on the topics of spectrum sensing, frequency agile systems, and cognitive radio systems to build and adapt radio performance. Each of the authors has recognized the need for enabling research to compare performance and results. Thus far, many different techniques have been proposed in the literature for the different aspects of a cognitive radio.

Firstly, we define what we mean by a cognitive radio and the key parts that comprise a cognitive radio. A cognitive radio is a radio that can sense its environment and optimize its performance to satisfy quality of service requirements.

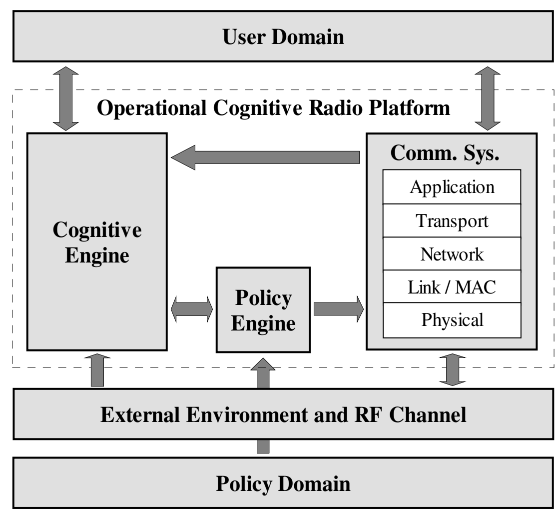

Figure 1. Generic Cognitive Radio

The major components of a cognitive radio are:

- Highly reconfigurable radio platform
- Sensing techniques
- Optimization and adaptation routines
- Learning system

A high-level concept of a cognitive radio is illustrated in Figure 1. Here, a cognitive engine is a separate process from the communications system that performs the intelligent aspects of the cognitive radio. The cognitive engine receives information from external domains to describe the user, RF, and policy environments. The policy engine is a concept often discussed to ensure legal compliance of the waveforms. This component is described separately in this figure to distinguish it from the intelligent processing of the cognitive engine. It is an important part of the solution to ensure compliance with the regulatory environment.

This paper first introduces the known aspects of the proposed testbed before leading into the areas of required discussion and analysis of the system. Section 2 discusses the location of the testbed and why it is selected. Section 3 provides an overview of the SDR systems either currently available or under development. Section 4 discusses some of the current cognitive radio research and systems and addresses the needs associated with the different capabilities. Section 5 discusses some architectural requirements of a testbed node, and Section 6 concludes with discussion about the properties and needs of the system as developed through this treatment.

2. TESTBED LOCATION

The work done by cognitive radios addresses challenges associated with complex RF and network environments. This work highlights the real performance of the intelligence and adaptation. While simulations are initial proofs-of-concept, they do not provide the necessary environmental complexity and uncertainty of real deployment. At the same time, deployment is often limited because of spectrum regulations. In Ireland, the Commission for Communications Regulation (Comreg) has an innovative licensing scheme to help promote the development of new wireless communications systems and concepts. The Centre for Telecommunications Value-Chain Research (CTVR) is composed of nine Third Level institutions and two industry partners covering many areas of expertise, including RF, communications and networking, test and reliability, and optimization and management. Under Comreg's Wireless Test and Trial Scheme, CTVR has been allocated 50 MHz of spectrum for experimental tests in several locations in Ireland. This license is for two 25 MHz bands centered at 2.08 and 2.35 GHz. During April 2007, CTVR also availed of a trial license involving several leading global companies and research facilities, who conducted trials of their own developing technologies in collaboration with CTVR. These trials used licensed spectrum in the TV and microwave frequency bands.

The CTVR centers located throughout Ireland offer a wide variety of environments and network deployment capabilities.

3. RADIO PLATFORMS

The radio platform is an important component of the cognitive radio system. There are a number of currently available systems for SDR and cognitive radio research as well as many in development. This is a review of some of the SDR devices directly related to the testbed collaboration and of current interest to the authors.

3.1. Implementing Radio In Software (IRIS)

CTVR has developed a mature reconfigurable radio platform called Implementing Radio in Software (IRIS) [1]. Work on this platform began in 1999 and a considerable code base has been developed since that time. This platform comprises two parts:

1. A suite of software components that implement various functions of wireless communications systems.
2. A system for managing the structure and characteristics of the components and signal chain.

The radio manager builds a radio configuration chosen by the user/designer using any or all of the available components. The term *manage* encompasses the process of reconfiguring the radio components in response to various triggers and observations throughout its operating lifetime.

The platform has been designed to offer the designer/developer a significantly high degree of flexibility and rapid-prototyping capabilities in a wireless platform. This platform is being used for wireless tests in the 2 GHz band. During April 2007, CTVR conducted trials in Dublin, Ireland, of a reconfigurable orthogonal frequency division multiplexing (OFDM) system involving frequency rendezvous using embedded cyclostationary signatures, which was created using this platform in the TV and microwave frequency bands.

3.2. Kansas University Agile Radio (KUAR)

The Kansas University Agile Radio (KUAR) platform [2] is a low cost, flexible RF, small form factor SDR implementation that is both portable and computationally powerful. This platform features a flexible-architecture RF front-end that can support both wide transmission bandwidths and a large center frequency range, a self-contained, small form factor radio unit for portability, a powerful on-board digital processing engine to support a variety of cognitive functions and radio operations, and a low cost build cycle to easily facilitate broad distribution of the radio units to other researchers within the community. The KUAR platform was demonstrated at IEEE DySPAN 2007 in Dublin, Ireland. This demonstration involved an OFDM-based link operating in the 5GHz band.

3.3. Winlab at Rutgers

The Winlab facility at Rutgers is an initiative to develop a novel cognitive radio hardware prototype for research on adaptive wireless networks. This is a network-centric cognitive radio architecture aimed at providing a high-performance platform for experimentation. The platform will support various adaptive wireless network protocols from simple etiquettes to more complex ad-hoc collaboration. The design emphasized high performance in a networked environment where each node may be required to carry out high throughput packet forwarding functions between multiple physical layers. Key design objectives for the cognitive radio platform include [3]:

- multi-band operation, fast frequency scanning, and agility;
- software-defined modem including waveforms such as DSSS/QPSK and OFDM operating at speeds up to 50 Mbps;
- packet processor capable of ad-hoc packet routing with aggregate throughput ~100 Mbps;
- spectrum policy processor that implements etiquette protocols and algorithms for dynamic spectrum sharing.

3.4. GNU Radio

The GNU Radio is a world-wide GPP-based open source software defined radio [4]. The GNU Radio is a pure software package that provides signal processing blocks. Each block is a C++ class that is wrapped into a Python module. The signal processing is done in efficient C++ code while the wrapped modules available in Python provide interconnects between blocks. Blocks are connected to other blocks to create a *flow graph*. A block can be a source with only output ports, a sink with just input ports, or a general block with both inputs and outputs. Blocks supported in the GNU Radio currently include basic signal processing elements like filters and mathematical operations as well as complex blocks to perform specific tasks such as synchronization and timing routines. Blocks can also be combined into hierarchical blocks such as the available blocks that perform digital modulations like DBPSK and OFDM. Future plans for the project include an all-C++ implementation (to remove the need for Python) and full online reconfiguration of flow graphs.

A parallel project with the GNU Radio to provide an air interface is the Universal Software Radio Peripheral (USRP) [5]. The USRP is an RF unit that performs up/down conversion, decimation/interpolation, and filtering. Along with the USRP board are a set of daughterboards to perform analog up and down conversion, filtering, and amplification at RF frequencies. The USRP and GNU Radio are parallel development projects yet they do not necessarily depend on one another. Other SDR platforms may use the USRP (e.g., IRIS), and other RF front ends can run GNU Radio as the signal processing system.

As has been previously shown, the GNU Radio can rather easily be configured and controlled using XML files [6]. This feature is easily exploited for using the GNU Radio in the cognitive radio testbed.

4. COGNITIVE RADIO TECHNOLOGIES

4.1 Sensing Technology

Perhaps the area of cognitive radios to receive the most significant amount of attention has been the sensing technology. Research and development of cognitive radio sensors (as distinct from sensor networks) has come mainly in the form of spectrum sensing in the pursuit of building dynamic spectrum access (DSA) systems. As we have said, DSA systems are a subset of cognitive radios, and so spectrum sensing techniques are of great interest to the development and deployment of cognitive radios.

Spectrum sensing techniques require high accuracy and fast results. Many of the proposals for spectrum sensing are directly related to reusing underutilized TV spectrum, known as white space spectrum. In this scenario, a primary user exists with licensed rights to the spectrum while other radios opportunistically use the spectrum until the licensed user is active and detected. It is therefore the responsibility of the cognitive radio nodes to monitor for the presence of the primary user and quickly change frequencies. To facilitate this, the spectrum sensing technology must be highly accurate under low signal strength as well as provide fast responses to the cognitive radio to move quickly. Current sensing techniques are based on measuring the energy of signals within a band and applying rules based on a set detection threshold, or by detecting features within a received signal in an attempt to identify the signal properties. Examples of current technology related to detecting white space and using it for digital communications include the White Space Coalition [7] and the DARPA NeXt Generation (XG) project [8].

Another popular area of cognitive radio sensing research is in building modulation and signal detection and classification algorithms. Instead of detecting only the presence of a signal, these techniques use intelligent signal processing algorithms to identify signal properties, such as modulation and symbol rate. Such capabilities help cognitive radios recognize not only the presence of a radio, but actually determine if the signal originates from a particular primary user. We still have much to learn from the potential uses and designs of signal classification sensors.

Like energy detection systems, there are many implementations of signal classifiers going back years. Early systems used a decision theoretic approach [9] while contemporary and more successful designs use neural networks [10,11] and cyclostationary detectors [12]. These newer systems have proven successful under certain conditions and for different modulations and signal power.

In addition to the signal and spectrum sensors, other information received through sensors may be useful to a cognitive radio, including time, location (both absolute longitude and latitude as well as relative position defining the type of building or room the radio is in), environmental conditions, and social environment (e.g., "kid's ballgame," or "conference call"). It still remains to be seen how some of this information will be collected and used.

Through its modular component structure, the proposed testbed will enable online comparison of the efficiency and accuracy of the different techniques under real-world conditions. It will then allow research to study and develop the potential uses of many new and innovative sensors.

4.2 Optimization / Adaptation

A large part of the cognitive radio solution is in the algorithms and technology used to build and adapt waveforms. Given the environment returned by the sensors, the cognitive radio will build or select a waveform to best respond to the new conditions, whether it includes a change in the frequency, routing, or a whole new redesign of the waveform. In addition to the topic of sensing technologies, there exists ongoing and developing research in the field of waveform optimization.

In these techniques, the general method is to use an optimization algorithm to build a waveform that satisfies certain metrics used to measure the system performance. These metrics may include (but are not limited to) power consumption, error rates, and throughput, and different implementations propose different methods of analyzing, combining, and optimizing the metrics. Rondeau, *et al.*, [13] and Newman, *et al.*, [14] have independently demonstrated the use of genetic algorithms for waveform optimization. Weingart, *et al.*, [15] have implemented a waveform design system based on a *design of experiment* approach that uses statistical analysis of simulated experiments to apply waveforms to observed scenarios in the future. Clancy, *et al.*, [16] use separate reasoning and learning engines to build and apply knowledge of learned conditions and responses. In another use of classic artificial intelligence, Baldo and Zorzi [17] have demonstrated waveform adaptation using a fuzzy logic system. Both Thomas, *et al.*, [18] and Neel [19] use network-centric and game theory approaches to analyze and optimize cognitive radio network performance.

As with the spectrum sensing and signal classification systems, the different waveform optimization procedures discussed here have all analyzed a similar problem but used different methods to realize the implementation. A full, on-line comparison of these techniques can help build a better understanding of waveform adaptation and the success of different algorithms in speed of developing solutions and the computational power and time required. A more general understanding of the nature of waveform optimization, such as what knowledge is required or how uncertainty in the received information affects the results. The proposed testbed will facilitate this type of comparison and lead to new and better methods of analysis and processing of waveform design.

5. TESTBED CONSIDERATIONS

An accessible testbed implementation designed for cognitive radio systems developing and testing should ideally take a modular design approach. The challenges associated with implementing and managing multiple independent development efforts and a vast range of possible cognitive radio components, sensing techniques, and optimization algorithms, in addition to other features including policy engines are significant. A modular approach can reduce the complexity associated with implementation. Researchers should be able to slot in their versions of algorithms and cognitive radio components for use with the rest of the cognitive radio solution.

The modular component structure offers a number of design benefits. As some researchers have specific concerns and interests in certain aspects of cognitive radio research, the testbed will contain a set of open source components that researchers can use to test and build their individual pieces. Furthermore, each component also lends itself to unit testing. A component can be built and tested independently from the rest of the system and integrated with known working devices.

Each cognitive radio testbed unit consists of a structure based on that of Figure 2. Each of the cognitive radio components is a separate module connected through a generic interface. When testing a new algorithm or cognitive radio system, the system under test is wrapped into a component. The interface is any method that allows the component process talk to the central controller, which aggregates the data and facilitates the information flow between components. Although the interface can be any method that allows data to pass between processes, it would be better suited to have an interface that allows communications between processes on different physical computing elements either on the same host or different hosts on a network. A socket-based transport interface would provide this capability.

The components are wrappers for the actual processing system designed for a particular cognitive radio task to facilitate ease of integration and management of their lifecycles. The component structures take care of the transfer of information between the component and the rest of the cognitive radio system. The components also handle calls to the processing algorithm. In this design, the system under test can be composed of a separate application or library to perform some functions on data. During the component's work state, it calls the system under test, transfers any appropriate control information and data, and then receives any information or data returned by the process. Because each system under test may have different methods of

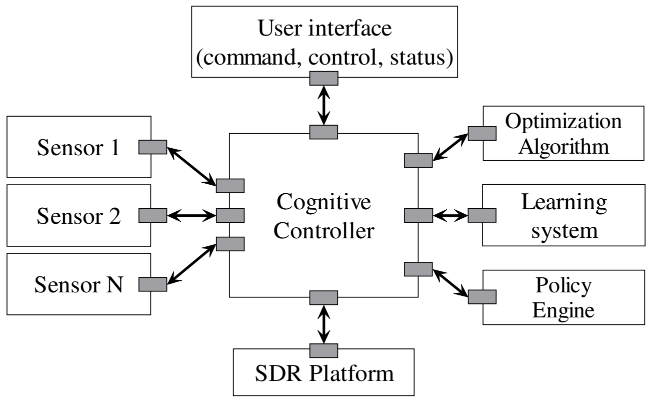

Figure 2. Cognitive Radio Components

control and data format, some amount of programming is required to properly integrate the system into the component structure. The idea of this structure is to allow independent researchers and developers a structure that minimizes the burden of integration. However, because we do not want to specify rigorous demands on formatting from the designers, some programming and interface work is required.

After the simple interfacing between the component and the system under test, the components then manage the interfacing to the controller. The components manage the initialization routines, setup with the cognitive controller, and maintenance of the communication link to the controller.

To communicate between components and the controller, some standard language to format the data is required. An obvious choice for the formatting is XML, which has a number of benefits. First, XML is both machine and human readable. Second, it is a standardized language with many available tools for easy integration with different programming languages and systems. Finally, document type definition (DTD) files specify the expected format of the XML document, which the cognitive radio can use to validate the XML data and, more importantly, use this information to properly structure and decode information returned by the components. For example, when the cognitive controller receives information from a sensor, the DTD can be used to build a table in a database for storing the sensor information.

Although there are many more details yet to be discussed, these are the major points of consideration when developing a testbed for the purpose of scientific research, experimentation, and comparison of the various cognitive radio algorithms. The design structure enables this functionality with a minimum of programming required by the system designers.

6. CONCLUSIONS

The diverse range of research and development work associated with cognitive radio-based technologies necessitates a platform to test and compare these systems under real-world conditions. These systems and cognitive radio algorithms need proper evaluation and testing to enable transfer from the lab experiments to deployed cognitive radios. We have already seen many implementations of spectrum sensing and signal classification techniques as well as various techniques to optimize waveforms. The work the authors are pursuing is to develop a system capable of allowing the comparison of the different possible techniques under similar but real-world test conditions. The system consists of a centralized controller that coordinates a set of components. The components provide access to different aspects of cognitive radio technologies being developed while other pieces of the cognitive radio solution are provided to allow research to continue unhindered by lack of available tools and wasted time in reinventing already existing technologies.

The system is designed to use separate processes for the controller and each component, which offers a number of benefits. On benefit in particular is the ability to run and distribute component among different hosts. With this capability, the testbed supports different hardware structures and processor architectures, which can offer testing and experimentation on different systems. On the other hand, by separating the components in this fashion and decoupling the system, latency and speed of transferring information may become a bottleneck when processing spectrum sensing data to design new waveforms. The speed of the interfacing will be an issue to work through during the development of the system.

Because the component structure design can call external processes and libraries, we do not mandate that the code for the components be open or closed source. The component wrapper structure easily allows links to pre-compiled libraries to protect the source code if desired.

This system is not meant to be a deployable system but to test and validate components. For example, security of information between components is not a major design consideration (although transport layer security (TLS) or secure socket layer (SSL) is easily implemented on a socket-based interface). Because of this structure, concepts like the policy engine, as an attached method, provides no protection from being bypassed, and so does not provide a solution for legally-compliant and tamper-proof systems. The testbed is meant to enable testing of such concepts internally while the system integration for full regulatory compliance of a deployed system is beyond the scope and capabilities of the system.

Although working details have not been discussed here, this paper focuses on the need and considerations for a cognitive radio testbed design. Its purpose is to facilitate the scientific method in designing and analyzing cognitive radio systems under development. The range of available techniques suggests that such comparisons are required to better understand the current capabilities and the future needs.

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