AN APPLICATION-INDEPENDENT MODEL OF THE COGNITIVE RADIO DOMAIN

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ABSTRACT

Cognitive Radio[1] is a technology by which Software Defined Radio functionality is augmented to permit a radio system to autonomously adjust its operations. This capability offers a variety of benefits.

This paper proposes a picture of Cognitive Radio that can be adapted to a wide range of radio system considerations. With this model the relationships between system architecture, radio capabilities, application needs, and cognitive network functions can be explored, and the resulting system implications understood.

The combination of cognitive capability and the high-performance Software Defined Radio performance made available by the HYPRES Digital RF capability offer significant opportunity for improved communications network capability and performance in the future.

1. INTRODUCTION

Communication is the process of conveying information, and for thousands of years involved either close proximity for voice or the time delay associated with transportation of a letter or other physical medium. With nineteenth century invention of the telegraph and telephone, information could be moved by electronic means through a wire in real time, eliminating the transportation delay.

Radio is capable of wireless communication using electromagnetic radiation, and has been available for practical use for nearly one hundred years. It relaxes the constraint of a physical connection and supports moving communication with one or many receivers.

Software Defined Radio (SDR) is a fairly recent development. SDRs use digital electronics, computer technology, and digital signal processing to enhance radio functionality and flexibility beyond analog circuits and components. An SDR must still, however, operate in accordance with the directions contained in its software. Changing SDR functionality involves commanding the radio to change to an alternative set of software.

Cognitive Radio endows a radio with capabilities derived from the field of artificial intelligence[2]. The following definition for Cognitive Radio is currently before the Software Defined Radio Forum for consideration:

> a.) Radio that is aware of its environment, internal state, and location, and can make decisions about its operating behavior based on that information.
> b.) Cognitive Radio that utilizes Software Defined Radio, Adaptive Radio and other technologies to autonomously adjust its operations to achieve desired objectives.

Introducing autonomous decision-making provides a radio system with enhanced capability to adjust to operating circumstances, improve its own performance, take advantage of available spectrum in a flexible manner, and improve communications security.

2. COGNITIVE RADIO BENEFITS

The following list indicates functional advances enabled by Cognitive Radio:

- Find spectrum that is currently available for use
- Decide what waveform to instantiate
- Broker for service among competing suppliers
- Monitor the local area and the radio's own operation for regulatory compliance
- Adapt radio operation for radio state and environmental conditions
- Learn from actions taken in the current context to adapt and improve future operation
- Provide location awareness
- Avoid contention with known licensed users in a given geographical area
- Adapt radio operation to provide interoperability with other radio systems
- Develop actions necessary to bridge between incompatible systems
- Interact with central authority to obtain authentication materials to permit secure operation

[1] Wikipedia, Cognitive Radio, http:/en.wikipedia.org/wiki/cognitive_radio

[2] Wikipedia, Artificial Intelligence, http://en.wikipedia.org/wiki/artificial_intelligence

- Change radio operating parameters to optimize for the current Quality of Service mix
- Interact autonomously with other radio nodes to develop effective ad-hoc network structure

Cognitive Radio provides dynamic operational decision making with a reaction time of minutes or seconds. Some of these capabilities were formerly static as part of system architecture, meaning that the corresponding timeframe was years or decades.

With the breadth of extended functionality arising from Cognitive Radio deployment, it is useful to consider Cognitive Radio functionality in the context of extended application requirements. New and more capable systems can then be developed in conjunction with the cognitive capability.

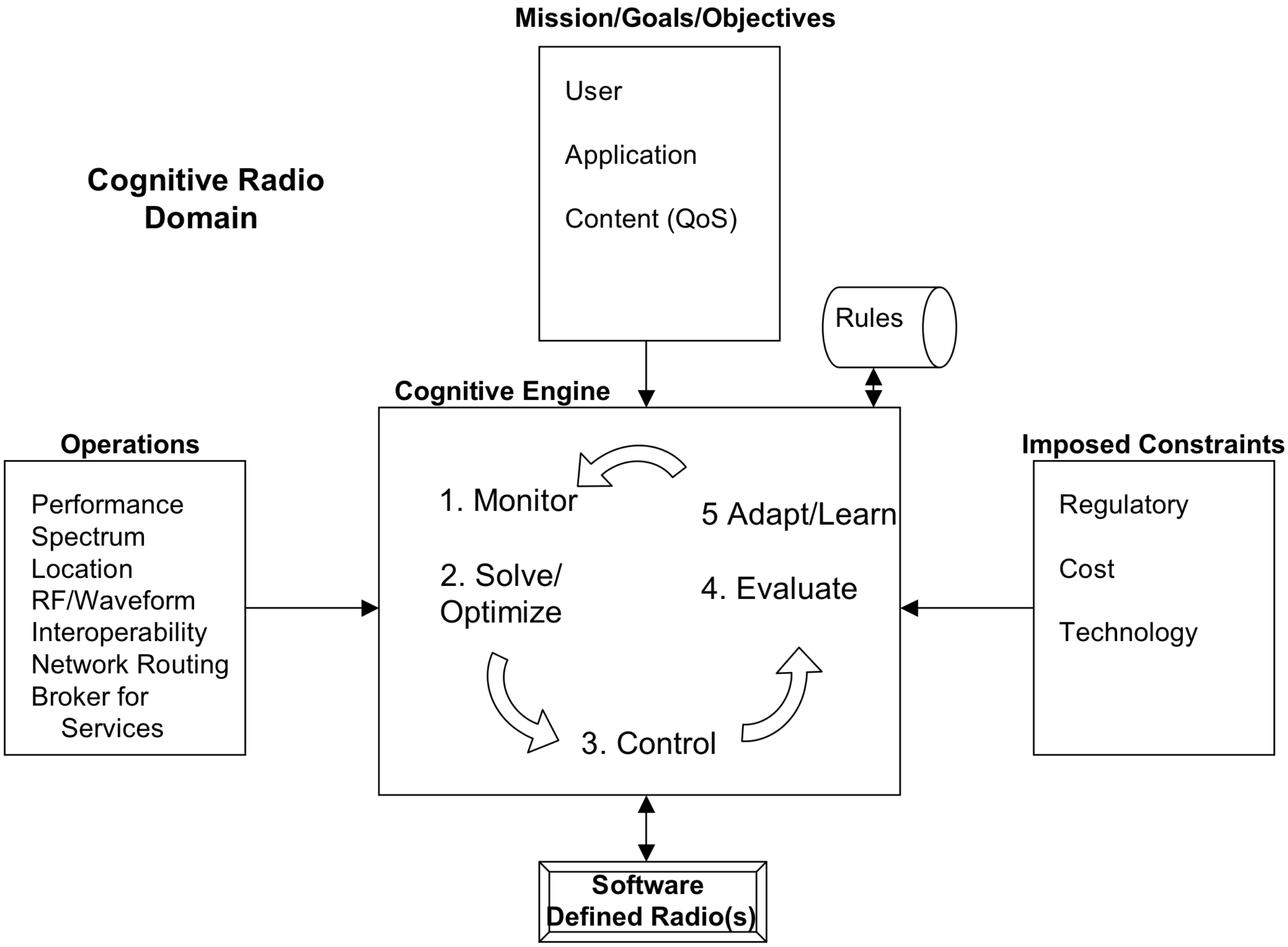

Figure 1. Cognitive Radio Domain Model

3. THE COGNITIVE RADIO DOMAIN MODEL

Figure 1 is a diagram of the model. At the center is a Cognitive Engine, controlling a Software Defined Radio and receiving reports from it. Operating in response to a set of rules, the engine monitors various aspects of its environment, makes decisions about what changes to make, and evaluates the results.

It is important to note that this model is functional, and has no relation to the physical modularity of the system. Model elements can be dispersed across the system, and no specific means of communications are assumed.

The whole radio system is operating in response of some goal set or mission, and the characteristics of that mission are available from the user domain in the box labeled Mission/Goals/Objectives. Technical capabilities and state information about the equipment and the operating environment are derived from the box labeled Operations. Additional considerations about the system and its operation come from the box labeled Imposed Constraints.

In the center is the Cognitive Engine that controls the connected Software Defined Radio to optimize operations. Institutional memory is stored in the form of a rules data base.

We will consider each of these elements in the following sections.

4. OPERATIONS

These parameters consider the engineering characteristics of the radio and the architecture of the system or systems in which it is operating.

4.1 Performance

This parameter includes both the underlying capabilities of the equipment and current operating variables, such as battery condition and buffer availability. Information on these characteristics is used by the Cognitive Engine in optimizing system performance. For example, low battery condition might lead to a decision to operate slower to keep critical data flowing longer.

The system is also aware of its performance levels, and will adjust operating parameters such as power and buffer size to optimize that performance.

4.2 Spectrum

One of the most promising capabilities of Cognitive Radios is to improve spectrum utilization. There is a great deal of underutilized spectrum at present due to fixed and inflexible allocations. Cognitive Radios offer the potential to monitor spectrum, and configure the radio to make use of available spectrum, avoid interference with other systems or services, and yield access when needed by higher priority traffic.

Different rules apply to licensed channels vs. unlicensed spectrum, and the rules made available to the Cognitive Engine permit the Cognitive Radio to operate in either.

4.3 Location

A Cognitive Radio has provisions to maintain information about where it is located. For terrestrial applications location is known with respect to the surface of the earth, in relation to other communication nodes or networks, and with regard to political considerations of country of operation, local jurisdictions, and relevant regulatory authority.

4.4 RF/Waveform

Analog components at the front end of any radio are needed to operate at radio frequencies. Variations of operating frequency, bandwidth, power levels, and modulation variables are collectively are called an air interface or a waveform. Propagation characteristics and ambient noise levels impact link quality.

In response to the current RF conditions, and demands of the user and application, the Cognitive Engine can negotiate, select, instantiate, and adjust a waveform to provide optimal communications.

4.5 Interoperability

In the past communications systems were developed in response to the requirements of specific user communities, resulting in a number of incompatible radio systems. SDRs offer capability to instantiate waveforms from two incompatible radio systems, and bridge across them so they function as if they were able to operate together. Cognitive Radios provide potential to make decisions about the operating details of interoperability, and to provide information needed for secure operation between different systems, including authentication and key delivery..

4.6 Network Routing

An emerging capability is the ability of a group of radio systems to organize themselves into ad-hoc networks and optimize the flow of information between network members and into connections with other networks at the periphery. The Cognitive Engine plays an important role in organizing the communication needed to maintain good performance, capacity optimization, and assured connectivity in these systems.

4.7 Broker for Services

Under a given operational scenario there may be several different types of infrastructure in view that can provide backhaul functionality. Part of the optimization role of the Cognitive Engine is making an optimal solution from available services under the optimization criteria provided.

5. MISSION/GOALS/OBJECTIVES

Radios are put in service to assist in the achievement of achieving some goal or providing some service. This element of the Cognitive Radio domain considers the objective or mission aspect of Cognitive Engine utilization.

5.1 User

Users are both sources and sinks for information. Source data varies from voice communication to the state of a fireman's breathing gas supply. Sink behavior of the user ranges from passive television watching to issuance of military orders during combat. User needs are dynamic, and may change rapidly during operation.

The role of a Cognitive Radio is to support the user both by instantiating connectivity and byproviding needed levels of flexibility and functionality while relieving the need for interaction with a complex user interface. It should provide the user needed information in a timely fashion and an easy to use form, so the user interface is of prime concern.

The user interface is a very important component of this area. In normal operation it is unobtrusive, but can provide feed back to the user of the state of the system. The user can conveniently request to receive more or less information, or be advised regularly on the state of some particular parameter or variable of interest.

5.2 Application

The application is the context within which the Cognitive Radio understands what the user wants and needs, and operates to develop and present needed information. There are two aspects of Cognitive Radio operation. One is functionality associated with operation of the radio itself, and the other is execution of application programs to provide support desired by the user.

Multiple applications will frequently coexist in a Cognitive Radio. The radio responds to both input from the user and changes in the environment to activate applications.

5.3 Contents (QOS)

Operation of several application programs in the Cognitive Radio often leads to a mixture of data with differing needs. Voice and streaming video need to have continuity of service with consistent information flow. Too slow will lead to gaps in the picture, while too fast can lead to buffer overflow. Data transfer has a reduced requirement for a consistent rate of transfer, and can often be prioritized and some elements deferred if circuits are too busy.

Reserve capacity is necessary to handle peak loads and maintain response time. The Cognitive Engine needs to know about the operating mix and how much operating margin exists. It can also explore alternate routing if overloading and congestion are encountered.

6. IMPOSED CONSTRAINTS

Some constraints are imposed the external environment, regulatory considerations, financial factors, technological limits, and decisions made during system design.

6.1 Regulatory

Any emitted RF energy is subject to restrictions imposed by government agencies to maintain order in the use of spectrum. Operation may require a license. Operation is usually subject to radiated power restrictions. The rule base contains information derived from currently imposed operational constraints.

6.2 Cost

Radio systems are built under cost constraints that may limit the performance of the unit. At design time, trade-offs are made between the range of available reactions and system cost. Need to control equipment cost may result in choices that compromise some aspects of performance or functionality.

Cognitive Radio systems also often interact with other networks, such as commercial services, that impose additional charges for traffic. Cost structures of alternative routings can be included as part of the optimization criteria.

6.3 Technology

The state of the art at time a design is finalized is an important constraint. It cannot easily be changed in the field for a particular radio model, but will almost certainly be different for the next generation. Sometimes design modularity can be used to make provision for technological developments, and the rate of emergence of new technology often influences when engineering for a new version is undertaken.

7. THE COGNITIVE ENGINE

The Cognitive Engine is at the heart of this Cognitive Radio model. During system initiation it starts with current Operations information, Constraints, and Objectives uses that information to update the Rule database. During operation the Engine iterates regularly through its cycle, and generates control information to change the state of the radio.

7.1 Monitor

The Cognitive Engine receives information from the radio, auxiliary transducers, environment, and the user. It maintains current state information, and is aware of state changes.

7.2 Solve/Optimize

At regular intervals, or when triggered by a change of state, the Cognitive Engine develops updated solutions for radio configuration. It then tests to see if objective function values can be improved.

The solution is done in the context of rules available in the Rules database, and each iteration may change some of the data stored there.

7.3 Control

Based on differences between current radio state and the new optimization, the Cognitive Engine develops control data to move toward the desired state. Control data is taken it its broadest sense; it may include information presented to the user through the user interface, changes in SDR performance, notification to a remote authority of status changes, or input to operational application programs.

7.4 Evaluate

Impact of the control information is evaluated as an inherent part of each iteration, and may involve further state evaluation or changes to the rule base to achieve learning. The concepts of control theory are invoked to maintain stable radio operation and avoid hunting, inappropriate feedback, or other pathological behavior.

7.5 Adapt/learn

Changes to the rule base are made in a much slower fashion than the main control loop in order to avoid erratic behavior. Response from the user is very important in learning, especially messages through the user interface that indicate what information elements the user does or does not want to receive.

7.6 Cognitive Operation

By iterating through the five steps of this loop, the Cognitive Engine is able to generate controls for the Software Defined Radio to optimize its performance, enhance accomplishment of the user's application objectives, and to fine-tune its own operation. In this view, the scope of cognitive undertaking is not limited to any subset of the benefits set forth in the list in Section 2. It can be applied to any portion of the domain.

If, however, the Cognitive Engine is not involved with the RF performance of the associated Software Defined Radio, then the term Cognitive Radio is probably not applicable – it is perhaps a cognitive system.

8. NETWORK IMPLICATIONS OF COGNITIVE RADIO CAPABILITY

The term Cognitive Radio is often thought of as implying facilities for cognition collocated with the associated RF and Software Defined Radio capability. In terms of a hierarchical network, however, enhanced operational optimization may also be achieved by locating cognitive capability at higher architectural levels in the system.

If cognitive activities take place at a point in the system above the RF terminal nodes, then information delivered by all of the subordinate nodes can be considered. In fact, the level can be moved up or down: at higher levels the perspective will be broader and shallower; at lower levels more focused and more detailed.

For example, from the perspective of a single node, any received signal might be an interferer. At a higher level in the system, a controller will be aware of that node's operation, and can determine the location of available spectrum for all of them.

The operating level for cognitive capability thus becomes another aspect of system architecture, trading off breadth and scope against depth and detail. One very important consideration, however, is that areas of responsibility must be carefully delineated. The possibility of different portions of the system cognitive elements issuing conflicting commands must be controlled.

9. MULTI-PURPOSE NETWORKS

Communication network capability is developing at a rapid rate. RF capability, analog/digital conversion, signal processing, geolocation, and addressability are becoming flexible enough to consider networks that serve a variety of different application needs.

If a commercial cellular service provider, for example, has coverage in a particular area, it may be possible for an application vendor to purchase information delivery service on an as-needed basis rather than erect a new, overlying, separate infrastructure at a substantial cost saving.

Careful system design is required to ensure that all users are fully aware of the system trade-offs they are accepting. Cognitive facilities can be of significant value in permitting such systems to react dynamically to changing needs and environment.

HYPRES Digital RF [1] superconducting circuits are part of new developments that provide the capabilities needed for flexible and responsive systems to support enhanced networks capable of supporting such networks.

10. CONCLUSIONS

We have presented a model that describes the elements of Cognitive Radio functionality, and illustrates the relationship between them and Software Defined Radio. Using these elements, it is possible to discuss where in system topography various cognitive elements will be located, and how they will communicate with each other.

We have looked at how placing the cognitive functions at different levels in the system can influence the information available for decision making. Finally we proposed that the capabilities of Software Defined Radio, Cognitive Radio, and advanced system component technologies offer an opportunity for multi-purpose communications systems that are cost effective, increase spectrum utilization, and provide enhanced performance.

11. REFERENCE

[1] HYPRES, Inc. : see www.hypres.com