A FRAMEWORK FOR IMPLEMENTING COGNITIVE FUNCTIONALTY

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ABSTRACT

A realizable cognitive radio, capable of exploiting the abilities of observation, decision making, learning and acting, requires a combination of a highly-reconfigurable core and a control system implementing the desired cognitive functionality. This paper describes a joint Virginia Tech (VT) and University of Dublin, Trinity College (TCD) collaborative project where the Center for Wireless Telecommunications (CWT), VT has coupled their cognitive engine to a highly-reconfigurable communications stack and controller interface implemented by CTVR, headquartered in TCD. A description of both systems is presented in this paper in addition to an outline of some current and future work planned for this joint collaborative project.

1. INTRODUCTION

The main objectives of cognitive radio are to enhance the ability of a device to convey information wirelessly anywhere and at anytime, increase the efficiency of how frequency spectrum is used to achieve this, and to provide a solid foundation for the creation of new wireless communications-based services and techniques in the future.

Cognitive radio can be described as a 'radio' with cognitive functionality [1]. In fact, the descriptive term 'radio' used in this context is not absolutely complete. Cognitive functionality can encompass the entire communications stack, the operating and the control system encapsulation, and even the network that each cognitive radio may be a part of. The foundation of a cognitive node is a highly-reconfigurable core, which can both implement and react to change, and cognitive functionality in the form of interactions between awareness, decision-making, learning, and action mechanisms. This cognitive engine can direct the actions of this core based on a set of objectives, constraints and operational rules derived from internal and external contextual information sources [2][3].

This entity can be viewed as an element of a network, referred to in this paper as a *node*. Two or more of these devices can form a network when a wireless communications link exists between them. Network operation is almost always the case as wireless communications involves one source and sink (even if only a unidirectional link exists in the case of a receive-only device with a source).

It is therefore more accurate to describe a single 'cognitive radio' as a node with cognitive functionality. A cognitive node is a software-defined radio system that can acquire and use contextual information to help achieve designated objectives. Cognitive functionality is not an unbounded system due to several constraints. In fact, cognitive functionality can also be described as set of multi-dimensional optimization problems where the parameters, objectives and constraints may be time-varying.

This paper describes the reconfigurable radio core, the control system used to co-ordinate cross-layer reconfiguration, and cognitive functionality used to implement the cognitive node. This design comprises three specific key elements:

1. A heteromorphic reconfigurable radio core capable of dynamic application, structural and parameter-level reconfiguration, both influencing, and being directed by, a cognitive engine.
2. Cognitive functionality in the form of a Multi Objective Genetic Algorithm implementation charged with the task of obtaining a set of optimal, or near optimal, communications stack parameters and configurations, within a specific timeframe.

Section 2 describes the Reconfigurable Core and Stack Manager Interface designed and implemented by CTVR, Section 3 moves onto to a description of the Cognitive Engine designed and implemented by CWT. Following this, an outline of the complete joint system is given in Section 4. Section 5 describes some of the initial findings and direction of research that this collaborative project is taking, and Section 6 concludes.

2. RECONFIGURABLE CORE

The Reconfigurable Core being used in this joint project is based on a multi-threaded General-Purpose-Processor platform. This system is known as the Plastic Project [6] and has two main objectives in the context of this project. The first main objective of the Reconfigurable Core is to implement any and all of the required changes in the entire communication stack from the Application to Physical Layer (PHY). The second main objective of the core is to provide awareness information to the Cognitive Engine. This information may include both internal radio communication system awareness and external radio environment awareness. The Cognitive Engine may then use this information as a key element of its cognition cycle.

A communications stack is implemented in this highly Reconfigurable Core as a structure containing a hierarchy of individual processing modules called Components. Considered individually, each Component can implement some or all of the functionality of a signal processing stage of the transceiver signal chain in the PHY, or even one or more entire layers in the communications stack. The granularity of a Component is dependent on the Designers needs. In addition to Components existing exclusively in software, the set of Components includes hardware modules with software and firmware interfaces.

Each Component may have a number of parameters associated with it. Examples include a routing layer which may have a cache size and beacon interval, the RF front-end operating frequencies and power levels, physical layer modulation and coding schemes and almost any other related aspect of a communications stack which affects its operation. These parameters may be exposed by Components and reconfigured dynamically in order to alter the manner in which those Components operate.

Fig. 1 illustrates the Reconfigurable Core communications stack, which uses a Stack Manager Interface to handle the reconfiguration events and cross-layer dependencies.

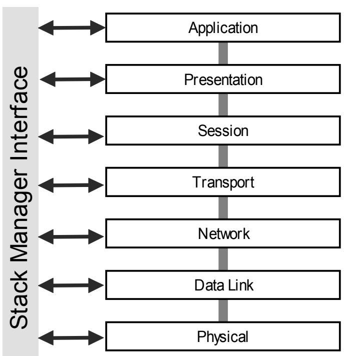

Fig. 1: The Reconfigurable Core facilitates reconfiguration of the entire communications stack and layer parameters, and handles cross-layer dependencies, using the Stack Manager Interface.

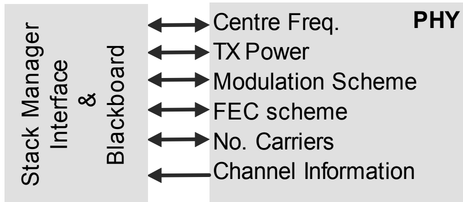

Fig. 2: Illustration of some of the many PHY-related parameters that can currently be reconfigured using the Cognitive Engine.

Together with *Parametric* reconfiguration, the Plastic Project provides two additional levels of reconfiguration that serve to fulfill the key objective of implementing change in the communications stack. The second level of reconfiguration is referred to as *Structural* reconfiguration and involves the removal, addition, replacement or interchange of individual Components within the Plastic Project structure. *Application* reconfiguration forms the third and highest level of reconfiguration provided by the Plastic Project and describes the ability to replace, remove and add entire communications stacks.

In order to fulfill the second main objective of providing awareness information to the cognitive engine, the Plastic Project maintains a shared system database referred to as the Blackboard. Each Component within the Plastic Project structure is provided with access to the Blackboard in order to expose awareness information which may become available. Examples of such awareness information include the current Bit Error Rate (BER) observed within a decoding Component, the Power Spectral Density (PSD) for the radio channel obtained through the Fast Fourier Transform (FFT) stage of an Orthogonal Frequency Division Multiplexing (OFDM) demodulation component or simply the current modulation scheme complexity being used by the modulation Component of a PHY transmitter chain. Fig. 2 illustrates some of the many PHY layer parameters and external information sources that can currently be accessed and manipulated by the Cognitive Engine (via the Stack Manager Interface) and Reconfigurable Core.

The following section provides an overview of the CWT cognitive engine. The manner in which awareness and reconfiguration information is exchanged between the Reconfigurable Core and the Cognitive Engine is outlined in Section 4.

3. COGNITIVE FUNCTIONALITY

The cognitive engine described in this section has been developed at the Center for Wireless Telecommunications (CWT) based in Virginia Tech [4][5]. This engine implements the awareness-processing, decision-making and learning elements of cognitive functionality. Specifically, this engine is capable of learning the behaviour of the radio in the different environments over time, and intelligently changing the communications stack to new wireless communications scenarios and problems efficiently based on a set of objectives and constraints. A genetic algorithm (GA) approach is used to optimize the communications stack layer parameters. Called the Wireless System Genetic Algorithm (WSGA), this is a powerful method for exploiting the features of the highly-reconfigurable core and optimizing the operation of this core across layers in the stack.

It is important to point out that one of the main objectives is to devise and implement a sufficient solution within a specific timeframe and not an optimal solution after an implementation deadline has expired. For example, consider the example where a cognitive engine is required to deduce a suitable transmitter power level to use within a certain timeframe (7ms for example). The cognitive engine may decide that the optimum TX power level is -30.003dBm but 10ms is the time required to produce this result. A sufficient solution may be -30dBm or even -29dBm, and to produce this result, it may only require 5ms. However, the value of this result is greatly increased because it is a sufficient solution achieved within the specified deadline.

In their original and most basic form, genetic algorithms (GAs) were designed as single-objective search and optimization algorithms. Common to all GAs is the chromosome definition—how the data are represented; the genetic operators of crossover and mutation; the selection mechanism for choosing the chromosomes that will survive from generation to generation; and the evaluation function used to determine the fitness of a chromosome [4].

The establishment and maintenance of effective wireless communications over a volatile communications channel requires a careful balance of the correct PHY parameters and order in which, the signal chain in implemented. This balancing act can be effectively viewed as a complex multi-dimensional optimization problem, where the choice of the radio parameters on all layers affects the radio's behaviour in many dimensions including (and not limited to) the bit error rate (BER), transceiver bandwidth, energy consumption, and network latency. Each of these dimensions has some relationship to the set of user and system objectives in mind. In fact, these relationships can also change in their relative importance according to the desired wireless communications application. For example, maintaining low latency in a wireless network is important for multi-player games and audio/video communications, however for file and short message transfers, the emphasis is generally on maintaining a specified Quality of Service (QoS).

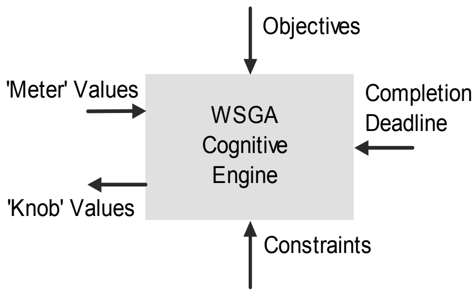

Fig. 3: The WSGA-based Cognitive Engine decides what the Reconfigurable Core parameter values (the 'knobs') should be based on the observations, objectives and constraints..

The WSGA is a Multi-Objective Genetic Algorithm (MOGA) that can influence the behaviour of a reconfigurable communications stack by modelling the stack as a biological organism and optimizing its performance through genetic and evolutionary processes. In the WSGA, radio *behaviour* is interpreted as a set of layer operation parameters defined by *traits* encapsulated in the *genes* of a *chromosome*. Other general radio functional parameters (including, but not limited to, payload size, power, coding techniques, encryption, equalization, number of sub-carriers, network protocol, retransmission requests, and spreading technique/code) are also identified as possible genes in the chromosome definition to cater for all of the layers in the communication stack.

The WSGA analyzes the chromosome's fitness by considering a set of fitness functions defined by performance evaluations of the current communication stack. Each fitness function is weighted to represent the relative importance the user has associated with each objective. The stopping condition for deciding when an optimal or sufficient solution has been obtained is based on the user's QoS and application requirements. Efficiency and optimization can be subjective quantities therefore it is important that over-maximizing is essential a waste of radio resources such as spectrum and energy in addition to the extra time required to complete the optimisation task(s).

4. JOINT SYSTEM OVERVIEW

A key element of the framework for implementing cognitive functionality is the link provided between the Reconfigurable Core and the Cognitive Engine. This link serves to facilitate the flow of both awareness and reconfiguration information between both entities, effectively completing the cognition cycle required by the framework. This section describes that link and the manner in which it is used to exchange information between the Reconfigurable Core and the Cognitive Engine.

Java Remote Method Invocation (RMI) is used to provide the distributed, cross-platform solution required to

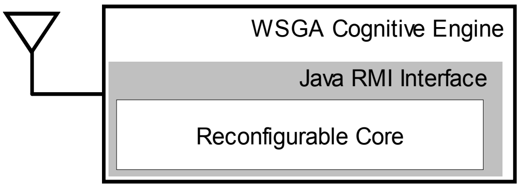

Fig. 4: The Reconfigurable Core and Cognitive Engine are connected using a Java RMI Interface.

join both systems. Both the Reconfigurable Core and the Cognitive Engine are encapsulated within Java server applications which interact using RMI calls. This relationship is illustrated in Fig. 4. Awareness and reconfiguration information is captured within eXtensible Markup Language (XML) documents which are parsed on both sides of the link.

As described in Section 2, awareness information within the Reconfigurable Core is contained in a shared system database referred to as the Blackboard. A key property of the Blackboard is the ability to capture all data contained at a given time in an XML document. In order to provide the awareness required by the Cognitive Engine, these Blackboard snapshots may be generated and transferred from the Reconfigurable Core. Within the Cognitive Engine, the snapshots are parsed and the relevant data is input to the WSGA.

XML documents form an essential part of the Reconfigurable Core as they are used to describe the initial system configurations. A configuration document effectively outlines the structure of the Components to be used within the system as well as the initial values of the parameters exposed by those Components. A Configuration Parser is used together with a Stack Manager to create the communication stack on the basis of the configuration provided. As well as being used to specify the initial system configuration, these configuration documents may also be used to perform reconfigurations on each of the levels discussed in Section 2, namely Parametric, Structural and Application.

When a reconfiguration is required, a new XML configuration document containing the changes is created. This document is then passed through an interface provided by the Stack Manager. Upon receipt of the new document, a comparison is made between the current active communications stack configuration and that described. Each difference identified during this process triggers either a single reconfiguration event or a sequence of events. The sum total of these reconfiguration events may amount to either minor changes within the PHY for example, or result in the implementation of an entirely new communications stack.

The principal output of the Cognitive Engine is an XML configuration document describing the reconfigurations which need to take place within the Reconfigurable Core. By simply passing the new document via a RMI call, the structure of the Reconfigurable Core may be re-shaped and its operation altered, in order to help achieve the desired Cognitive Engine objectives.

5. CHALLENGES AND DIRECTION

One of the main challenges in this joint system is ensuring that the total time taken to observe, decide if reconfiguration is required, work out what specific reconfigurations are required, and then implement these changes is within a certain timeframe. Of course, deciding what a suitable timeframe is another challenge. For non-critical wireless communications, and where reconfiguration may only be required once or twice a day, it is feasible that longer reconfiguration times may not have a significant impact on the communications link. However, it is also feasible that for critical wireless communications traffic and where the cognitive engine is required to change the behavior of the radio several times a second, there may be increased pressure to complete these cognitive radio changes within a much tighter timeframe.

The lowest common denominator is essentially the time-lag between initiating a reconfiguration event and observing it's completion. Therefore, the first joint work using this system was to investigate the time taken to reconfigure on a parametric level and on a structural level. For the parametric reconfiguration tests, one parameter in the reconfigurable core was reconfigured $1e6$ times. In the structural reconfiguration test, a Component in the Reconfigurable Core was replaced $1e3$ times. These tests were performed using a 3GHz PIV x86 single core processor using a high resolution timer operating at the PC clock rate.

The average time taken to perform $1e6$ single-parameter reconfigurations in the Reconfigurable Core was 12.38 secs seconds. The average time required to perform $1e3$ structural reconfigurations, where one Component was replaced $1e3$ times was 65.47secs.

The next stage of this project is to test the joint system's abilities in a Dynamic Spectrum Access context involving the optimization of TX power and spectrum usage in order to maintain a specific QoS, and to minimize interference to other users, in a common frequency band. These tests will involve the use of the 2.4GHz Industrial, Scientific and Medical (ISM) band in the US and the 2.08GHz and 2.35GHz frequency ranges in Ireland, which are currently dedicated licensed spectrum segment centre frequencies for testing software-defined radio, cognitive radio, and dynamic spectrum access techniques in several sites across Ireland [6]. Currently the Cognitive Engine is located in Virginia Tech, USA, and the Reconfigurable Core is located in Trinity College Dublin, Ireland. The cognition loop therefore spans the Atlantic Ocean. However due to the Java RMI interface connecting the two systems, this geographical separation only results in a slightly longer implementation time-lag.

6. CONCLUSIONS

This paper has described a joint CTVR and VT collaborative project where the Center for Wireless Telecommunications (CWT), VT has coupled their cognitive engine to a highly-reconfigurable communications stack and controller interface implemented by CTVR, Trinity College Dublin. A description of both systems was presented. In addition, initial analyses of the time taken to reconfigure the system were presented before concluding with an outline of the current and future work planned for this joint collaborative project.

7. REFERENCES

[1] Haykin S., “Cognitive Radio: Brain-Empowered Wireless Communications”, IEEE Journal on Selected Areas in Communications, February, 2005.

[2] Sutton, P., Doyle, L., Nolan, K.E.,"A Reconfigurable Platform for Cognitive Networks**",** to appear in Proceedings of the 1st International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM 2006), June 8-10, 2006.

[3] Nolan, K.E., Sutton, P., Doyle, L., An Encapsulation for Reasoning, Learning, Knowledge Representation, and Reconfiguration Cognitive Radio Elements, 1st International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM 2006), Greece, June 8-10, 2006.

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

[5] Rieser, C.J.; Rondeau, T.W.; Bostian, C.W.; Gallagher, T.M., "Cognitive radio testbed: further details and testing of a distributed genetic algorithm based cognitive engine for programmable radios," *Military Communications Conference*, 2004. MILCOM 2004. IEEE , vol.3, pp. 1437- 1443 Vol. 3, 31 Oct.-3 Nov. 2004.

[6] Doyle, L.E., Forde T.K. et al., " A Platform for Dynamic Spectrum EXperimentation ", under review for the First International Workshop on Technology and Policy for Accessing Spectrum (TAPAS), Boston, August 1-5 2006.