Chapter 9: Conclusions

"<What good is it if it means nothing?>" - O. Card, Xenocide

In *Xenocide* four different sentient alien species come to inhabit the same planet, one of which is human at one point two aliens from different species discuss why humans dream. One completely fails to see the point while the other thinks that dreaming is the key to humanity's creativity and thus to humanity's success as a species.

This dissertation is intended to formalize the modeling and analysis of cognitive radio networks and from this formalization draw insights into how cognitive radios should be designed. Because of its heavy reliance on game theory, responses to this research over the last several years have almost exclusively fallen into two very different categories. Like the aliens contemplating dreaming in humans, either the research is viewed as absolutely critical to the success of cognitive radio or it is viewed as little better than a creative, but useless, intellectual exercise.

For many situations, the latter view has merit. What good is game theory if we can do the same analysis with traditional techniques? What algorithm has been designed with game theory that couldn't be done using more traditional means? Why do we care about the goals of the radio at all? What does game theory bring to cognitive radio?

Strictly, every algorithm we analyzed in the previous four chapters could have been analyzed using more traditional techniques. We could've shown convergence of our algorithm in Chapter 7 using techniques from Zangwill's convergence theorem. We could've shown the stability of the power control algorithms in Chapter 5 with only a direct application of Lyapunov's theorem. We could show the existence of steady-states via more direct fixed point theorems. We could just as well cast each algorithm as a distributed controls (or dynamical systems) problem and use the evolution function and techniques of Chapter 3 to evaluate steady-states, convergence, and stability of the algorithm we are studying.

In response, we can point to the analysis and design benefits of a game theoretic listed in the following.

1) *Suitability for ontological and random procedural radios*

For ontological cognitive radios and procedural cognitive radios whose decision rules incorporate a degree of randomness, it is not generally possible to express the network behavior in terms of an evolution function needed for traditional analysis as the same input may produce very different outputs. Further, in the case of ontological radios we may only know the radio's available actions and its goal.

Lacking an evolution function, the dynamical systems and the contraction mappings approaches considered in Chapter 3 will be insufficient for modeling or analyzing these systems. At least for genetic algorithms, the network could be modeled and then analyzed using Markov models. However, any useful transition matrix would have to be determined empirically – the very process we are seeking to avoid. So if we were limited to traditional engineering analysis techniques, modeling and analyzing of most cognitive radio network behavior would be impractical.

Thus the techniques presented in this document permit us to analyze a problem which we could not handle with traditional approaches.

2) *More Efficient Analysis*

If we solve for a fixed point of an evolution function, we have identified a steady-state for a particular combination of decision rules. If a different combination of decision rules is deployed, then the analysis will need to be repeated.

On its own, this does not seem like a significant burden. But consider the deployment of cognitive radios in unlicensed bands – the location where cognitive radio (in the form of 802.11h) is already being deployed. One of the benefits of opening up unlicensed spectrum is that it permits the fielding of numerous different devices from different vendors which drive down prices for consumers. To differentiate their products different vendors typically employ different algorithms – permissible as wireless standards frequently do not specify radio resource management algorithms. For instance, while 802.22 specifies times within which a radio has to vacate a band when a primary user is detected, it does not currently specify the algorithm by which a new band is selected. Likewise 802.11h mandates DFS and TPC and specifies messages to support these operations, the algorithms by which frequency and power are adjusted are not specified.

Considering just 802.11h, in July 2006, the WiFi alliance already listed 13 different vendors and 72 different products for 802.11h. If the WiFi alliance, the FCC, or any radio designer wanted to ensure that all WiFi certified 802.11h products will not negatively interact, they would have some 2^{13} -1 combinations of decision rules to analyze if every vendor used their own algorithm.

Using game theoretic techniques, we only need to know the goals of the radios and the permissible actions, with the latter almost certainly defined as part of any standard, in order to determine the steady-states using the Nash equilibria concept. Thus instead of performing an 2^{13} -1 analyses for 802.11h, only a single analysis would need to be performed – meaning that only 1/8191 as much effort needs to be expended!

3) *Simplified Spectrum Management of Cognitive Radios*

The preceding implies another advantage of a game theoretic approach to analysis – simplified spectrum management. If the FCC or some primary spectrum holder specifies a particular combination of goals and allowable actions as part of a licensing agreement, then device testing can be simplified to merely verifying that the radio's algorithms act to increase one of the allowable goals.

Currently spectrum policy focuses solely on a specification of permissible actions (e.g., a spectral mask), but it seems likely that an additional specification of permissible goals would be sufficient to ensure acceptable performance while still permitting vendors and secondary users to use varying decision rules to differentiate their products.

Additionally, a predominately game theoretic approach permitted us to make the analysis and design insights listed in Sections 9.1 and 9.2. Section 9.3 reviews the research contributions presented in this dissertation, and the chapter concludes in Section 9.4 by identifying avenues for future research and describing additional planned publications.

9.1 Modeling and Analysis Summary

Using the model based approach to analysis proposed by this research, an analyst is able to immediately determine detailed information about steady-states, convergence, and stability simply by applying simple model identification criteria to the cognitive radio network. This will enable future cognitive radio network analysts to know within minutes the results this document showed over hundreds of pages. This approach should be able to cut months to years of man-hours off of the design cycle for novice cognitive radio algorithm designers (which virtually everyone is at this moment) and likely days for more experienced designers.

The set of models span all known cognitive radio implementation platforms (procedural, ontological, and nondeterministic procedural) and include dynamical systems, contraction mappings, standard interference functions, Markov models, potential games, and supermodular games. These models and the techniques for establishing if a cognitive radio network satisfies the conditions of the model are summarized in Table 9.1.

Table 9.1: Presented Models

Model	Basic model	Identification
Dynamical System	$\dot{a} = g(a,t)$, evolution equation $a(t^{k+1}) = d^t(a(t^k))$	$\dot{a} = g(a,t)$ always exists Solve g for d^t. d^t exists if g satisfies Picard-Lindelöf theorem
Contraction Mapping	$\Vert d(a), d(b) \Vert \leq \alpha \Vert a,b \Vert$ $\forall b, a \in A$	Blackwell's conditions
Standard Interference Function Power Control	$d_j(\mathbf{p}(t^k)) = p_j(t^k) I_j(\mathbf{p}(t^k))$	$I(\mathbf{p})$ satisfies positivity, montonicity, and scalability
Finite Ergodic Markov Chain	$P(a(t^{k+1}) = a^k \mid a(0),\ldots,a(t))$ $= P(a(t^{k+1}) = a^k \mid a(t^k))$	$\exists\, k$ such that $\mathbf{P}^k$ has all positive entries
Absorbing Markov Chain	$\mathbf{P}' = \left[\begin{array}{c\|c} \mathbf{Q} & \mathbf{R} \\ \hline \mathbf{0} & \mathbf{I}^{ab} \end{array}\right]$	Apply model definition
Normal Form Game	$\Gamma = \langle N, A, \{u_j\} \rangle$	Map from cognition cycle
Mixed Strategy Strategic Form Game	$\Gamma = \langle N, \Delta(A), \{U_j\} \rangle$	Map from cognition cycle
Repeated Game	$\Gamma = \langle N, A, \{u_j\}, \{d_j\} \rangle$	Map from cognition cycle
Myopic Repeated Game	$\Gamma = \langle N, A, \{u_j\}, \{d_j\}, T \rangle$	Map from cognition cycle
Potential Game	$\Delta u_i(a, b_i)$ everywhere related to $\Delta V(a, b_i)$	$\frac{\partial^2 u_i(a)}{\partial a_i \partial a_j} = \frac{\partial^2 u_j(a)}{\partial a_j \partial a_i}$ (others in Chapter)
Supermodular Game	(1) A_i is a complete lattice; (2) u_i is supermodular in a_i; and (3) u_i has increasing differences in (a_i, a_{-i})	(1) A_i is a closed interval in $\mathbb{R}^{k_i}$, (2) u_i is twice continuously differentiable on A_i (3) $\partial^2 u_i / \partial a_{ik} \partial a_{im} \geq 0$ for all $i \in N$ and all $1 \leq k < m \leq k_i$ (4) $\partial^2 u_i / \partial a_{ik} \partial a_{jm} \geq 0$ for all $i \neq j \in N, 1 \leq k \leq k_i$ and $1 \leq m \leq k_j$

For these game models, this chapter presented analysis insights that can be gleaned by demonstrating that a cognitive radio network satisfies the modeling conditions for one of the models listed in Table 9.1. The steady-state properties, the convergence properties, and the stability properties for each of these models are summarized in Table 9.2 Table 9.3, and Table 9.4, respectively. As we saw in Section 15.5.2, sometimes cognitive radio networks satisfy the conditions of multiple models. In these cases, the analytic insights from each of the applicable multiple models are available.

Table 9.2 Steady-State Properties by Model

Model	Existence	Identification
Dynamical System	Maybe, evaluate Leray-Schauder-Tychonoff theorem on evolution equation	Exhaustive Search Solve $a^* = d\left(a^*\right)$
Contraction Mappings	Yes (Banach's Theorem)	Recursion (Unique steady-state)
Standard Interference Function Power Control	Yes ([Yates_95])	Recursion (Unique steady-state), $\mathbf{Zp} = \vec{g}$
Finite Ergodic Markov Chain	Yes (Ergodocity theorem)	Recursion (Unique distribution), Solve $p^{*T}\mathbf{P} = p^{*T}$
Absorbing Markov Chain	Yes (Definition)	$p_{mm} = 1$
Normal Form Game	Maybe, evaluate Glicksberg-Fan theorem on cognitive radio goals	Exhaustive Search Solve $a^* = \hat{B}\left(a^*\right)$
Mixed Strategy Strategic Form Games	Yes for A finite (Nash's Fixed Point Theorem)	Solve $a^* = \hat{B}\left(a^*\right)$
Repeated Game	Maybe, evaluate Glicksberg-Fan theorem on cognitive radio goals, or evaluate for feasible enforced equilibria (numerous typically exist)	Exhaustive Search Solve $a^* = \hat{B}\left(a^*\right)$ Feasible enforced equilibrium
Myopic Repeated Game	Maybe, evaluate Glicksberg-Fan theorem on cognitive radio goals	Exhaustive Search Solve $a^* = \hat{B}\left(a^*\right)$
Potential Game	Yes, if A is compact and V bounded	$\underset{a \in A}{\operatorname{argmax}}\, V(a)$
Supermodular Game	Yes	Exhaustive Search (must lie in a lattice) Solve $a^* = \hat{B}\left(a^*\right)$

Table 9.3: Convergence Properties by Model

Model	Sensitivity	Rate
Dynamical Systems	Apply Lyapunov's direct method (when possible)	No general technique
Contraction Mappings	Everywhere convergent	$\left\| a\left(t^k\right), a^* \right\| \le \frac{\alpha^k}{1-\alpha} \left\| a\left(t^1\right), a\left(t^0\right) \right\|$
Standard Interference Function Power Control	Everywhere convergent	$\left\| \mathbf{p}\left(t^k\right), \mathbf{p}^* \right\| \le \alpha^k \left\| \mathbf{p}(0), \mathbf{p}^* \right\|$
Finite Ergodic Markov Chain	Converges to distribution from all starting distributions	Transition matrix dependent
Absorbing Markov Chain	$\mathbf{B} = \mathbf{NR}$	$\mathbf{t} = \mathbf{N1}$
Normal Form Game	Convergence not defined	Convergence not defined
Mixed Strategy Strategic Form Games	Convergence not defined	Convergence not defined
Repeated Game	Assumes no adaptations	Assumes no adaptations
Myopic Repeated Game	Apply IESDS, FIP, weak FIP	Length of longest improvement path
Potential Game	All autonomously rational decision rules converge	Length of longest improvement path
Supermodular Game	All locally optimal decision rules converge	Length of longest improvement path

Table 9.4: Stability Properties by Model

Model	Lyapunov Stability	Attractivity
Dynamical Systems	Apply Lyapunov's direct method (when possible)	Apply Lyapunov's direct method (when possible)
Contraction Mappings	Global	Global
Standard Interference Function Power Control	Global	Global
Finite Ergodic Markov Chain	No	No
Absorbing Markov Chain	No	Only if unique steady-state
Normal Form Game	Stability not defined	Stability not defined
Mixed Strategy Strategic Form Games	Stability not defined	Stability not defined
Repeated Game (assuming correct differentiation of punishment and deviation)	Yes	Yes
Myopic Repeated Game	Not implicit to model	Not implicit to model
Potential Game	Isolated potential maximizers are Lyapunov stable for all rational decision rules.	Attractive to potential maximizers if finite action space or finite step size.
Supermodular Game	Best response decision rules if unique NE	Best response decision rules if unique NE

We also presented two different model independent approaches to determining the desirability of network behavior – Pareto optimality and evaluation of a network objective function. Showing that a network state is Pareto optimal was shown to be of less value than demonstrating that the state maximized the intended network objective function.

We must also acknowledge certain analytical difficulties that arise when information is limited. We may not be able to precisely describe a network's evolution function pre-deployment if decision processes and goals evolve to better reflect a user's preferences. A radio's available actions may also evolve in time to incorporate new waveforms that we could not anticipate ahead of time. From an analysis perspective, this situation can be analogized to attempting to solve a system of equations of unknown order with unknown coefficients and an unknown number of variables. This indicates that much caution should be taken before deploying radios for which we do not know a priori the radios' actions or the goals. Perhaps, it will be possible to broadly classify the decision update processes action sets, and goals based on what is known about the implementation of the radios. In which case a game theoretic preference approach should be able to address this situation, but barring this condition, analysis of such a system currently appears intractable.

9.2 Design Summary

Leveraging the modeling and analysis techniques, we were able to develop new algorithms, design guidelines, and insights into cognitive radio design issues. Specific algorithms for general waveform adaptation, power control, and sensor network formation were proposed, analyzed, and shown to have desirable steady-state, convergence and stability properties.

The proposed interference reducing network (IRN) design framework ensures that loner radios (procedural or ontological) converge to an interference minimizing steady state under the scenarios of global altruism, local altruism, isolated clusters, close proximity, and with controlled observations. This framework achieves these results by ensuring that the network constitutes an exact potential game whose potential function is a negated scalar multiple of the sum network interference, thereby allowing us to leverage the steady-state, convergence, and stability results of Chapter 5 and adding an assurance of a desirable equilibrium.

The global and local altruism IRNs wherein each radio's interference minimization goal incorporates other radios' interference observations were seen to be applicable to any waveform adaptation algorithm, but to scale badly. By ensuring that the network satisfied bilateral symmetric interference, it was seen that loner radios would implement an IRN for the isolated cluster, close proximity, and controlled observation scenarios. These last three scenarios require no coordination between cognitive radios to ensure interference minimization implying that in these scenarios low network overhead, low device complexity algorithms realize an IRN.

It was seen that waveform adaptation algorithms will frequently have non-isolated NE, so stabilization requires the radios employ ε-better response algorithms. It was also seen that if certain assumptions were made about legacy systems then the network consisting of legacy radios and cognitive radios would still comprise an interference reducing network and that even when these assumptions fail, the self-interested adaptations of the cognitive radios would generally reduce the interference experienced by the legacy systems.

The IRN design framework was leveraged to develop a new dynamic frequency selection (DFS) algorithm for 802.11h. By requiring the access points to observe the RTS/CTS messages of other access points to guide their decision process, bilateral symmetric interference is achieved and an IRN results without any additional coordination between access points and as long as the access points act to reduce their own observed interference. It was analytically shown that this algorithm performs well under a variety of relaxed assumptions including policy variations, the presence of legacy radios, noise corrupted observations, private frequency preferences, and asynchronous timings, and empirically shown to perform well different access points transmit their RTS/CTS signals at different power levels within the same channel.

Numerous design inferences were also drawn from analysis. It was seen that a network of myopic loner radios cannot be guaranteed to converge under autonomous rationality unless the underlying game has weak FIP. It was seen that guaranteeing the convergence of arbitrary ontological radios under autonomous rationality requires the underlying game to have FIP. Potential games ensure permit the lowest complexity loner radio algorithms to converge. For radios with a finite set of available adaptations, it was seen that incorporating randomness into the decision rules ensures convergence over the broadest set of conditions but that well designed procedures will generally converge faster. This implies that the genetic algorithm implementation approaches being considered by various researchers will be an excellent choice when the radio must operate in broad set of scenarios.

The ubiquitous presence of unbounded noise informs us that cognitive radio networks will always constitute ergodic Markov chains, but we do know identified NE will still have a relatively higher probability of being occupied and that frequently many states will have an extremely small probability of being occupied making the occupancy of certain states a theoretical, though generally not a practical, concern. Noise, however, is a more serious problem for social radios which try to influence the adaptations of other radios via punishment as noise ensures eventual catastrophic failure if the network does not include some additional mechanism to differentiate between punishment and deviation. It was also seen that the ability to negotiate will be critical to the deployment of social radios due to the variances of goals and adaptations likely to be encountered.

9.3 Research Contributions

The primary goal of this research was to develop a methodology for analyzing the interactions of cognitive radios with a particular interest in addressing the identification of steady-states, the optimality of those steady-states, the conditions for convergence, and the stability of the cognitive radio algorithms. Achieving this goal required the refinement of game theoretic concepts and techniques, the identification of typical cognitive radio applications that satisfy the conditions of these models, and the development of simulations to verify the analytic results implied by this methodology.

Original research contributions are made in every chapter in this dissertation and are highlighted in Table 9.5.

Table 9.5: Major Novel Contributions Made as Part of this Work

Chapter	Research Contributions
Chapter 1	Definition of procedural and ontological cognitive radios. Definition of waveform
Chapter 2	General model of cognitive radio interactions
Chapter 3	Application of dynamical systems to the analysis of procedural radios Stability of standard interference function (SIF) Application of SIF to ad-hoc networks
Chapter 4	Application of game theory to cognitive radios General game model of cognitive radio networks Novel random better response algorithm with broader convergence conditions Convergence analysis for basic game theoretic properties under different

	decision timings Ergodic Markov chain model of noisy cognitive radio networks Necessary condition for convergence of myopic rational cognitive radios
Chapter 5	Application of potential games to wireless network design Multilateral Symmetric Interference Games Identification of ordinal potential games via better response 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

Another objective of this research was developing, standardizing, and popularizing techniques for analyzing and designing cognitive radio networks. Beyond influencing the direction of many other researchers at Virginia Tech, this work has also had a significant impact on the work of cognitive radio researchers throughout the world. The following sections list the publications generated as part of this work and external citations of these publications.

9.3.1 Publications

The following is a listing of publications that have been created as part of the research presented in this document. The list includes two award winning papers, one chapter in the first textbook on cognitive radio, two journal papers, and one magazine article.

1) [submitted] J. Neel, R. Menon, A. MacKenzie, J. Reed, R. Gilles, "Interference Reducing Networks," submitted to *IEEE JSAC on Adaptive, Spectrum Agile, and Cognitive Wireless Networks.*

2) [accepted] J. Neel, J. Reed, "Situational Awareness for Cognitive Radios," Submitted to *SDR Forum 2006*.

3) [accepted] J. Neel, J. Reed, Performance of Distributed Dynamic Frequency Selection Schemes for Interference Reducing Networks," Accepted to *Milcom 2006* Oct. 23-25, 2006.

4) J. Neel, J. Reed, A. MacKenzie, "Analyzing Cognitive Radio Networks" in **Cognitive Radio Technology**, ed. B. Fette, Elsevier Publications, August 11, 2006.

5) V. Srivastava, J. Neel, A. MacKenzie, J. Hicks, L.A. DaSilva, J.H. Reed and R. Gilles, "Using Game Theory to Analyze Wireless Ad Hoc Networks," *IEEE Communications Surveys and Tutorials* 4th quarter 2005, vol. 7, no 4, pp. 46-54.

6) J. Neel, "Game theory can be used to analyze cognitive radio," *EE Times*, August 29, 2005.

7) J. Neel, R. Menon, A. MacKenzie, J. Reed, "Using Game Theory to Aid the Design of Physical Layer Cognitive Radio Algorithms," accepted on basis of abstract to *Conference on Economics, Technology and Policy of Unlicensed Spectrum*, May 16-17 2005, Lansing, Michigan.

8) J. Hicks, A. MacKenzie, J. Neel, J. Reed, "A Game Theory Perspective on Interference Avoidance," *Globecom 2004*, November 29 - December 3, 2004.

9) [Named outstanding paper] J. Neel, J. Reed, R. Gilles, "Game Models for Cognitive Radio Analysis," *SDR Forum 2004 Technical Conference*, November 2004.

10) J. Neel, J. Reed, and R. Gilles, **"**Convergence of Cognitive Radio Networks," *WCNC2004*, March 25, 2004.

11) S. Ginde, R. Buehrer, and J. Neel, "A Game Theoretic Analysis of the GPRS Adaptive Modulation Schemes," *Fall VTC 2003*.

12) [Named outstanding paper] J. Neel, J. Reed, R. Gilles, "The Role of Game Theory in the Analysis of Software Radio Networks," *SDR Forum Technical Conference* November, 2002.

13) J. Neel, R. Buehrer, J. Reed, and R. Gilles, "Game Theoretic Analysis of a Network of Cognitive Radios," *Midwest Symposium on Circuits and Systems 2002*.

9.3.2 External Citations

Despite having a very narrow window for citations to appear, the publications generated as part of this research have already been cited in several publications, classes, and proposals. The following lists works generated as part of this project and publications that cited those works from authors external to Virginia Tech – a reasonable metric for determining the extent which this research is influencing others' research around the world.

Publication: J. Neel, R. Menon, A. MacKenzie, J. Reed, "Using Game Theory to Aid the Design of Physical Layer Cognitive Radio Algorithms," accepted on basis of abstract to *Conference on Economics, Technology and Policy of Unlicensed Spectrum*, May 16-17 2005, Lansing, Michigan.

1) W. Lehr, "Managing shared access to a spectrum commons," *DySPAN 2005*, pp. 420-444, Nov. 8-11, 2005.

Publication: J. Hicks, A. MacKenzie, J.Neel, J. Reed, "A game theory perspective on interference avoidance", *GLOBECOM 2004*, pp. 257-261.

2) A. Fridman, R. Grote, S. Weber, K. Dandekar, M. Kam, "Robust optimal power control for ad hoc networks," *2006 Conference on Information Sciences and Systems*, Princeton University, March 22–24, 2006.
3) C. Liang, K. Dandekar, "Power Management in MIMO Ad Hoc Network: A Game-Theoretic Approach," Submitted to *IEEE Transactions on Wireless Communications* (http://www.ece.drexel.edu/faculty/dandekar/Papers/Liang_WirelessComm05.pdf)

Publication: J. Neel, J. H. Reed, R. P. Gilles, "Game Models for Cognitive Radio Algorithm Analysis," *SDR Forum 2004 Technical Conference*, November, 2004.

4) R. Nuti, "Criteri distribuiti di allocazione delle risorse nelle reti wireless ad hoc," PhD Dissertation, University of Pisa, Oct 2005.

Publication: J. Neel, J. Reed, R. Gilles "Convergence of Cognitive Radio Networks," *Wireless Communications and Networking Conference*, March 2004.

5) S. Seidel, R. Breinig, "Autonomous Dynamic Spectrum Access System Behavior and Performance," *DySPAN 2005*, Nov, 2005.
6) G. Scutari, S. Barbarossa, D. P. Palomar, "Potential Games: A Framework for Vector Power Control Problems with Coupled Constraints," *ICASSP 2006* vol. 4, pp. 241-244, May 2006.
7) N. Nie, C. Comaniciu, "Adaptive Channel Allocation Spectrum Etiquette for Cognitive Radio Networks,: to appear in *ACM MONET* (Mobile Networks and Applications), special issue on "Reconfigurable Radio Technologies in Support of Ubiquitous Seamless Computing", 2006
8) T. Martin, K. Chang, "A distributed data fusion approach for mobile ad hoc networks," *Information Fusion, 2005* **8th International Conference on** vol.2 pp. 1062-1069, July 25-28 2005.

Publication: J. Neel, "How does game theory apply to radio resource management?" PhD. Qualifier, Virginia Tech, Jan 2004.

9) P. Khaskel, "PHY layer access misbehavior in WLAN networks: A game theoretical approach," Master's Thesis, KTH Stockholm, Sweden November 2005.

Publication: J. Neel, J. Reed, R. Gilles, "The Role of Game Theory in the Analysis of Software Radio Networks," *SDR Forum Technical Conference* November, 2002.

10) F. Jondral, "Software-defined radio: basics and evolution to cognitive radio" *EURASIP Journal on Wireless Communications and Networking* vol. 5, issue 3, pp. 275-283, Aug. 2005.
11) N. Nie, C. Comaniciu, "Adaptive channel allocation spectrum etiquette for cognitive radio networks," *DySPAN2005*, Nov. 2005 pp. 269-278.
12) J. Mitola, "Cognitive INFOSEC," *Microwave Symposium Digest*, 2003, vol. 2, pp. 1051 – 1054, June 8-13 2003.

Publication: J. Neel, R. Buehrer, J. Reed, and R. Gilles, "Game Theoretic Analysis of a Network of Cognitive Radios," *Midwest Symposium on Circuits and Systems 2002*.

13) W. Krenik, A. Batra, "Cognitive Radio Techniques for Wide Area Networks," *DAC 2005*, pp. 409-412, June 13–17, 2005, Anaheim, California, USA.
14) J. Huang, "Wireless Resource Allocation: Auctions, Games and Optimization," PhD Dissertation, Northwestern 2005. (http://www.princeton.edu/~jianweih/publication/Huang_thesis_scaled.pdf)
15) F. Granelli, H. Zhang, X. Zhou, S. Maran, "Research advances in cognitive ultra wide band radio and their application to sensor networks," *Mobile Network Applications,* vol 11, pp. 487-499, May 2006.

9.4 Future Work

While this document made an extensive presentation of techniques for the modeling, analysis, and design of cognitive radio networks, this is far from an exhaustive treatment of all cognitive radio algorithms. This section presents topics of research that still should be addressed beyond the interference avoidance, node participation, and topology control applications being developed for the ONR project and the ongoing cognitive radio research a Virginia Tech and additional publications planned based on the material presented in this document.

9.4.1 Research Topics

The following lists some of the research topics identified in the body of this document that merit further research.

Joint power/frequency adaptation

The target SINR utility function appears to be an attractive algorithm for power control and frequency adaptations. To date all simulations of these algorithms have converged under numerous decision rules, but no theoretical basis for this is known. It may be that as we saw with DFS and legacy radios that there exist conditions that confound application of the game models but that these conditions are empirically rare.

Modeling and analyzing network routing

To an extent the queues used in the routers in the internet can be analogized to facilities which under IPV4 all devices experience approximately equally. Loosely, the choice of routes dictates the choice of "facilities" indicating that this problem should be susceptible to potential game analysis.

Asymmetric potential games

Designing the IRN framework and the IRN DFS algorithms required that we identify and exploit symmetry conditions implicit to BSI games. To make such an approach more generalizable, it would be valuable to characterize how much asymmetry can be introduced to BSI and congestion games while still preserving the important convergence and stability properties of potential games. For example under what conditions would positive correlation of interaction terms or facility benefits be sufficient to imply an ordinal potential game? Would scaling these terms by a common factor yield a weighted potential game?

Cross-layer algorithms

In general the work presented in this document (and the work being performed as part of the ONR project) focused on single layer and single parameter algorithms. In general, we can treat adaptations over numerous parameters simply as more complex actions and then apply the techniques presented in this document. However, this research will likely be delayed by the immaturity of theoretical expressions of cross-layer problems as without a well-defined mapping from actions to outcomes, analysis is not possible.

Standards Applications

Development of algorithms that explicitly account for the implementation details of specific standards should hasten the deployment of cognitive radios. For instance, this could consider DFS / power control in an 802.22 setting and network formation algorithms for 802.11s.

Scenario Classification

As we saw different operational scenarios can be modeled as different game models which imply different algorithms are preferable. The capacity to recognize which scenario a radio is operating under should significantly enhance the performance of cognitive radio networks.

Bargaining Algorithms for Cognitive Radio

As we saw in Chapter 4, the implementation of punishment algorithms in cognitive radio networks should be accompanied by a negotiation capability because of the diverse combination of goals, operating conditions, and capabilities. Properly designed bargaining algorithms could simplify this problem and enhance the attractiveness of social radio networks.

Differentiating punishment from deviation

Punishment algorithms are doomed to catastrophic failure when they are unable to differentiate between punishments and deviations from an agreed operating point. Development of generalized and specific techniques for performing this will also enhance the attractiveness of social radio networks.

9.4.2 Planned Publications

The following is a listing and brief description of publications intended for submission to either a journal or a magazine after submission of this document based on material presented in this document.

1) *"Novel Dynamic Frequency Selection Algorithms"*

   This will be an extended treatment of the Milcom DFS paper including the additional material presented in Chapter 7.

2) *"Game Theoretic Insights into the Design of Cognitive Radio Networks"*

   Throughout this document, game theory has been leveraged to provide valuable insights into the design of cognitive radio networks. These will be collected into a single document with justification of these insights.

3) *"Potential Games in Wireless Networks"*

This paper will summarize the various insights that can be gained by applying potential games to cognitive radio networks and present some of the applications included in this report such as DFS, power control and waveform adaptation as well as others not included in this document such as network selection.

4) *“An Algorithm for Distributed Sensor Network Formation”*

   This paper will present the analytic sensor network formation presented in Chapter 8.

5) *“Convergence and Stability of Games with FIP and Weak FIP”*

   Intended for an economics journal, this research necessitated the development of numerous new results related to the convergence and stability implications of FIP, weak FIP, potential games, and supermodular games.

6) *“Identification of Ordinal Potential Games”*

   Intended as an economics letter, this will present the novel technique for identifying ordinal potential games developed as part of this research presented in Chapter 5.

Additionally, this document is intended to serve as the core for a text book on modeling, analyzing, and designing cognitive radio networks.