Chapter 1: Cognitive Radio

“Ai, ergo sum. [I think, therefore I am]” – René Descartes

Aided by advances in processors, RF technology, and software, software radio technology has rapidly progressed since the coining of the term “software radio” by Joe Mitola in 1991 [Mitola_00]. Software radio (SDR) currently forms the core of the US military’s multi-billion-dollar-a-year Joint Tactical Radio System (JTRS) which has resulted in SDRs being fielded by General Dynamics (DMR [GDDS]), Thales (JEM [Thales]), and Harris (RF-300M-HH [Harris]), to name a few. Beyond the military, commercial standards are beginning to be preferably implemented in software (802.16 [Picochip]) and commercial base stations are being implemented as software radios (Vanu [Vanu]). The reality of software radio and the support for moving a single radio through multiple standards has led the Institute of Electrical and Electronics Engineers (IEEE) to begin standardizing vertical handoffs between networks employing different standards (802.21 [802.21]).

However, the numerous envisioned applications for SDR – multiband multimode radio, porting waveforms across platforms, over-the-air updates – are accompanied by the numerous envisioned problems – viruses or worms that render the radio unusable, unforeseen software/hardware combinations that turn radios into jammers, and cell phones that crash to reveal a “blue screen of death.” Accordingly, SDR research and development has focused as much on overcoming the problems created by SDR as it has the opportunities and realization of SDR.

Now consider a radio that autonomously detects and exploits empty spectrum to increase your file transfer rate. Suppose this same radio could remember the locations where your calls tend to drop and arrange for your call to be serviced by a different carrier for those locations. These are some of the ideas motivating the development of cognitive radio\(^1\). In effect, a cognitive radio is a software radio whose control processes leverage situational knowledge and intelligent processing to work towards achieving some goal related to the

---

\(^1\) This term, too, was coined by Mitola in 1999 [Mitola_99].
needs of the user, application, and/or network. Arising from a logical evolution of the control processes of a software radio, cognitive radio presents the possibility of numerous revolutionary applications.

Opportunistic spectrum utilization can find available spectrum in a crowded network, leading to 10-fold gains in capacity [Marshall_05a]. By learning their environment, cognitive radios can dramatically improve link reliability and help networks autonomously improve coverage and capacity. True radio interoperability can be achieved when radios learn to autonomously negotiate services and protocols. Smart collaborative signaling techniques promise significant range extension and data-rate increases. Advanced network topologies can dramatically extend coverage and increase bandwidth. The global roaming of radios can be dramatically simplified when a radio is responsible for autonomously detecting the location specific operating requirements. Autonomous determination of bandwidth requirements and spectrum availability will greatly enhance the opportunities for rapid reallocation of spectrum resources. Finally, smart spectrum use can overcome the deficiencies of inexpensive analog components allowing lower-priced radios to be fielded [Marshall_05a].

But what’s to say that cognitive radios will not act maliciously – opportunistic spectrum use into spectrum bullying? Given the infinite number of environments that a radio will encounter and a design that how can we hope to verify that the radio will behave as intended? How can we be certain that radios will be able to even recognize the opportunities they are presented? What if the interaction of several seemingly benign algorithms yield disastrous network behavior – something that seems all too possible once selfish radios are competing for spectrum?

This work concentrates on this last problem – the interaction of cognitive radios in distributed radio resource management settings – by developing techniques for modeling and analyzing cognitive radio algorithms to determine steady-states, convergence, and stability and by developing frameworks for designing cognitive radio algorithms that yield good performance for the radio and for the network. Beyond cognitive radio, the
techniques developed and presented in this work can also be extended to the modeling, analysis, and design of distributed and automated radio resource management. Serving as a foundation on which to build the subsequent models, analysis techniques and development frameworks, this chapter focuses on the concept, implementation, and applications of cognitive radio and is organized as follows. Section 1.1 formally defines cognitive radio and differentiates cognitive radio from some closely related terms. Section 1.2 discusses high-level implementation aspects of cognitive critical to understanding the analysis of interactive cognitive radio. Section 1.3 discusses some of the frequently discussed applications of cognitive radio and some limited current deployments of cognitive radio. Section 1.4 presents some of the major technical hurdles that must be cleared for widespread deployment of cognitive radio. Section 1.5 briefly overviews the objectives and original contributions of this work. Section 1.6 presents work related to the big-picture objectives of this work and outlines the material to be presented over the remainder of the text.

1.1 Basic Cognitive Radio Concepts

While the cognitive radio community has had significant success popularizing the concept of cognitive radio and developing prototypes, applications, and critical components, the community has had a surprisingly difficult time agreeing upon exactly what is and is not a cognitive radio beyond. Perhaps echoing the sentiment of former Supreme Court Justice Potter Stewart, many members of the cognitive radio community believe that “they know it when they see it,” even if a precise definition is ineffable. Some have succeeded in formulating a definition of cognitive radio but have found their definitions at significant variance with others’ definitions.

While these definitions are likely to converge over time from either an international consensus (the goal of IEEE 1900.1 group) or from a de facto definition taken from the first cognitive radio to dominate the market, this dissertation must plunge ahead with some formalization of cognitive radio and related concepts to formally analyze their interactions. To that end, the remainder of this introductory section presents a definition of cognitive radio that is hopefully suitably encompassing and discriminating for other researchers to use and reasonably well-justified by its preceding discussion. To enhance
the offered definition’s usefulness, terms frequently discussed in relation to cognitive radio are subsequently defined and differentiated from cognitive radio.

1.1.1 Defining “Cognitive Radio”

Tautologically, a cognitive radio could be defined as “A radio that is cognitive,” or paraphrasing Descartes, “Cogitat, ergo est cognitive radio.” In the absence of a Turing test for radios, applying this definition is nontrivial and implies a level of functionality that many researchers consider excessive. Indeed, while many researchers and public officials agree that upgrading a software radio’s control processes will add significant value to software radio, there is currently some disagreement over how much “cognition” is needed which results in disagreement over the precise definition of a cognitive radio. The following provides some of the more prominently offered definitions of cognitive radio.

In the 1999 paper that first coined the term “cognitive radio”, Joseph Mitola III defines a cognitive radio as [Mitola_99]: “A radio that employs model based reasoning to achieve a specified level of competence in radio-related domains.”

However, in his recent popularly cited paper that surveyed the state of cognitive radio, Simon Haykin defines a cognitive radio as [Haykin_05]: “An intelligent wireless communication system that is aware of its surrounding environment (i.e., outside world), and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters (e.g., transmit-power, carrier-frequency, and modulation strategy) in real-time, with two primary objectives in mind:

- highly reliable communications whenever and wherever needed;
- efficient utilization of the radio spectrum.

It thinks, therefore it’s a cognitive radio.
Coming from a background where regulations focus on the operation of transmitters, the FCC has defined a cognitive radio as [FCC_05]: “A radio that can change its transmitter parameters based on interaction with the environment in which it operates.”

Meanwhile, the other primary spectrum regulatory body in the US, the NTIA [NTIA_05], adopted the following definition of cognitive radio that focuses on some of the applications of cognitive radio: “A radio or system that senses its operational electromagnetic environment and can dynamically and autonomously adjust its radio operating parameters to modify system operation, such as maximize throughput, mitigate interference, facilitate interoperability, and access secondary markets.”

The international spectrum regulatory community in the context of the ITU Wp8A working document is currently working towards a definition of cognitive radio that focuses on capabilities as follows: “A radio or system that senses and is aware of its operational environment and can dynamically and autonomously adjust its radio operating parameters accordingly.”

While aiding the FCC in its efforts to define cognitive radio, IEEE USA offered the following definition [IEEEUSA_03]: “A radio frequency transmitter/receiver that is designed to intelligently detect whether a particular segment of the radio spectrum is currently in use, and to jump into (and out of, as necessary) the temporarily-unused spectrum very rapidly, without interfering with the transmissions of other authorized users.”

The broader IEEE tasked the IEEE 1900.1 group to define cognitive radio which has the following working definition [IEEE 1900.1]: “A type of radio that can sense and autonomously reason about its environment and adapt accordingly. This radio could employ knowledge representation, automated reasoning and machine learning mechanisms in establishing, conducting, or terminating communication or networking functions with other radios. Cognitive radios can be trained to dynamically and autonomously adjust its operating parameters.”
Likewise, the SDR Forum participated in the FCC’s efforts to define cognitive radio and has established two groups focused on cognitive radio. The Cognitive Radio Working Group focused on identifying enabling technologies uses the following definition: “A radio that has, in some sense, (1) awareness of changes in its environment and (2) in response to these changes adapts its operating characteristics in some way to improve its performance or to minimize a loss in performance.”

However, the SDR Forum Special Interest Group for Cognitive Radio, which is developing cognitive radio applications, uses the following definition: “An adaptive, multi-dimensionally aware, autonomous radio (system) that learns from its experiences to reason, plan, and decide future actions to meet user needs.”

Finally, the author of this text participates in the Virginia Tech Cognitive Radio Working Group which has adopted the following capability-focused definition of cognitive radio [VT CRWG]: “An adaptive radio that is capable of the following:  
  a) awareness of its environment and its own capabilities,  
  b) goal driven autonomous operation,  
  c) understanding or learning how its actions impact its goal,  
  d) recalling and correlating past actions, environments, and performance.”

While it appears to be unlikely that there will be a harmonization of these definitions in the near future, an examination of the salient functionalities of these definitions, as summarized in Table 1.1, reveals some commonalities among these definitions. First, all of these definitions assume that cognition will be implemented as a control process, presumably as part of a software defined radio. Second, all of the definitions at least imply some capability of autonomous operation. Finally, the following are some general capabilities found in all of the definitions:

1. **Observation** – whether directly or indirectly, the radio is capable of acquiring information about its operating environment.
2. **Adaptibility** – the radio is capable of changing its waveform.
3. **Intelligence** – the radio is capable of applying information towards a purposeful goal.

<table>
<thead>
<tr>
<th>Definer</th>
<th>Autonomous</th>
<th>Environment</th>
<th>Can sense</th>
<th>Transmitter</th>
<th>Receiver</th>
<th>“Aware” Environment</th>
<th>Goal Driven</th>
<th>Learn the Environment</th>
<th>“Aware” Capabilities</th>
<th>Waveforms</th>
<th>Negotiate</th>
<th>No interference</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCC</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Haykin</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IEEE 1900.1</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IEEE USA</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ITU-R</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mitola</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NTIA</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SDRF CRWG</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SDRF SIG</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VT CRWG</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1.1: Cognitive Radio Definition Matrix.

Note that this definition of intelligence\(^3\) implies that even those definitions that do not explicitly mention a goal (or provide a specific goal such as performance) still implicitly require the existence of some goal for intelligent adaptation. By using only these common features of all these definition we arrive at the definition of cognitive radio given in Definition 1.1.

**Definition 1.1:** Cognitive Radio (*)\(^4\)

A cognitive radio is a radio whose control processes permit the radio to leverage situational knowledge and intelligent processing to autonomously adapt towards some goal.

---

\(^3\) Intelligence as defined by [American Heritage_00] as *The capacity to acquire and apply knowledge, especially toward a purposeful goal.* The definition for intelligence as applied to cognitive radio differs only in that the acquisition of knowledge has been subsumed into the observation process.

\(^4\) The asterisk denotes that this definition is original to the author. Throughout this document when chapters present both original and prior work by others, original definitions and theorems are noted by an asterisk.
Throughout the remainder of this text Definition 1.1 will be what is meant when the phrase “cognitive radio” is used. When different capabilities (sometimes more, sometimes less, sometimes more specific) are required, we will make use of different terms defined in the following section.

1.1.2 Related Terms
As part of our discussion of cognitive radio, we will find it useful to rigorously define some related terms. Specifically we will find it useful to make use of the terms software defined radios, policy based radios, procedural radios, and ontological radios.

The logical authority for a definition of software defined radio, the Software Defined Radio Forum defines a software defined radio (SDR) as shown in Definition 1.2 [SDR Forum_05].

**Definition 1.2: Software Defined Radios (SDRs)**

“Radios that provide software control of a variety of modulation techniques, wide-band or narrow-band operation, communications security functions (such as hopping), and waveform requirements of current and evolving standards over a broad frequency range. The frequency bands covered may still be constrained at the front-end, however, requiring a switch in the antenna system.”

While others consider Definition 1.2 to be that of a “software controlled radio,” this text will utilize the definition of SDR provided by the SDR Forum and will refer to radios whose functionality is primarily realized in software as “software implemented radios.”

While a radio could be implemented via software or hardware and controlled via software, the emphasis on software control is important to the cognitive radio concept as software control permits rapid adaptation of the radio’s operation – perhaps as short as the time required to readdress a program address counter – and provides a logical mechanism on which to implement a cognitive radio’s “control processes [that] permit the radio to leverage situational knowledge and intelligent processing to autonomously adapt towards achieving some goal.” It should be pointed out that while many treat that cognitive radio as an SDR with enhanced control processes (as was done in the introduction to this chapter), some researchers correctly emphasize that a cognitive radio

---

5 Here, the term “others” includes this author.
need not be implemented on an SDR as the control processes could be implemented in hardware and indeed have implemented a hardware cognitive radio [Rondeau_04]. However, such “hardware controlled cognitive radios” appear likely to share the fate of Babbage’s Analytical Engine due to the far greater flexibility and ease of programming provided by SDR cognitive radios.

Although the definition of the term *waveform* is a frequent point of discussion at conferences due to variances in usage, we have used the term repeatedly throughout the preceding and hope its usage has been clear from context up to this point. However, as we just wrote “waveform requirements” as part of a formal definition, completeness dictates we formally define waveform.

**Definition 1.3:** *Waveform* (*)

A protocol that specifies the shape of an electromagnetic signal intended for transmission by a radio.

Implicit to Definition 1.3 is the fact that a waveform is not solely defined by its physical layer algorithms. If specified as part of the protocol, then link layer, network layer, transport layer, and application layer algorithms will all influence the shape of the electromagnetic signal. However, not all waveforms specify algorithms at all layers. For example the FM broadcast radio waveform is a purely physical layer standard. In general, the only influence of signal shape that is excluded from the term “waveform” is the information bits being carried by the signal.

Because cognitive radios and SDRs could conceivably be configured (or autonomously configure themselves) to implement almost any waveform, spectrum regulators need some mechanism to ensure that cognitive and software defined radios have a limited impact on licensed systems. To provide this mechanism, many researchers have proposed the use of *policy radios*. The IEEE 1900.1 group currently defines a *policy radio* as given in Definition 1.4 [IEEE 1900.1].

**Definition 1.4:** *Policy Radio*

“A radio that is governed by a set of rules for choosing between different waveforms. The definition and implementation of these rules can be:

- during the manufacturing process
- during configuration of a device by the user;
Particularly for cognitive radios, it is convenient to refer to the set of set of rules as the radio’s *policy* and a policy radio that is also a cognitive radio as a *cognitive policy radio*. In practice, a policy might specify a spectral mask which defines a set of maximum transmission powers for a number of different frequency bands that are specific to a particular location. Then as the policy-based radio is moved around the world, the policy-based cognitive radio would be responsible for inferring and applying the policy that applies to its particular location, perhaps via GPS, a radio environment map [Zhao_06], or from a primary spectrum holder. Because of the needs of spectrum regulators and primary spectrum holders, it is expected that all cognitive radios will eventually be cognitive policy radios. In fact, the incorporation of policy into cognitive radio has been a major focus of DARPA’s xG program [Marshall_06].

Especially assuming the use of an SDR platform, the actual implementation of the cognitive and policy-related processes permits significant variation. The more traditional approach implements the control processes in a procedural language, such as C, where the adaptations spawned from specific observations can be traced to a specific pre-coded function. Such a cognitive radio is termed a *procedural cognitive radio* which is more formally defined as given in Definition 1.5. [Neel_06]

**Definition 1.5: Procedural Cognitive Radio (*)&

A cognitive radio whose adaptations are determined by hard coded algorithms and informed by observations.

Most implemented cognitive radio prototypes exhibit a significant degree of hard coding in their adaptation algorithms and are thus procedural cognitive radios. This includes Adapt4’s xG1 cognitive radio [Adapt4_06] which implements a dynamic frequency selection algorithm to adapt around legacy systems and CWT’s cognitive radio [Rondeau_04] which utilizes a genetic algorithm\(^6\) to generate adaptations from

---

\(^6\) A genetic algorithm is a search algorithm from optimization theory which generates sequences of candidate solutions by using an algorithm based on the gene theory of evolution. As such the algorithm exhibits both randomness (e.g., “mutations” and random “chromosome” cross-overs to generate “children”)
observations. Due to its significant parameterization, the CWT radio is significantly more flexible than the Adapt4 radio and is significantly less hard-coded, but it remains a procedural cognitive radio. Also the CWT radio illustrates that though procedural, the adaptations of a procedural radio may be nondeterministic. Thus when possible we will distinguish between deterministic and nondeterministic procedural cognitive radios.

However, as discussed in the text related to Fig 6 in the April 1900.1 draft, many researchers do not believe that a radio whose adaptations are determined by hard coded algorithms constitutes a cognitive radio. This is primarily because these researchers utilize a definition of cognitive radio which emphasizes a different implementation approach that utilizes a form of artificial intelligence. To provide this intelligence in a radio, [Mitola_00] proposes model-based reasoning using the Radio Knowledge Representation Language (RKRL) and [Baclawski_05] and [Kokar_06] propose ontological reasoning for cognitive radio applications. As defined by the IEEE 1900.1, an ontology is “the representation of terms in a vocabulary and their inter-relationships.” As such, RKRL would satisfy the IEEE 1900.1 definition of an ontology, thus these two different approaches could be said to be of the same “genus” (a cognitive radio that employs ontologies) if not the same “species” of ontology. The primary difference between the two approaches being the former’s usage of a vocabulary restricted to radio information while the latter uses the Web Ontology Language (OWL) to extend the radio’s knowledge base beyond radio-specific information.

In the context of cognitive radio, ontologies are intended to permit a reasoning engine to make inferences about the radio’s operating environment and what actions would be in the cognitive radio’s interest. Such an ontological approach has been employed by the DARPA xG program to demonstrate the feasibility of multiple cognitive radios implementing dynamic frequency selection (DFS). For the purposes of this text, we consider cognitive radios that adapt based on the decisions of a reasoning engine and

---

and determinism (e.g., picking “surviving populations” based on their “fitness” which for cognitive radios is expressed in terms of the goal of the cognitive radio). More information on genetic algorithms and CWT’s genetic algorithm cognitive radio is available in [Reiser04].
incorporate ontologies to be *ontological cognitive radios* which we formally define in Definition 1.6. [Neel_06]

**Definition 1.6: Ontological Cognitive Radio (*)**

A cognitive radio whose adaptations are determined by some reasoning engine which is
guided by its ontological knowledge base (which is informed by observations).

Though this distinction is blurred for nondeterministic procedural cognitive radios, e.g.,
the biologically inspired cognitive radio [Rondeau_04], an ontological cognitive radio
could conceptually perform both much better and much worse than a procedural
cognitive radio. Whereas for a procedural cognitive radio we typically know what action
the radio will take when a known collection of observations are input to the radio, the
same can not be said for an ontological cognitive radio as it truly has a mind of its own
(the reasoning engine). Instead, for an ontological cognitive radio we only know that the
radio will take an action the radio believes (or the engine calculates) furthers the radio’s
goal. While this imprecision appears to be a significant hurdle to analyzing the
interactions of cognitive radios, we introduce techniques for analyzing these radios
beginning in Chapter 4.

1.2 Cognitive Radio Implementation and Standardization

The differences in the definitions for cognitive radio can be largely attributed to
differences in the expectations of the functionality that a cognitive radio will exhibit. In
his dissertation [Mitola_00], Joseph Mitola III considers the nine levels of increasing
cognitive radio functionality shown in Table 1.1, ranging from a software radio to a
complex self-aware radio.
Table 1.1: Levels of cognitive radio functionality. Adapted from Table 4-1 [Mitola_00].

<table>
<thead>
<tr>
<th>Level</th>
<th>Capability</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Pre-programmed</td>
<td>A software radio</td>
</tr>
<tr>
<td>1</td>
<td>Goal Driven</td>
<td>Chooses Waveform According to Goal. Requires Environment Awareness.</td>
</tr>
<tr>
<td>2</td>
<td>Context Awareness</td>
<td>Knowledge of What the User is Trying to Do</td>
</tr>
<tr>
<td>3</td>
<td>Radio Aware</td>
<td>Knowledge of Radio and Network Components, Environment Models</td>
</tr>
<tr>
<td>4</td>
<td>Capable of Planning</td>
<td>Analyze Situation (Level 2 &amp; 3) to Determine Goals (QoS, power), Follows Prescribed Plans</td>
</tr>
<tr>
<td>5</td>
<td>Conducts Negotiations</td>
<td>Settle on a Plan with Another Radio</td>
</tr>
<tr>
<td>6</td>
<td>Learns Environment</td>
<td>Autonomously Determines Structure of Environment</td>
</tr>
<tr>
<td>7</td>
<td>Adapts Plans</td>
<td>Generates New Goals</td>
</tr>
<tr>
<td>8</td>
<td>Adapts Protocols</td>
<td>Proposes and Negotiates New Protocols</td>
</tr>
</tbody>
</table>

As a reference for how a cognitive radio could achieve these levels of functionality, [Mitola_00] introduces the cognition cycle, shown in Figure 1.1, as a “top-level control loop for cognitive radio.” In the cognition cycle, a radio receives information about its operating environment (Outside world) through direct observation or through signaling. This information is then evaluated (Orient) to determine its importance. Based on this valuation, the radio determines its alternatives (Plan) and chooses an alternative (Decide) in a way that presumably would improve the valuation. Assuming a waveform change was deemed necessary, the radio then implements the alternative (Act) by adjusting its resources and performing the appropriate signaling. These changes are then reflected in the interference profile presented by the cognitive radio in the Outside world. As part of this process, the radio uses these observations and decisions to improve the operation of the radio (Learn), perhaps by creating new modeling states, generating new alternatives, or creating new valuations.
As the learning process can be quite cycle intensive and is not necessary for many of the envisioned applications and as artificial intelligence is not yet ripe for deployment, many researchers have assumed lower levels of functionality in their cognitive radio. For instance, in his remarks at the 2005 MPRG Technical Symposium, Bruce Fette, Chief Scientist at General Dynamics Decision Systems, noted that many members of the defense community refer to the cognition cycle as the “OODA” loop – emphasizing only the observation, orientation, decision, and action portions cognition cycles. Even the source of the most expansive interpretation of cognitive radio [Mitola_00] suggests that learning would occur during sleep or “prayer” (insight gained from external entities) epochs and that during wake epochs the cognitive radio would primarily operate as an OODA loop augmented by some light planning capabilities. Whether implemented as an ontological cognitive radio or as a procedural cognitive radio, all cognitive radios are likely to make use of a goal driven OODA loop for its adaptations. This assumption of an explicit or implicit OODA loop is reflected in the modeling introduced in Chapter 2.
1.2.1 Radios
The following sections briefly describe some initial cognitive radio implementations and their relationship to the levels of cognitive radio functionality and our classification of cognitive radios. The first two radios discussed – CR1 and DARPA’s xG architecture – are examples of ontological reasoning radios. The next two radios – a biologically inspired cognitive radio and CORTEKs – are examples of nondeterministic procedural radios. The last cognitive radio presented – XG1 – is an example of a deterministic procedural radio.

1.2.1.1 CR1
CR1 or Cognitive Radio 1 is the cognitive radio architecture developed by Mitola as part of his dissertation [Mitola_00]. CR1 utilizes case-based and natural language reasoning guided by an OODA loop and an ontological description of the radio’s capabilities (Radio Knowledge Representation Language) to determine the adaptations of the radio.

1.2.1.2 xG
Though hesitant to call its work cognitive radio, DARPA’s xG program is pursuing an implementation of cognitive radios that incorporate ontological reasoning into the decision process. A general architecture for their radio is shown in Figure 1.3 where
software control is exerted over the radio platform (making the platform an SDR). Note that their radio actually includes two different reasoning engines – one dedicated to policy and one dedicated to waveforms (strategy).

Figure 1.3: DARPA XG High-Level Architecture from [IEEE 1900.1]

1.2.1.3 Biologically Inspired Cognitive Radio
The biologically inspired cognitive radio was the dissertation topic of Christian Rieser [Rieser_04]. Leveraging earlier work on channel sounding, this cognitive radio uses channel measurements to build a hidden Markov model (HMM) of its environment. This HMM is then used by a genetic algorithm to internally predict the performance of different combinations of waveform components for the observed channel conditions.
Originally intended for use on a Proxim hardware radio, the architecture has since been updated (see Figure 1.5) for use on a software radio. This updated architecture now includes support for policy, classification of signals via neural nets, and user driven inputs. Further, this cognitive engine is intended to be portable across hardware platforms [Scaparoth_06] and as such the engine has been applied to a GNU™ radio and to a radio built using Fujitsu test equipment, and will be applied this year to the Innovative Wireless Technologies (IWT) Unified Radio Architecture (URA).

---

7 GNU is a recursive acronym which stands for “GNU is Not Unix”
1.2.1.4 CORTEKS

The CORTEKS radio is another procedural cognitive radio implemented at Virginia Tech using a PC that leverages Virginia Tech’s OSSIE SCA implementation and the following test equipment from Tektronix

- Arbitrary Waveform Generator AWG430 – used to create a multi-mode transmitter
- Logic Analyzer – used for signal characterization (identifying bit patterns, protocols, etc.)
- Real Time Spectrum Analyzer (RSA3408A) – used to perform signal demodulation.

Governed by software defined policy, the CORTEKS radio acts as a secondary spectrum user and adapts its frequency and modulation to maximize goodput while avoiding interference with primary users. To help determine the presence of primary spectrum users, the CORTEKS radio employs neural nets for signal classification.
1.2.1.5 Adapt4 XG1
Adapt4 has developed and is currently fielding a cognitive radio called XG1 depicted in Figure 1.7. Intended to operate as secondary spectrum devices, their radio uses a proprietary algorithm known as Automatic Spectrum Adaptation Protocol (ASAP). According to [Adapt4_technology] this algorithm incorporates dynamic frequency selection, frequency hopping, and transmission power control with the intent of avoiding (when possible) and minimizing interference to primary spectrum users.
1.2.2 **Cognitive Standards**

As highlighted in Section 3, many currently envisioned cognitive radio applications represent “low-hanging-fruit” that could be implemented by incorporating knowledge about the environment and the device into a software radio’s control process. Thus it should not be surprising to see that some efforts are already underway to develop cognitive radios with some

1.2.2.1 **Policy Radio Deployments**

Policy based radios are the logical result of software radio and global mobility. Because of varying historical local needs, different regions of the world implement different sets of regulations. While there has been some movement towards spectrum harmonization, e.g., the push to harmonize the 5 GHz access for unlicensed 802.11, it seems unlikely that all spectral regulations around the world will be harmonized in the near future.

Accordingly, as a radio moves around the world, it requires some mechanism for determining which set of regulations it is operating under. In addition to global phones which are in some sense policy-based radios, though not cognitive policy-based radios, WLAN standards 802.11e and 802.11j can be seen as establishing a protocol that necessitates the use of a policy based radio when operating in the 5GHz band.

A more generalized policy-based radio suitable for cognitive radio is being developed by DARPA under the xG program. As noted in [Berlemann_05], an XML based policy description language has been developed which is loosely based on concepts from game
theory. As noted in [Marshall_05b], these declarative policy languages have had significant success with Dynamic Frequency Selection algorithms.

1.2.2.2 Emerging Cognitive Radio Standards and Deployments

The IEEE 802 community is currently developing two standards the directly relate to cognitive radio – 802.22 and 802.11h. Additionally, 802.11k is developing techniques for incorporating radio resource management information into WLAN operation – in effect incorporating knowledge about the environment and the radios.

1.2.2.2.1.1 802.22

There are three applications typically discussed for coexistence with initial trial deployments of cognitive radios: television, microwave point-to-point links, and land mobile radio. Each of these applications has been shown to dramatically underutilize spectrum on average. However, only television signals have the advantage of incumbent signals that are easy to detect (as opposed to a microwave point-to-point links) and not involved in life-critical applications (as would be the case for many land mobile radio systems).

Throughout its history, the UHF bands were under-allocated as regulators underestimated the cost-effectiveness of establishing new TV towers in these bands. It was not until the advent of cable TV that smaller TV stations were capable of cost-effective operation. Now with the introduction of HDTV technology, regulators in the US plan to force a nation-wide switch to this more efficient modulation by 2009 [Rast_05] accompanied by a completion of a de-allocation from analog TV of 108 MHz of high quality spectrum.

With these bands in mind, the 802.22 working group is pursuing the development of a waveform intended to provide high bandwidth access in rural areas using cognitive radio techniques. In a report presented at DySPAN [Cordeiro_05], it is stated that the 802.22 standard intends to achieve spectral efficiencies of up to 3 bits/sec/Hz corresponding to peak download rates at coverage edge at 1.5 Mbps. Simultaneously, the 802.22 system hopes to achieve up to 100 km in coverage.
While the PHY and MAC are still under development, the MAC will provide the cognitive capabilities as it manages access to the physical medium, responsible for quickly vacating a channel as needed. The standard under development has specified the following thresholds for vacating a channel for the following signals:

- Digital TV: -116 dBm over a 6 MHz channel
- Analog TV: -94 dBm at the peak of the NTSC (National Television System Committee) picture carrier
- Wireless microphone: -107 dBm in a 200 kHz bandwidth.

Thus these radios will be required to both detect and classify signals in its environment. To help minimize the interference induced to these signals, the 802.22 protocol is currently considering using spectrum usage tables that will be updated both automatically and by the system operator. To limit the impact when the systems fail to detect the incumbent systems, the standard also places traditional maximum transmission power limits and out-of-band emission limits.

While a promising approach, it is difficult to estimate how wide-scale a deployment 802.22 will enjoy as WiMAX was first to market with deployments in Korea (WiBro) and planned deployments in the US [Segan_06] and will be able to provide the same target service: high data rates to rural users.

1.2.2.1.2 802.11h
Unlike 802.22, 802.11h is not formulated as a cognitive radio standard. However, the World Wireless Research Forum [WWRF_04] has noted that a key portion of the 802.11h protocol – dynamic frequency selection – has been termed a “cognitive function”. To see why an 802.11h WLAN might be considered a cognitive radio, consider that the 802.11h protocol requires that a WLAN be capable of the following tasks.

- **Observation** – 5.4.4.1 in [802.11h] requires WLANs to estimate channel characteristics such as path loss and link margin and 5.4.4.2 further requires the radios estimate channel characteristics such as path loss and link margin.
• **Orientation** – Based on these observations, the WLAN has to determine if it is operating in the presence of a radar installation, in a bad channel, in band with satellites, or in the presence of other WLANs.

• **Decision** – Based on the situation that the WLAN is encountering, the WLAN has to decide to change its frequency of operation (**Dynamic Frequency Selection**), adjust the transmit power (**Transmit Power Control**), or both.

• **Action** – The WLAN has to then implement this decision.

Reviewing most of the definitions from before, only learning or “recalling and correlating past actions, environments and performance” is not required as part of the standard. However, if we move beyond the requirements of the standard to expected implementations, it seems reasonable that many vendors will include and leverage some memory of past observations (useful for detecting intermittent transmitters) which implies that both cognitive radio definitions will be satisfied.

### 1.2.3 Institutional Initiatives

Beyond these initial deployments, several entities have started publicly acknowledged initiatives into cognitive radio including DARPA, the SDR Forum, IEEE, and the FCC.

#### 1.2.3.1 DARPA

DARPA sees cognitive radio as a key enabling technology to their vision of advanced networking by allowing less individually capable radios to perform complex operations needed make better use of spectrum and support high data rate applications. Currently, DARPA is exploring many different aspects of cognitive radio as part of the xG program and other ongoing programs. Unfortunately, many of the results of the DARPA programs are not currently in the public domain. However, Preston Marshall, program manager for DARPA’s cognitive radio initiatives has promised that contracting organizations will be required to disclose most of their results online in the near future. In the interim, Marshall highlighted many of DARPA’s plans and results in a presentation at DySPAN [Marshall_05a] and during a panel session at the SDR Forum [Marshall_05b].

In the area signal classification and detection, DARPA has developed a sensor capable of processing 5 GHz/second frequency capable of sub-noise-floor signal detection (20 dB
below) by exploiting cyclostationarity properties. DARPA has contracted with Rockwell to miniaturize this sensor.

Believing that procedural approach would result in too much code and too many detailed policies, DARPA has developed a declarative policy language that is independent of the implementation platform. Already successfully demonstrating small networks of Dynamic Frequency Selection networks, DARPA hopes to extend their policy work to construct a “provable framework” that supports policy enforcement and optimization (current focus is just on making the technology work, the Wireless Networking After Next program is intended to include optimization as a goal). Another demonstration of radios from Lockheed-Martin, Shared Spectrum, and Raytheon with the target of 90% connectivity and 90% chance of finding available spectrum found that 15 times more radios could be fielded using the xG approach. By August 2007, DARPA plans to have field trialed systems of interacting and collaborating 25 xG nodes.

DARPA also believes that advanced network topologies will be a key application of cognitive radios and is starting the CBMANET program to explore advanced networking topologies based on the xG radio. To help support these new dynamic topologies and the proposed optimization routines Marshall believes there may need to be new layers inserted into the protocol stack for topology an optimization because of the intelligence required in those operations.

The most notable anticipated activity from DARPA is the launching of the Wireless Adaptable Node Network (WANN) project this September. WANN hopes to demonstrate reduced device cost (targeting ~$500/node) via intelligent adaptation and greater node density. Additionally, the WANN program is hoping to achieve significant gains in throughput and network scalability through the incorporation of intelligence in the radios.

1.2.3.2 SDR Forum
The SDR Forum chartered two groups in 2004 to explore cognitive radio issues: the Cognitive Radio Working Group and the Cognitive Radio Special Interest Group. The working group is tasked with standardizing a definition of cognitive radio and identifying
the enabling technologies for cognitive radio. The special interest group is tasked with identifying attractive commercial applications of cognitive radio for which the working group should identify the enabling technologies.

At the 2005 SDR Forum Technical Conference, significant emphasis was given to cognitive radio with two paper sessions, one panel session, a tutorial, and a keynote talk dedicated to the subject of cognitive radio. Then in April 2006, the SDR Forum held a Cognitive Radio Workshop in San Francisco.

1.2.3.3 IEEE
The IEEE has expressed significant interest in cognitive radio. As a body, IEEE submitted the proposed definition to the FCC noted in Section 2. To allow for more focused development, the IEEE has started the IEEE 1900 group to study the issue of cognitive radio. Currently, the 1900 group has three subgroups with the following focuses:

- 1900.1 - Standardize definitions and terminology related to cognitive radio
- 1900.2 - Standardizing a process for testing and verifying the operation of cognitive radios.
- 1900.3 - Standardizing approaches for qualifying software modules.
- 1900.a - Regulatory certification of cognitive radios.

The IEEE Communications Society held its first Dynamic Spectrum Access Networks (DySPAN) in November 2005 with a primary focus on how cognitive radio, including the following:

- technologies needed to implement cognitive radio ranging from sensing, analysis of interactions, and advanced networking technologies
- appropriate regulatory approaches for cognitive radio
- potential market opportunities for cognitive radio
- trial implementations of cognitive radio systems.
The IEEE is playing an expanding role in the development of cognitive radio forming the 1900.4 workgroup (joining the 1900.1, 1900.2, and 1900.3 groups described in the December 2005 report) to support standardization of radio regulatory compliance, sponsoring CrownCom2006 – a cognitive radio focused conference – and two special issue journals on cognitive radio, and the 802.22 group which merged its final two proposals in March implying that the standard could be agreed upon within the next year.

1.2.3.4 FCC

On May 19, 2003, the FCC convened a workshop to examine the impact that cognitive radio could have on spectrum utilization and to study the practical regulatory issues that cognitive radio would raise. After a series of public interactions, the FCC adopted the transmitter-centric definition of cognitive radio listed in Section 2 and appears interested in adjusting its regulations in a way that will accommodate the deployment of cognitive radio in unlicensed bands and possibly in a portion of the new bands being opened up by the upcoming UHF reallocation with possible later extensions to the public safety and ISM bands.

Since then, the Federal Communications Commission (FCC) has also taken steps to increase the opportunities for cognitive radio deployment by expanding the unlicensed 5 GHz and requiring that devices operating in those bands support both Dynamic Frequency Selection (DFS) and Transmit Power Control (TPC) – characteristics of 802.11h which was characterized in the December 2005 report as indicative of minimal cognitive radios. In light of the expanded introduction of cognitive radios, the FCC issued proposed rules for compliance testing DFS radios in April [FCC_06a] with comments due on May 15. The results of this process were compiled into a document released on June 30, 2006 that provides a standard for testing DFS and TPC compliance with regard to radar avoidance and minimizing interference with satellites [FCC_06b]. It is expected that these actions will enhance the opportunities for cognitive radio deployments.
1.2.3.5 Other Institutions
Several other institutions are also currently pursuing cognitive radio research including
E$^2$R, Virginia Tech, Winlab, and BWRC.

E$^2$R is a European initiative into supporting End-to-End Reconfigurability with numerous
participating European universities and companies. E$^2$R is focused primarily focused on
incorporating dynamically radio resource management schemes into existing cellular
structures to achieve advanced end-user services with efficient utilization of spectrum,
equipment and radio resources on multi-standard platforms.

Virginia Tech currently has several significant cognitive radio initiatives. Two different
cognitive radio testbeds that leverage test equipment to effect powerful yet easy to
implement software radios are under development with a focus on both public safety and
commercial interests. These two projects are exploring techniques for enhancing
detection and classification capabilities, learning algorithms, knowledge representation
and the effect of interaction of cognitive radios. Work is being performed exploring
techniques to exploit collaborative radio to improve network performance. Other projects
are exploring techniques for analyzing the interactions of cognitive radios, developing
environmental awareness maps, and MAC protocols that can trans. Virginia Tech also
maintains a publicly accessible cognitive radio wiki as part of its cognitive radio special
Additionally, Virginia Tech is organizing the MANIAC (Mobile Ad Hoc Networking
Interoperability And Cooperation) challenge wherein researchers from numerous
universities will independently design cognitive radios which will then be brought
together to “compete” to see which cognitive radio algorithms yield desirable network
behavior. A similar competitive cooperative contest is in the planning for DySPAN 2007
though details are unclear at this point.

Winlab at Rutgers University is developing a cognitive radio testbed for disaster response
using commercially available components. BWRC is currently developing a cognitive
radio for sensing and opportunistically using the spectrum. Additionally, BRWC is researching techniques for improving spectrum sensing algorithms.

1.3 Cognitive Radio Applications

Applications are often included in the definition of cognitive radio because of the compelling and unique applications afforded by cognitive radio. Additionally, there are many existing SDR techniques that cognitive radio is expected to enhance. This section reviews the following frequently advocated applications of cognitive radio some of which will be used as inspiration for example analyses later in this document:

- Improving spectrum utilization & efficiency
- Improving link reliability
- Less expensive radios
- Advanced network topologies
- Enhancing SDR techniques
- Automated radio resource management.

Figure 1.8: Cognitive Radio Applications
### 1.3.1 Improving spectrum utilization and efficiency

Wireless technologies and wireless devices have proliferated over past decade dramatically increasing the demand for electromagnetic spectrum. Because of the current approach to spectrum access, spectrum supply has not kept up with spectrum demand leading to the appearance of scarcity in the electromagnetic spectrum.

However, research performed by various entities such as the FCC indicates that this assumption is far from reality; there is available spectrum since most of the spectrum allocated sits underutilized. In a recently completed NSF funded study of allocated spectrum utilization, researchers at Kansas University found an average U.S. spectrum occupancy of 5.2% with a maximum occupancy of 13.2% in New York City. Figure 1.9 shows the specific measurements by band as averaged over the following six locations: 1. Riverbend Park, Great Falls, VA, 2. Tysons Corner, VA, 3. NSF Roof, Arlington, VA, 4. New York City, NY, 5. NRAO, Greenbank, WV, 6. SSC Roof, Vienna, VA [McHenry_05].

So while the dramatically increasing demand for spectrum has fostered a perception that spectrum is scarce, the reality is that spectrum is abundant but poorly utilized.
This underutilization is the result of a number of different factors including overly conservative allocation of guard bands; a migration from spectrally inefficient analog waveforms to more efficient digital waveforms, and the natural gaps in utilization that occur throughout the day due to variations in demand. As an example of variations in demand, Figure 1.10 shows a Matlab depiction of spectrum measurements made in Germany at Karlsruhe in a more heavily used band. As the figure illustrates there is significant variation in spectrum underutilization in time and frequency, and though not depicted, there is also significant variation in terms of location.
To improve spectrum utilization, *opportunistic spectrum utilization* has been proposed wherein devices occupy spectrum that has been left vacant. An illustrative example of opportunistic spectrum utilization is shown in Figure 1.11. In the left half of the figure, a pair of transmitted carrier signals is present in the lower frequency bands while a random access system and a TDMA system are operating in the upper bands. After observing the *spectrum holes* - points in time and frequency where spectrum is underutilized – opportunistic devices could fill in these holes to support concurrent services as illustrated in the diagram on the right.
According to the xG program manager [Marshall_05a], cognitive radios that employ opportunistic spectrum utilization have been shown to provide a 10-fold gain in capacity by implementing dynamic frequency selection algorithms.

Of course, opportunistic use of spectrum presents significant challenges to the technical and regulatory communities. From a technical perspective, the devices must be able to autonomously resolve conflicts over spectrum access and when operating opportunistically should be able to avoid interfering with incumbent signals. While avoiding introducing interference to a signal that is continuously present, it is more difficult with regularly structured, but intermittent signals such as a TDMA signal, and impossible to guarantee with a random access signal. To some extent this implies that the control processes of cognitive radios will need to be able to operate over multiple time scales as is proposed in [Moessner_05].

Since there is a technical problem, there is also a regulatory problem. Current spectrum licensees are generally only amenable to opportunistic spectrum access when they can be assured that their signals will not be degraded. Figuring out how to achieve the 10-fold gain in capacity while limiting the impact of existing services is currently a topic of much debate in the regulatory community.
1.3.2 Improving Link Reliability

After improving spectrum utilization, the second most commonly discussed application of cognitive radio is improving link reliability. Many adaptive radios currently improve link reliability by adapting transmission power levels, modulations or error correction. However, a cognitive radio that is capable of remembering and learning from its past experiences can go beyond these simple adaptations as can be shown via the following simple example.

Figure 1.12 illustrates a path that a mobile subscriber might follow on his daily commute through a particular area of a city where signal quality usually drops to an unacceptable level (shown in red) due to a coverage gap. Perhaps the first time or perhaps after several occurrences, the cognitive radio would become aware of this problem. Then via some geo-locational capability or by learning the expected time of day when this occurs, the radio could anticipate the coverage gap and signal to the base station the need to alter the signal characteristics as the user approaches the coverage gap.

![Figure 1.12 Path and associated signal quality for a cognitive radio.](image)
The same concept of detecting coverage gaps could also be employed at the base station where the base station would learn to correlate particular areas of its coverage area with a gap and then could adjust its operation (perhaps via beam forming) to eliminate the gap. Without including a cognitive base station, cognitive mobiles could share such information among themselves so that the mobiles may learn to improve their link performance without first experiencing the coverage gap. This, however, highlights another key challenge to realizing cognitive radios – how to represent the knowledge a cognitive radio needs to operate in a machine-usable and machine-to-machine translatable way.

### 1.3.3 Less Expensive Radios

While adding complexity to a radio’s control processes would appear at first glance to necessarily increase cost, the inclusion of a cognitive control process may significantly decrease device cost when cognition is enabled. To resolve this apparent paradox of adding features but reducing cost, it is important to note that many of the proposed applications of cognitive radios represent “low-hanging fruit” that can be implemented via low complexity control processes. Further, these cognitive processes would be implemented in a software defined control process for which additional computations are relatively insignificant, especially when compared to the cost of improving the performance of analog components. Adding a couple hundred software cycles per second is virtually costless; improving the performance of a RF front end by 3 dB can be a very expensive undertaking.

As noted in the preceding, the inclusion of opportunistic spectrum utilization permits significant gains in terms of capacity. Instead of only improving capacity, some of the spectrum gain could be “given” to accommodating lower performance analog components in the transmitter which generally result in signal energy outside of the intended band. These lower performance transmitter analog components can be included in the cognitive radios or among “dumb” radios.

For example consider the spectrum utilization diagram shown below in Figure 1.13 where the signal from one device exhibits significant spurious components and the

---

34
remaining cognitive devices are capable of observing this signal and adapting around these spurs. In this particular example, there would be no degradation in total informational throughout bandwidth when compared with the example considered in Figure 1.11 as all opportunistic devices are still capable of finding spectrum holes to transmit in. However, any degradation in terms of out-of-band energy necessarily decreases the available bandwidth for opportunistic spectrum utilization so some tradeoff has to be made.

![Figure 1.13: Opportunistic spectrum utilization in the presence of device with significant signal degradation.](image)

If the lower performance analog components are present only at the receiver, then there is no direct effect on the observable spectrum. However, cognitive radio processes similar to those assumed necessary for ensuring link reliability can be applied to overcome the limitations of poorly performing analog front ends. For example, adaptive beam forming
or nulling can provide additional SINR or opportunistic spectrum utilization routines could seek “deeper” spectrum holes to overcome low-Q anti-aliasing filters.

Whether included in transmitter or the receiver, cognitive radio facilitates the use of lower cost analog components. Of course, these gains can be supplemented by software radio techniques such as dithering data converter inputs and predistortion for power amplifiers.

1.3.4 Advanced network topologies

Under a MANET operational scenario, the access points or base stations do not have to maintain direct connections to the more distant regions of their clusters or cells. Instead, each base station only needs to be able to reach a handful of the closest subscribers while the devices farther from the base station gain access by communicating through a sequence of intermediate devices to reach the base station. As illustrated in Figure 1.14, in a MANET the average propagation distance for each link is much shorter than would be the case for a star topology with the same number of base stations. The shorter propagation lengths means that greater effective spectral reuse factors can be achieved which some have said would lead to a gain of up to 30 dB in system capacity [Fette_05].

Figure 1.14: Star and Ad-hoc Topologies
While the deployment and advantages of MANETs do not inherently require the use of cognitive radio, cognitive radio can be seen as an enabling technology. For a MANET to successfully operate two criteria should be satisfied. First, a high node density should be present to permit the use of lower power links. In general, the denser the network of devices is, the greater the theoretical capacity of the MANET. Second, the devices must be capable of supporting the dynamic routing and link maintenance routines required to ensure network connectivity.

As described previously in this document, cognitive radios can be used to significantly increase the usable bandwidth and decrease device cost which in turn implies that many more devices can be expected to be fielded in the future, thus implying greater device density. For the second criterion, the environmental and device awareness implicit to a cognitive radio facilitate implementation of the algorithms needed to support the MANET routing and link maintenance algorithms.

1.3.5 Collaborative Techniques
A collaborative radio is a radio that leverages the services of other radios to further its goals or the goals of the networks. As introduced in the previous section, collaborative radio can be viewed as an application of cognitive radio. However, a collaborative radio could be implemented without a full implementation of cognitive radio. For instance, many collaborative applications require only trivial learning processes. Nonetheless, cognitive radio can be viewed as an enabler of collaborative radio in that cognitive processes simplifies the identification of potential collaborators and intelligent observation processes facilitates the inclusion of distributed sensing – a characteristic of many collaborative radio applications.

One of the more frequently discussed ways in which radios can collaborate is by implementing relay channels. In a relay channel, a radio serves as an intermediate node in the path between the client device and the access node. In general, this relaying process can be implemented at the relay node by amplifying and forwarding the received signal or by decoding and forwarding the signal. In the former case, radio complexity is relatively low as the signal does not have to be received; in the latter, radio complexity is
generally much higher as the relay has to completely receive the transmitted signal. However, the added complexity incurred by a decode-and-forward approach is generally accompanied by improved performance (low latency waveforms being the most noticeable exception) so there exists a tradeoff between the two approaches.

The concept of using relay radios is currently the focus of the 802.16j workgroup which considers three types of relays: fixed relays, nomadic relays, and mobile relays. As illustrated in Figure 1.15, the relay radios in 802.16j are intended to extend the coverage of 802.16 networks where the relay nodes are intended as an extension of the 802.16 infrastructure.

Figure 1.15: Conceptual operation of 802.16j Modified from Fig 1 in IEEE 802.16mmr-05/032

While the relays in 802.16j are dedicated infrastructure installations, the existence of mobile relays (intended to support mass transportation) implies that the relaying concept should be extendable to subscriber units. While relaying with subscriber units implies that performance may be more difficult to guarantee, it should be possible to improve overall network performance and coverage with less deployment costs by judicious choice of relay nodes. However, wisely choosing which subscriber units should act as relay nodes implies some knowledge of the state of the network and the traffic and
mobility characteristics of other subscriber units in the area. For a traditional radio, this knowledge would be difficult to come by, but if the subscribers were cognitive radios then presumably the radios would be gathering and processing the relevant information as part of the normal processing.

1.3.5.1 Distributed Antenna Arrays

Of course there will be situations where a group of subscribers is out of range of an access node and no subscriber device will be positioned well enough to serve as a relay node. However, if the subscriber devices collaborate, their effective range can be dramatically increased, perhaps far enough to reach an access point.

In this form of collaboration, several radios collaborate to realize an antenna array thereby leveraging the processing gains of an antenna array without each subscriber unit needing to have its own antenna array. Because of the likely spacing of devices, it seems unlikely that beamforming will be a readily used application for a collaborative array of radios, but diversity applications should be usable. For instance, two different diversity-based collaborative antenna applications are illustrated in Figure 1.16. In a simple diversity scheme a number of radios can coordinate to transmit or receiver the same signal thereby realizing a transmit or receive diversity algorithm. With some additional coordination, those same collaborating radios could implement a MIMO, MISO, or SIMO algorithm depending on the operational context.
Particularly for the distributed MIMO/MISO/SIMO schemes and to a lesser extent the collaborative transmit and receive algorithms, good timing and localization information will be of significant aid to the performance of these algorithms. Again, the normal processes of cognitive radio may be able to provide the information necessary or perhaps this information could be collaboratively collected into some environmental map.

1.3.5.2 Distributed Mapping

Assuming radios are aware of their location and capable of making observations, it should be possible for radios to collaborate to build maps of their environment. One such map could be the radio environment map discussed in [Zhao_06] which can help inform cognitive radio adaptations. Maps targeted to the service providers and subscribers instead of the radios themselves could also be built via radio collaboration.

For instance, by collecting signal strength measurements and feeding this information back to the infrastructure, a network’s coverage map can be built. With this continually
updated coverage map, service providers can quickly identify coverage holes and take steps to rectify the problems. Assuming the network infrastructure is implemented using cognitive radio technology, these coverage holes could be automatically filled, significantly decreasing the chances of a subscriber experiencing a dropped call and improving subscriber perception of service.

As another example, suppose the mobiles are continuously returning their location information to the network’s base stations. By integrating this information, the network can get an accurate picture of its subscriber density by location. While a subscriber density map will be useful for network planning, it also implies a unique subscriber service – real time traffic maps and real time traffic updates. Specifically, when higher subscriber densities are located on roads, this should be indicative of higher density automobile traffic – information which other drivers may be willing to pay so as to avoid traffic jams. Thus by simply collecting location information from each of its subscribers, a service provider can provide a novel service of real time traffic updates.

1.3.5.3 Enhanced Security
Certain radios will tend to be used in close proximity with other radios. For instance, the various Bluetooth devices in an automobile will typically be operated with the mobile (or mobiles) of its owners onboard. By learning and recognizing the MAC addresses of the mobiles of an automobile’s owners, the automobile should be able to flag situations that are inconsistent with normal operation, for instance if the car was in operation and a different mobile than the owners’ mobiles was on board. In and of itself, this situation will not be sufficient to know that the automobile has been stolen, but it should be enough to make the situation a scenario worth further examination. Conceptually, this could be viewed as similar to the process wherein credit card companies flag purchases that do not fall into normal patterns. Similarly, this sort of information could be incorporated into an enhanced authentication system where contextual information gleaned from other authorized radios can provide degrees of authentication assuredness.
1.3.5.4 Collaborative Sensing
For many emerging wireless standards, such as 802.22, it will be important for radios to be able to detect and classify signals in its environment to ensure proper network behavior. Introductory statistics courses teach that an increasing number of independent (and unbiased) observations reduce the variance of estimated parameters. Thus the decisions as to if a signal is present and what kind of signal is present (for example is a TV broadcast present or more generally is the incumbent user transmitting) could be improved by incorporating more observations from other devices. Beyond 802.22 applications, collaborative sensing should be able to help mitigate the hidden node problem endemic to most standards.

In fact, collaborative radio itself holds the potential for numerous applications, including relay channels, distributed antenna arrays, improved localization algorithms, and collaborative mapping. However, many of these algorithms lack agreed upon models and algorithms. Without some unified approach, collaborative radios will likely go the way of networking and lack a sound theoretical basis. Lacking this theoretical basis, it will be important to construct prototypes and demonstration system before implementation or standardization can occur.

1.3.6 SDR techniques enhanced by cognitive radio
Similar to how cognitive radio will hasten the wide scale deployment of MANETs without being a requisite technology, several other techniques that require a software radio can be significantly enhanced by the use of cognitive radio. These SDR techniques include antenna array algorithms, spectrum trading, and interoperability.

Smart antenna technology is a traditionally discussed advantage of software radio. However, network performance can be greatly improved by adding environmental awareness to smart antenna algorithms. For example consider the beamforming example shown in Figure 1.17 where two links are present – one between the gray nodes and one between the white nodes. When the bottom left node chooses to implement transmit beamforming, a significant gain in performance for the gray nodes’ link can be expected.
However, from a network perspective, this choice is not desirable as the benefit accrued by the beamforming link will not be as great as the added interference that the intermediate white node will experience. However, if the gray nodes are cognizant that one of the white nodes is operating within the potential beam, then the gray nodes could choose a different adaptation that would not impact the white nodes, perhaps via a combination of spatial and frequency multiplexing.

Figure 1.17: An example of ad-hoc beam forming that would have negative effects on network performance.

Spectrum trading has long been discussed as a potential benefit of the frequency agility of software radio. In spectrum trading, different spectrum owners purchase and sell spectrum to varying service providers in response to changes in market demand. In theory – the practice of spectrum trading is in its infancy having recently received limited approval in the UK and Guatemala [Hatfield_05] and FCC approval in the US for trading among public safety users – spectrum trading facilitates the allocation of spectrum in the most efficient manner in terms of demand.

Fundamentally, the only technology required to support spectrum trading is software radio. With software radio, subscriber nodes can be instructed to change their band of operation following any spectrum trade. However, this implies spectrum trading at the service provider level which implies a process that requires weeks to months to complete. However, if each subscriber unit is capable of determining its own bandwidth
requirements, is aware of its environment and the availability of spectrum, and is capable of negotiating with service providers for bandwidth, then spectrum trading transactions could be conducted on the order of milliseconds for significantly smaller pieces of spectrum. Similarly cognitive base stations operated by service providers could quickly and dynamically shift spectral resources between providers to adjust to variations in spectral demand, significantly reducing the probability of a dropped or blocked call.

Interoperability is another frequently touted benefit of the reconfigurability of software radios. Assuming perfect reconfigurability, a software radio can be readily reprogrammed to communicate using any waveform necessary to communicate with another radio, whether the second radio is a software radio or a legacy radio. One commonly discussed technique for supporting interoperability among different legacy systems is to utilize one radio as a gateway device and automatically retransmit messages using the waveforms that each legacy device understands.

Elided in this discussion are the control processes that translate device reconfigurability into interoperability. With a software radio acting as the gateway, it is necessary for a network administrator to set up the connections between disparate legacy devices as the gateway node may have no idea of what devices are present or what connections need the services of the gateway. If a cognitive radio serves as the gateway, the cognitive radio can assume responsibility for these tasks in an automated fashion.

1.3.7 Automated Radio Resource Management
After a wireless network is deployed, wireless engineers typically spend a few weeks tuning the radio parameters to get the most out of a network. Channels allocations between sectors, call drop thresholds, power levels, timers, antenna patterns and many more parameters are all adjusted to improve network performance based on post-deployment measurements. With the increasing number of wireless networks and the movement from centralized service providers to home and office wireless LANs, the need to optimize wireless networks will become an increasingly important but will be impractical to be performed at home or in rapidly deployed networks. For instance, Virginia Tech spent months carefully planning and checking up on the deployment of its
wireless LAN in order to maximize coverage with an acceptable capacity level – an unacceptable amount of time in a disaster response scenario.

Because of its capacity to observe and learn how to improve its performance, cognitive radio networks could take over the task of post-deployment tuning and automatically update the radio parameters to best suit the needs of the particular deployment. Such an application would have a significant impact on rapidly deployed networks where emphasis, in home WLANs (which are rarely tuned), and in fixed commercial infrastructure where cognitive radio should be able to reduce the demand for post-deployment engineering.

1.4 Key Issues to Wide-Scale Deployment of Cognitive Radios

Of course there are always significant challenges accommodating revolutionary changes. First, unleashing the revolutionary changes of cognitive radio demands the development of new regulatory ideas – traditionally a glacial process. Second, programming intelligence has always been a difficult undertaking, and for the first time intelligence needs to be included in the radio. Third, many cognitive radio applications assume advanced capabilities to detect and classify signals and identify unused spectrum in a timely manner – capabilities that still need improvement. Fourth, to the extent that cognitive radio is an evolved software radio, cognitive radio will also benefit from enhanced control over the hardware, increased processing power, smaller form factors, and improved software verification techniques. Finally, autonomous adaptations of cognitive radios lead to complex interactive decision processes that make performance guarantees and network planning difficult.

Before deploying cognitive radios in a wide-scale manner, there are a number of issues that should be addressed. These include being able to predict how the interactions of cognitive radios influence network performance, addressing regulatory issues, improving environmental observational capabilities, and a number of SDR issues that are exacerbated by cognitive radio.
1.4.1 Regulatory Issues

Partially caused by the present uncertainty in predicting the effect of interacting cognitive radios and partially caused by ideological differences, how to regulate cognitive radios has emerged as a significant point of disagreement, dividing the policy community into two camps: property-rights and commons. While both camps agree that the traditional command and control model wherein spectrum is licensed for a particular application is less desirable and on the way out, there is little agreement between the two models how cognitive radios will be governed in the future.

Under the commons model (also called the unlicensed model), a pure opportunistic usage approach would be adopted wherein a cognitive radio could make use of any available spectrum that it observed. Under the property rights model (also called the exclusive-use model), entities would “own” their spectrum instead of licensing it, thus entitling them to implement different waveforms as well as subdivide their spectrum for resale to secondary spectrum users for a variety of applications including opportunistic spectrum use.

Property-rights proponents claim that the commons model will lead to a tragedy of the commons. A tragedy of the commons is a situation that can occur with a publicly-held finite resource where each person assigns receives a positive benefit from using more of the resource leading to overuse of the resource to the point of catastrophic results. Commons proponents are quick to point out that spectrum is an infinitely renewable resource so we will never run out and thus cannot experience a tragedy of the commons. However, property rights proponents respond that per unit time, spectrum is indeed finite and many apparently boundless resources have been overused when regulated with a commons approach.

Commons advocates claim that a property-rights model may limit the development of technology and could lead to a tragedy of the anti-commons wherein a small number of entities secure the rights to spectrum and exclude others from using the spectrum thus increasing the value of their spectrum and leading to underutilization of the spectrum.
However, property-rights advocates note that spectrum presumably would not be used any worse than it is now and anti-trust laws exist for handling such an anti-commons situation.

While the property-rights approach appears to have the better theoretical argument and while many incumbent service providers have explicitly stated their opposition to the commons model [Lynch_05], it is difficult to argue with the success of 802.11 which was deployed under a commons regulatory scheme in the ISM bands.

While there are significant differences between the two camps, as noted in the remarks of Andy Mudar [Mudar_05], both communities have expressed interest in a simple regulation that could ensure proper and predictable operation of cognitive radios. However, no such regulation has yet to be identified.

1.4.2 Knowledge Representation
The capability to intelligently reason about the environment implies the existence of some language that captures the knowledge that the radio has about the environment. The need for such a language formed a significant portion of the discussion in the dissertation that proposed cognitive radio. Specifically, [Mitola_00] proposed the use of a Radio Knowledge Representation Language (RKRL) to describe the knowledge a radio may have about its own capabilities and its environment.

Similarly the xG program has developed an XML-based language for representing in a declarative manner the policies that govern a cognitive radio’s actions [Berlemann_05]. In remarks at a cognitive radio panel discussion at the 2005 SDR Forum, Preston Marshall noted that this declarative language approach had shown significant success with Dynamic Frequency Selection (DFS) algorithms. However, at that same panel concern was expressed over how to validate an debug a radio whose operation is determined by a declarative language, such as Prolog, as opposed to a traditional procedural language, such as C. OWL – Web-based Ontology Language – has also been proposed as a language for representing radio knowledge in a declarative manner, but
primarily for the purpose of supporting knowledge queries between radios [Baclawski_05].

Taking an entirely different though potentially complementary route, [Mohammed_05] has shown that significant amounts of information related to cellular channels can be collected and represented using a hidden Markov models (HMM). Further, these HMMs can be used to gain context and environmental awareness by correlating HMMs generated from run-time observations with.

At this point, it is uncertain how these languages will interoperate and if the combination will provide a sufficient basis for implementing the reasoning capabilities needed for cognitive radio. Once these knowledge representation languages have crystalized, additional work is expected to be performed in the area of artificial intelligence (AI), e.g., inference machines, which will further enhance the capabilities and advantages of cognitive radio. Fortunately, however, cognitive radio does not require fully operation AI for any of the applications discussed in Section 1.3.

1.4.3 Improved Sensing Capabilities

To properly respond to changes in its environment, cognitive radios will need to be able to detect and classify the signals in its environment. If deployed in an opportunistic manner, it will be important for the cognitive radios to differentiate between primary spectrum licensees whose signals must be protected from interference and from other opportunistic signals for which less complicated measures are required. Additionally, there may be a variety of different primary signals in the same band, each of which can handle a different level of interference. For example in the UHF bands in the US which have been suggested for initial cognitive radio deployments, there are currently three primary signals that must be protected - analog TV, digital TV, and wireless microphones – with the possibility of many more in the future.

Somewhat repeating the process when spread spectrum moved from the military sphere to the commercial market, many of the needed technologies already exist, but are not publicly known. However, public researchers are now actively exploring the issue of
signal detection and classification with initial promising results from combinations of algorithms that exploit cyclostationarity properties to extract signal information and neural networks to make sense of the information [Fehske_05].

Even with the best sensing capabilities, there exists the possibility of failing to find the operating primary devices due to hidden node problems. To help combat this, a variety of solutions have been proposed [Brown_05] including maintaining spectrum usage tables, network assisted detection, and placing beacons on the primary license devices. Of these approaches, network assistance (wherein cognitive radios share their observations in the network) and spectrum usage tables (updateable by primary and secondary service providers) appear to be the most promising approaches. The IEEE 802.22 standardization committee is currently considering requiring the maintenance of spectrum usage tables as a part of its standard [Cordeiro_05].

1.4.4 Software Radio Issues
As cognitive radio is just an evolution of the software radio control processes, all software radio issues will also be issues for cognitive radio. This includes improving frequency flexibility and agility, enhancing data converter technologies and careful software architecting.

Frequency flexibility and agility is critical to successful implementation of opportunistic spectrum utilization. While MEMS controlled RF devices should soon be able to provide both high performance and rapid RF reconfiguration, an intermediate solution may be available now using FETs to implement the same switches that would be used with MEMS. [Oh_04] has proposed the use of FETs to implement reconfigurable antennas and [Domalapally_04] has proposed the use of FETs to implement reconfigurable oscillators and anti-aliasing filters. Using FET-controlled RF, cheap reconfigurable RF can be achieved now with a clear upgrade path to MEMS.

To sense available spectrum and other signals in the environment, wider bandwidth ADCs will be needed. Advances in data converter technologies appear to have accelerated recently [Le_05] so this may not be a significant limitation. Likewise
improved processors will greatly aid the development of the intelligent routines needed
the advanced topology routines, learning, and environmental models. This too appears to
be on a promising path with multiple core solutions being adopted by Intel and taken to
the logical extreme by PicoChip whose picoArray contains hundreds of ARM processors.

However, one of the more important unsolved issues facing cognitive radio is operational
validation. As is the case for software radio, validating software is an NP-complete
problem, i.e., for complete certainty in operation, every possible combination of inputs
must be tried. For a cognitive radio expected to operate in many different environments
with millions of possible adaptations, this could be a very lengthy process. While a
number of different entities have recognized the importance of developing techniques for
validating cognitive radio designs and implementations, e.g., testing for acceptable
interference is the topic of IEEE 1900.2 and software module qualification is the subject
of IEEE 1900.3, no generalizable techniques have yet been developed.

1.4.5 Interactive Cognitive Radios
While even minimally cognitive radios hold great promise, there is some concern that
cognitive radios may negatively impact network performance. While how a cognitive
radio can negatively impact network performance may not be immediately apparent from
cognition cycle shown in Figure 1.1, a more realistic diagram of the processes of a
cognitive radio in a network is shown in Figure 1.18 where cognitive radios react to both
“dumb” and cognitive radios. Specifically, many cognitive radios will be reacting to an
outside world whose state is jointly determined by the adaptations of several cognitive
radios, making any network of two or more cognitive radios an interactive decision
process.
While we intuitively understand the reaction of a cognitive radio to a collection of “dumb” radios, the interaction of a collection of cognitive radios is less clear as each cognitive radio waveform adaptation changes the state of the outside world for all the other radios. The actions of a collection of cognitive radios would then appear as a recursive interactive decision process as adaptation spawns adaptation after adaptation, perhaps infinitely as implied by Figure 1.19. Such an infinite process of adaptations makes performance guarantees difficult to make and networks nearly impossible to plan in a traditional sense. Further, while some authors have proposed having the receiver dynamically determine the adaptations of the transmitter; it seems more reasonable that any adaptations will be performed at least with the knowledge of the receiver, if not actually directed by the receiver. So an infinite recursion of adaptations may imply poor utilization of spectrum as bandwidth is consumed to signal these adaptations.
Even when these adaptations do not continue infinitely, the final state of the network might be quite undesirable. For instance, consider a single cluster DS-SS network with a centralized receiver where all nodes other than the centralized receiver are adjusting their transmitted power levels in an attempt to maximize their signal-to-interference-plus-noise ratio (SINR) as measured at the receiver. The initial state in terms of transmit power levels (blue) and SINR (green) for this network are shown in Figure 1.20. Following this implied adaptation scheme, the final state for this network is shown in Figure 1.21 where all terminals are transmitting at their maximum power levels. Clearly this is an undesirable outcome as (1) capacity is greatly diminished due to near-far problems (unless the nodes are all at the same radius from the receiver) and counter to a goal of MANET operation, (2) the resulting SINRs are unfairly distributed (the closest node will have a far superior SINR to the furthest node), and (3) battery life would be greatly shortened.
Abstracting the problem of interactive cognitive radios, consider a network of three radios where repeated adaptations define out paths in the action space (the combined set of all possible choices of waveforms by the three cognitive radios). Sometimes these paths terminate in a stable point; under different conditions the paths may enter an infinite loop. There may also be points in the action space which are fixed points of the decision update rule but are unstable as any small perturbation in initial conditions drive the network away from the point. Each of these concepts is illustrated in the example interaction diagram shown in Figure 1.22 where paths are shown by the arrows and fixed points are labeled as “NE” in reference to “Nash equilibrium” – a concept introduced in Chapter 4.
This conceptual interaction diagram illustrates the four different analysis questions that we would like to answer when considering a network of interactive cognitive radios.

- What is the expected behavior of the network?
- Does this behavior yield desirable performance?
- What conditions must be satisfied to ensure that adaptations converge to this behavior?
- Is the network stable?

To answer these questions, several researchers [Neel_06a] [MacKenzie_01] have proposed the use of game theory to analyze the interactions of autonomous adapting wireless devices.

### 1.5 Problem Statement and Research Contributions and Document Organization

This section refines the problem addressed by this work, describes the contributions made as part of this work.
1.5.1 Problem Statement

This research addresses the issue presented in Section 1.4.5 – how can we ensure that cognitive radio algorithms will behave well in a network? Tackling this issue requires us to handle three inter-related issues.

- How do we model an interactive cognitive radio network?
- How do we analyze an interactive cognitive radio network?
- How do we design an interactive cognitive radio network?

1.5.1.1 Modeling

Modeling a cognitive radio network is a non-trivial task as cognitive radios can be implemented as either procedural or ontological radios and both implementation classes may be present in a single network. Thus to accurately model a cognitive radio network, we need models that simultaneously capture the adaptations and interactions of ontological and procedural (both deterministic and non-deterministic) radios. Further this model should be amenable to a wide variety of possible networking architectures, decision timings, waveform adaptations (possibly governed by policies), and operating environments. Of course, our models should also facilitate our analysis and design efforts.

1.5.1.2 Analysis

When analyzing a cognitive radio network, the interactions of a cognitive radio network can be viewed as creating a recursion of adaptations that modify the network state. As highlighted in Section 1.4.5, we wish to be able to analyze the recursions of cognitive radio algorithms to answer the following questions.

- Will the recursion have a fixed point (steady state) and can we identify the steady-state (or steady-states) so we can anticipate performance?
- Will that performance be desirable?
- What conditions will be necessary to ensure convergence?
- Will the steady-states be stable or will the inherent variations of the wireless medium make the system unpredictable?
While we could attempt to address these issues via simulation and experimentation, this will be a very time consuming task even for limited systems considering limited scenarios. For example, in [Ginde_03], a desktop simulation of a modeled GPRS network that incorporated power and rate adaptations required days to fully simulate all possible combinations of powers and rates for a system with just seven subscriber units in a fixed position. Expanding this simulation to account for more units, different positions or even mobility would have required months of simulation time.

Instead, we would prefer to be able answer our questions in just minutes by mathematically analyzing the structure and characteristics of the interactions of cognitive radios algorithms. As such, the goal of this research is to present a methodology suitable for quickly analyzing many cognitive radio networks with interactive and recursive decision processes with a particular focus on the kinds of cognitive radio algorithms that are deployed today – transmit power control and adaptive interference avoidance.

Further, rather than effectively reinventing the wheel for each new network and algorithm, if our analysis can follow a model-based approach analytical effort can be more efficiently spent on establishing results for generalizable models and model identification criteria.

1.5.1.3 Design
If we are only able to model and analyze the interactions of cognitive radio networks, that would be a useful result in and of itself. However, the design of cognitive radio networks would remain a hit-or-miss affair as we would not know how a network would perform until we analyze it.

We would prefer to be able to leverage our insights from modeling and analyzing cognitive radio algorithms to formulate algorithm design rules that result in behavior that converges to stable desirable steady-states.
1.5.2 Research Contributions
This research presents an application-independent model of cognitive radio interactions which we can refine to application specific models dependent on the algorithms being studied. Addressing the analysis issues required the development of new models, new analysis results for contraction mappings, new applications of analysis techniques to cognitive radio algorithms, and the development of design frameworks. Techniques for analyzing procedural radios for determining steady-states, desirability, and stability are introduced based on dynamical systems, contraction mappings, and Markov chains.

A game theoretic approach is proposed for the analysis of ontological radios and this is shown to be applicable to procedural radios as well. This research also refines two attractive game models – potential games and supermodular games – so they become suitable candidates for analysis of cognitive radio algorithms which required significant work developing the theoretical convergence and stability implications of these models as well as novel identification criteria. These approaches are applied to dynamic frequency selection (DFS) and transmit power control (TPC) algorithms – the two algorithms most commonly discussed for use in cognitive radios. An additional study of a self-configuring sensor network is also presented.

These modeling and analysis results are leveraged to develop new algorithm design rules for cognitive radio networks. These rules are shown to yield cognitive radio networks that are low complexity, scalable, convergent to optimal performance, and suitable for implementation in either procedural or ontological radios.

1.5.3 Document Organization
The remainder of this document is organized as follows.

Chapter 2: Presents a model developed as part of this work suitable for modeling cognitive radio interactions. This model can be applied to all known cognitive radio algorithms and implementations and is amenable to a wide variety of analysis techniques. This model is used in all subsequent chapters.
Chapter 3: Discusses techniques for analyzing procedural cognitive radios. The chapter addresses dynamical systems theory, contraction mappings, and Markov chain theory. Techniques for establishing steady-states, optimality, convergence, and stability are presented.

Chapter 4: Describes how game theory can be used to model procedural and ontological cognitive radios. Normal form games and repeated games are covered. General game theoretic techniques for establishing steady-states, optimality, convergence, and stability are presented including the concepts of Nash equilibria (NE), Pareto optimality, and the Finite Improvement Property.

Chapter 5: Presents the theory of potential games which are particularly well suited as a design framework for ontological radios. The chapter shows how potential games simplify NE identification, introduces techniques for guaranteeing optimal performance, and exhibit broad convergence and stability conditions. Several novel game theoretic results are introduced.

Chapter 6: Leveraging potential game theory, proposes a novel framework for designing cognitive radio algorithms – the Interference Reducing Networks (IRN) framework. This framework is shown to result in behavior that minimizes sum network interference and is shown to be implementable with either procedural or ontological cognitive radios.

Chapter 7: Focuses on a particular realization of the IRN framework for Dynamic Frequency Selection (DFS) intended for implementation on procedural or ontological cognitive radios. This algorithm is a low complexity highly scalable algorithm that only requires local observations, yet reduces the interference of all cognitive radios in the network.
Chapter 8: As part of a process of introducing examples of a key game theory concept (weak FIP, this chapter presents the theory of supermodular games which are particularly well suited as a design framework for procedural radios. A commonly encountered class of ad-hoc power control algorithms is shown to be a supermodular game, and a sensor network algorithm is proposed and shown to have weak FIP.

Chapter 9: Based on the modeling and analysis covered in the preceding chapters, this chapter draws conclusions on the design and implementation of cognitive radio networks and summarizes the results of this dissertation.

Original research contributions are made in every chapter in this dissertation. Sometimes an entire chapter is an original contribution. Other chapters present theory which needed refining for application to cognitive radios. For chapters where original and previous related work are interspersed, original definitions and theorems are marked by an asterisk. Table 1.2 lists major original contributions to the modeling, analysis, and design of cognitive radio interactions made as part of this work. Papers and awards resulting from this research are listed in Chapter 9.

Table 1.2: Major Novel Contributions Made as Part of this Work

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Research Contributions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter 1</td>
<td>Definition of procedural and ontological cognitive radios.</td>
</tr>
<tr>
<td></td>
<td>Definition of waveform</td>
</tr>
<tr>
<td>Chapter 2</td>
<td>General model of cognitive radio interactions</td>
</tr>
<tr>
<td>Chapter 3</td>
<td>Application of dynamical systems to the analysis of procedural radios</td>
</tr>
<tr>
<td></td>
<td>Stability of standard interference function (SIF)</td>
</tr>
<tr>
<td></td>
<td>Application of SIF to ad-hoc networks</td>
</tr>
<tr>
<td>Chapter 4</td>
<td>Application of game theory to cognitive radios</td>
</tr>
<tr>
<td></td>
<td>General game model of cognitive radio networks</td>
</tr>
<tr>
<td></td>
<td>Novel random better response algorithm with broader convergence conditions</td>
</tr>
<tr>
<td></td>
<td>Convergence analysis for basic game theoretic properties under different decision timings</td>
</tr>
<tr>
<td></td>
<td>Ergodic Markov chain model of noisy cognitive radio networks</td>
</tr>
<tr>
<td></td>
<td>Necessary condition for convergence of myopic rational cognitive radios</td>
</tr>
<tr>
<td>Chapter 5</td>
<td>Application of potential games to wireless network design</td>
</tr>
<tr>
<td></td>
<td>Multilateral Symmetric Interference Games</td>
</tr>
<tr>
<td></td>
<td>Identification of ordinal potential games via better response</td>
</tr>
</tbody>
</table>
transformations
Convergence of round-robin/random better response algorithms for potential games with infinite action spaces
Convergence of asynchronous better response algorithms for finite action spaces
Stability of potential games for discrete time adaptations

Chapter 6
Interference Reducing Network (IRN) design framework
Global altruism algorithm
Local altruism algorithm
Bilateral Symmetric Interference identification condition
General algorithm for implementing an IRN in an isolated cluster
Close proximity algorithm
Impact of legacy devices

Chapter 7
Novel Dynamic Frequency Selection algorithm for ad-hoc networks and its performance under non-ideal circumstances

Chapter 8
Condition for uniqueness and stability of supermodular games
A convergence proof of typical ad-hoc TPC algorithms
Novel sensor network formation algorithm

1.6 References


[Harris] RF-300M-HH brochure http://www.rfcomm.harris.com/jtrs/RF-300M-HH.pdf


