2015

A Trust-Based Relay Selection Approach to the Multi-Hop Network Formation Problem in Cognitive Radio Networks

Brandy Michelle Tyson
Louisiana State University and Agricultural and Mechanical College

A TRUST-BASED RELAY SELECTION APPROACH TO THE MULTI-HOP NETWORK FORMATION PROBLEM IN COGNITIVE RADIO NETWORKS

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

in

The School of Electrical Engineering & Computer Science
The Division of Computer Science and Engineering

by
Brandy Michelle Tyson
B.S., Southern University and A&M College, 2001
M.S., Southern University and A&M College, 2003
August 2015

I dedicate my dissertation to my family and friends. Thank you for your prayers and patience as I pursued this lifelong dream. I could not have fulfilled this goal without your faith, encouragement, and advice. To you, I owe a couple of my letters.

ACKNOWLEDGMENTS

It is with great pleasure and zest that I express my sincere gratitude to everyone that has been present, both physically and emotionally, for me during this journey. Your support has made this a most rewarding experience.

I would like to thank Dr. Rajgopal Kannan, my committee chair, for his guidance and support throughout this research. He truly challenged me to create a work that I am proud of. I am thankful for his wisdom in allowing Dr. Sonja Wiley to guide me in his absence. I am deeply grateful for Dr. Sonja Wiley's insight, reassurance, and prayers. In addition, I would like to acknowledge my appreciation for committee members, Dr. Kevin McCarter and Dr. Konstantin Busch. I would never have been able to finish my dissertation without the guidance of my committee and their commitment to me, as a graduate student.

I would also like to thank Ms. Maggie Edwards, Mrs. Vera Watkins, and the Graduate School for their dedication and faith in me throughout the years.

I want to thank all of my family and friends for their love, generosity, and prayers. I have not been the easiest person to deal with throughout this process. Thank you for tolerating me. You too have made this dream a reality.

Lastly, I wish to express my deepest appreciation for my children, Caleb and Kaelin. You are my inspiration. I hope that I have made you proud.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

DEFINITIONS

1. *PT*: the primary transmitter
2. *PR*: the primary receiver
3. *SU*: a secondary user
4. *ITT*: the interference temperature threshold
5. P_I: the average interference power in Watts centered at m
6. m: a given measurement point
7. W: bandwidth measured in Hertz
8. k: Boltzmann's constant, 1.38 x 10^{-23} Joules per Kelvin degree
9. a: the effective communication area (ECA) for primary user 1
10. b: the effective communication area (ECA) for primary user 2
11. x_a: the measurement point for ECA a
12. x_b: the measurement point for ECA b
13. T: the interference temperature threshold for a certain ECA
14. T_a: the interference temperature threshold for primary user 1
15. T_b: the interference temperature threshold for primary user 2
16. p_i: user i's transmit power
17. p_i^{min}: user i's minimum transmit power
18. p_i^{max}: user i's maximum transmit power
19. P_i: user i's achievable power
20. N: the total number of secondary users
21. n: the number of secondary users interfering with the primary transmitter
22. N-n: the number of secondary users interfering with the primary receiver
23. g_{ij}: the link gain from user i's transmitter to user j's receiver
24. g_{im}: the link gain from user i's transmitter to a measurement point m
25. γ: represents the signal-to-interference noise ratio (SINR)
26. σ^2: represents the background noise at secondary receiver
27. $\boldsymbol{p}$: the transmit power vector of a given ECA
28. $\boldsymbol{p}^*$: the transmit power vector after the backing off process
29. u_i: the efficiency function which presents the throughput of communication systems in the high SINR regime
30. B: denotes the set of secondary users that have backed off their transmissions
31. U_i: denotes user i's utility
32. τ: the pricing function used to incorporate direct trust and reputation
33. C: the level of confidence that must be maintained in order to forward network traffic
34. α: the vector that represents the history of positive interactions with other users at a given time
35. β: the vector that represents the history of negative interactions with other users at a given time
36. t_i: denotes user i's measure of direct trust for any given one-hop neighbor

37. H: the set of one-hop neighbors for a specified user
38. S: the set of shared neighbors between a user that has received a request and the requester
39. L: denotes the requester of a cooperation link
40. G: represents the undirected network graph
41. V: the players in the network graph
42. E: the set of links connecting two interacting players in the network graph
43. D: a path
44. υ_k: a player on a directed link of a path
45. $\boldsymbol{S}$: the action space of a primary transmitter
46. $s(i)$: an action; add a link or back off a link
47. $\bar{S}$: an action preference list that represents the PT's beneficial actions sorted in increasing order by distance from the PT
48. $s(i^*)$: denotes the best action of the PT
49. K: the set of players on a path from PT to PR
50. d^*: a path profile that describes the Nash equilibrium for the reputation-based power control game
51. γ_e: the effective SINR, which is defined as the minimum SINR of all hops along the path D
52. e_i: the distance of each player from the PT in a given effective communication area
53. A: the distance of the player with the largest distance from the PT
54. x_i: the variable that drives the inverse linear distribution used to satisfy the Nash equilibrium
55. f_i: the function ($p_i g_{im}$) that describes the inverse linear distribution used to satisfy the Nash equilibrium
56. $\boldsymbol{E}$: the sum of all players' distances from the PT in a given ECA
57. θ: a numeric factor that represents the increase added to the ITT if a player violates the strategy
58. $\boldsymbol{p}'$: represents the new power vector that results if a player violates the strategy

ABSTRACT

One of the major challenges for today's wireless communications is to meet the growing demand for supporting an increasing diversity of wireless applications with limited spectrum resource. In cooperative communications and networking, users share resources and collaborate in a distributed approach, similar to entities of active social groups in self organizational communities. Users' information may be shared by the user and also by the cooperative users, in distributed transmission. Cooperative communications and networking is a fairly new communication paradigm that promises significant capacity and multiplexing gain increase in wireless networks.

This research will provide a cooperative relay selection framework that exploits the similarity of cognitive radio networks to social networks. It offers a multi-hop, reputation-based power control game for routing. In this dissertation, a social network model provides a humanistic approach to predicting relay selection and network analysis in cognitive radio networks.

CHAPTER 1
INTRODUCTION

The recent increase in wireless technology has led to much research related to spectrum leasing, resource allocation, prioritized traffic, and numerous other areas. Several solutions to these areas involve using cooperative communication among various wireless devices. Cooperative communication occurs in a multi-agent environment where nodes, often called users, cooperate with one another in order to improve their performance and that of the overall network, while maintaining power efficiency and reducing delay. Cooperative communication has potential applications in many different types of networks, including cellular, ad-hoc, and cognitive networks.

One of the major challenges for today's wireless communications is to meet the growing demand for supporting an increasing diversity of wireless applications with limited spectrum resource. Traditional wireless networks have predominantly used direct point-to-point (one-to-one) or point-to-multipoint (one-to-many) topologies. In cooperative communications and networking, users share resources and collaborate in a distributed approach, similar to entities of active social groups in self organizational communities. Users' information may be shared by the user and also by the cooperative users, in distributed transmission. This is different from conventional point-to-point communications. Cooperative communications and networking is a fairly new communication paradigm that promises significant capacity and multiplexing gain increase in wireless networks.

Cognitive radio networks (CRNs) have been well recognized for their ability to exploit the mutual beneficial relationship among users, distinguished here as primary users (PUs) and secondary users (SUs), to facilitate cooperative communication. Considerable research has been conducted on CRNs in relation to developing hardware, algorithms, and protocols that are needed for dynamic spectrum access (DSA) capable cognitive networks. However, there are fewer that address its network setup problem with emphasis on multi-hop infrastructures. More specifically, there are fewer proposed solutions to determine cooperative relay selection in these types of networks.

This research will provide a cooperative relay selection framework that exploits the similarity of cognitive radio networks to social networks. It offers a multi-hop, reputation-based power control game for routing. In this dissertation, a social network model provides a humanistic approach to predicting relay selection and network analysis in cognitive radio networks.

1.1. General Context of Research

1.1.1. Use Cases of Cognitive Radio Networks

Cognitive radio technology has been exploited in many real world applications. These applications include CR-enabled vehicles, emergency, military, and cellular networks, multimedia, and sentient spaces. CR-enabled vehicle (CRVs), as discussed by Felice et al. in [22], have “enabled a new class of in-car entertainment systems and enhanced the ability of emergency responders using opportunistic spectrum usage enabled by CR technology”. These vehicles are capable of using systems outside of the IEEE 802.11p

specified standard band. Additionally, they have enhanced features for drivers' safety, traffic monitoring, and in-car streaming video entertainment options.

Public safety and military users have direct applications for cognitive radios. In these markets, situation awareness is critical. Entities in these networks rely on Global Positioning Systems (GPS) and other instantaneous data to assist with disasters and other operations. Awareness of the user's physical setting in both space and time may diminish uncertainty and encourage better situation-based radio resource management [23]. Here, users may be first responders, soldiers, or other government personnel.

Another emerging consumer market are sentient spaces. This refers to environments where a wide variety of wireless products and services work together in a single location (i.e. a home, business, or apartment building). Often a diversity of cellular (e.g. 3G, 4G), broadcast (e.g. WiFi, Bluetooth), and broadband (e.g. WiMAX) radio resources are available in these environments. This could be applied to both elder care and child care. According to [23], sentient homes may include video cameras and voice recognition to assist elderly tenants in remembering to take their prescriptions, enabling home safety, and even turning off the stove.

1.1.2.Potential Correlation of CRNs to Social Networks

Cognitive radio networks are ideal communication systems for the aforementioned use cases because they are able to perform dynamic spectrum allocation and adapt their transmission and reception parameters, similar to the adaptive behavior of social entities. Cognitive radio networks aim to

stimulate interaction between a primary transmitter and the intended primary receiver through secondary users, just as online communities, such as Facebook, aim to stimulate social interaction among friends. The users of CRNs are capable of sensing active and inactive frequency channels, as well as, determining neighboring users to assist with cooperative relay. Similarly, Facebook users have established friends and are able to detect connections to other individuals and groups by analyzing relationships and other shared links. Cognitive users may share channel experience, interaction history, and path data, while users of online communities may share artefacts such as photos, videos, and games.

1.2. Problem Statement

This research examines the applicability of social networking and social capital theories in the context of cognitive radio networks' ability to form networks that improve the overall utility for primary users and to predict users' intentions in network formation, a technique that could be employed in urgent conditions, emergency situations and various other scenarios. A major concern in CRNs is relay selection in a distributed, multi-hop environment. Direct transmissions from a primary transmitter to the intended primary receiver are ideal but may be severely degraded by multi-path fading and shadowing due to the unstable, dynamic environment present in wireless communications [15].

The social phenomena underlying online communities can be directly related to network formation. These communities have become an integral part

of everyday life, with over 2 billion Internet users logging in countless hours per month [47]. Research in building, discovering and analyzing online communities is increasingly important as the Internet becomes the largest collection of ideas, personalities, and cultures in history [41]. These communities represent groups of individuals connected by some social relation, such as a trusted contact link in a business network, a family relationship, or a collegiate organization.

This dissertation focuses on a need to understand the social networking aspect of relay selection in cognitive radio networks. It aims to determine if humanistic behavior patterns may be applied to forming a successful communication chain in CRNs.

Prior research has proposed a trust-aware resource allocation scheme in a cognitive radio network with a system-level trust model in which trustworthiness is used as social capital to gain system resources [40]. The focus of [40] is to improve radio spectrum utilization in a centralized CRN. It describes a reputation model that grants access to resources (i.e. frequency bands) based on a reputation model. [43] develops a trust-based data aggregation scheme to cope with malicious secondary user attack in cooperative spectrum sensing. Their proposed solutions only partially address the use of social capital in CRNs. They do not examine the appropriateness of social networking theory to cognitive radio networks nor address its use in relay selection. Our research aims to provide a possible explanation or correlation to the phenomenon of multi-hop relay selection by testing

humanistic behavior patterns, which help to influence user intentions in social networking.

1.3. Research Objectives and Questions

The objective of this research is to help build a better understanding of social networking and social capital theory in the area of cognitive radio networks. The focus of this dissertation is on cognitive users' ability to predict network formation in cognitive radio networks based on social networking theories. Four primary goals for this study are presented here:

- First, to provide a game-theoretic approach to the multi-hop network setup problem in cognitive radio networks using a reputation-based power control model,
- Second, to provide empirical evidence about primary users' ability to form a network (i.e. the probability of establishing a path) in cognitive radio networks with a higher utility than direct transmission,
- Third, to test social network models' ability to predict network formation in the cognitive radio network environment, and
- Fourth, to build awareness about the potential uses of social networking theory in cognitive radio network environments.

The goal is a theoretical exploration for the discussion of cognitive users' intention to cooperate in network formation and the effectiveness of a social network model to predict such intentions. The research questions are based on literature from multi-hop CRN solutions as well as social network theories. Using a simulated cognitive radio network in the WiMAX module of the network

simulator ns-3 as a test bed, this investigation attempts to answer the following research questions:

1. Is the newly proposed reputation-based model comparable to existing trust schemes?
2. How is the quality-of-service (QoS) for primary users affected by incorporating the proposed game-theoretic approach to network formation?
3. Can network constructions derived from social network models predict actual linkages in a cooperative multi-hop relaying network?
4. What is the current use of social networking theory and social capital to predict relay selection in cognitive radio networks?

1.4. Guide to the Dissertation

In chapter 2, the definitions of cognitive radios and cognitive radio networks are presented. Because this dissertation is grounded in cooperative relay selection, section 2.2 of the literature review presents various cooperation frameworks for cognitive users. Section 2.3 discusses social networking theories and social capital, along with current research relevant to cognitive radio networks. Section 2.4 describes a social network model and its relevancy to CRNs.

In chapter 3, the research questions are reiterated and the propositions are introduced. A theoretical research model is also presented that provides a game-theoretic approach to the multi-hop network setup problem in CRNs using a reputation-based model.

Chapter 4 focuses on the methodology employed to investigate the research questions and test the propositions. The simulation environment is also described in this chapter. The overall procedures used for testing the social network models are presented in this chapter. Chapter 5 provides analyses of each research question and proposition, and Chapter 6 provides a conclusion.

CHAPTER 2
LITERATURE REVIEW

2.1. Background

2.1.1. Cognitive Radios

The definition of a cognitive radio is important here because they establish the foundation for this research. A cognitive radio (CR) is an intelligent radio that can be reconfigured dynamically. Such a radio automatically detects the current state of a network, by determining channel availability, traffic, neighboring users, and other network parameters. It adjusts transmission and reception parameters (i.e. transmit power, frequency, and modulation) in real-time to facilitate reliable communication and optimize concurrent wireless communications in a given spectrum band. The FCC defines a cognitive radio as “a radio that can change its transmitter parameters based on interaction with the environment in which it operates”. [8]

Cognitive radios adapt if interference is detected by exploiting both licensed and unlicensed spectrum bands. They can detect frequencies and bandwidth where conventional radios cannot; therefore, extracting more wireless bandwidth. This is accomplished by utilizing Software Defined Radio (SDR), which will be discussed shortly. This concept promotes flexible communication and efficient resource allocation to more sophisticated levels, by presenting spectrum sharing, coexistence, and interoperability and cooperation among heterogeneous wireless networks.

Mitola introduced this concept in [19]. His research states that cognitive radio “supports automated reasoning about the needs of the user” and “empowers software radios to conduct expressive negotiations among peers about the use of radio spectrum across fluents of space, time, and user context”. Mitola further explained cognitive radio as an extension to SDR through a Radio Knowledge Representation Language (RKRL).

Simply, RKRL is an algorithm in a software radio. It provides a standard language where data exchanges can occur dynamically. Data exchanges may include, but are not limited to, remote software programming for bug fixes and upgrades and location-aware services for emergency response and military use.

According to [24], a cognitive radio has two major subsystems, a cognitive unit that makes decisions based on various stimuli in the environment and a flexible SDR unit whose operating software is reconfigurable according to predefined policies and regulations. A separate spectrum sensing subsystem may be included to detect spectrum holes (i.e. frequency bands not used by licensed users or having limited interference with them) and to recognize the presence of radio resources, services, and/or users. These subsystems may not be defined as a single piece of equipment, but instead may be distributed across various components in a cognitive network.

The figure below from [24] more clearly defines the cognitive unit previously referenced. It is composed of a cognitive engine and a policy engine. The cognitive engine’s primary purpose is to optimize a performance goal based on inputs obtained from the radio’s current internal state and surrounding

environment. The policy engine partners with the cognitive engine to ensure that the solution it produced remains in compliance with predefined policies and regulations.

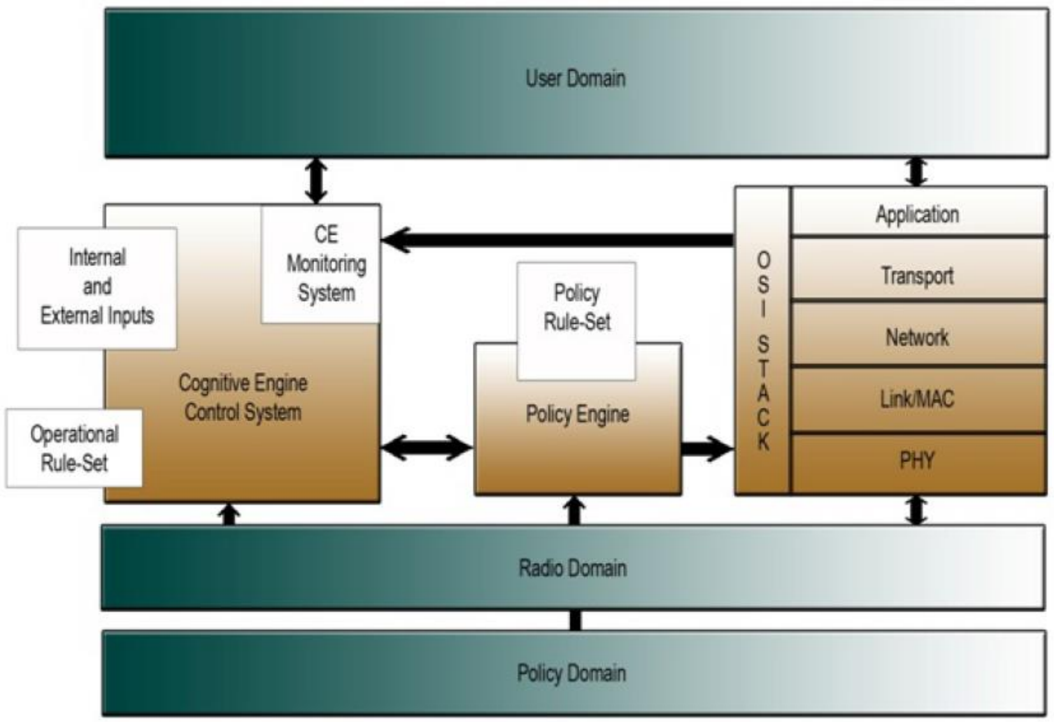

Figure 1: Cognitive Radio Concept Architecture [24]

[21] describes the capabilities of cognitive radios (cognitive, reconfigurable, and self-organized) by classifying them based on their functionality. Below are the features of each.

Cognitive Capability

1. Spectrum sensing: a CR's ability to sense radio spectrum and detect spectrum holes.

2. Spectrum sharing: refers to a mechanism that would enable sharing of spectrum under the terms of an agreement between a licensee and a third party. Negotiation may be permitted on an ad hoc, real-time basis.
3. Location identification: a radio's ability to determine its location and the location of neighboring nodes in its environment and then select and/or adjust corresponding transmission and reception parameters.
4. Network/System discovery: the detection of available one-hop or multi-hop access networks.
5. Service discovery: the determination of appropriate services needed from network or system operators.

Reconfigurable Capability

1. Frequency agility: the ability of a CR to change its operating frequency.
2. Dynamic frequency selection: a mechanism that dynamically detects signals from other radio frequency systems and avoids collisions with those systems.
3. Adaptive modulation/coding: strategies that modify operating parameters to provide more efficient solutions for spectrum access.
4. Transmit power control: a feature that enables a device to dynamically switch between several transmission power levels in the data transmission process.
5. Dynamic system/network access: a radio's ability to reconfigure itself or change modes to be compatible with multiple communication systems following different protocols.

Self-Organized Capability

1. Spectrum/Radio resource management: techniques to manage spectrum holes.
2. Mobility and connection management: features to enhance neighborhood discovery.
3. Trust/Security management: processes and procedures in place to address security issues.

2.1.2. The Cognition Cycle

The figure below provides a pictorial representation of the cognition cycle by Mitola from [23]. The phases of the cognition cycle are orientation, planning, learning, deciding, acting, and observation. Sensory stimuli is obtained from the surrounding environment. It then enters the cycle through sensory perception and object-level change detection initiates the cognition cycle. Information sources for sensory perception may be radio frequency, speech, text, location, etc.

According to [23], cognitive radios frequently observe their environment, orient themselves (SEE), create plans (THINK), make independent and cooperative decisions with other users and networks (TALK), and act on devised solutions. Thus, cognitive radios are comparable to persons. Actions may be physical or virtual. For instance, transmitting a signal, movement, and associating a user's action with the current situation are all considered actions.

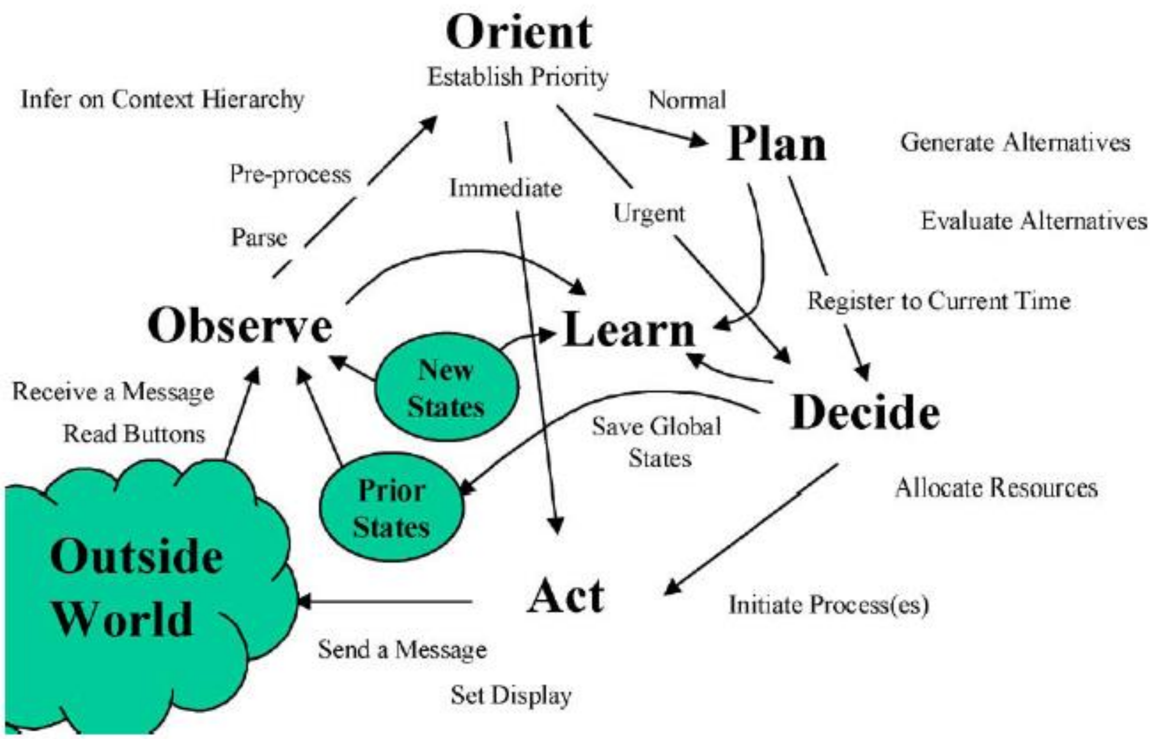

Figure 2: The Cognition Cycle as Defined by Mitola [23]

Another interpretation of the cognition cycle can be seen in the next figure.

2.1.3.Cognitive Radio Networks

A cognitive radio network (CRN) is an intelligent, self-organizing network that changes its transmission and reception parameters to communicate effectively, while avoiding interference from other licensed users. It is a complex adaptive system of heterogeneous entities that display nonlinear behavior. This wireless architecture utilizes a communication system that does not operate in a fixed, assigned band. Instead, spectrum sensing is used. This requires users to continuously scan channels to determine availability. The list of free channels may vary from node to node and cluster to cluster.

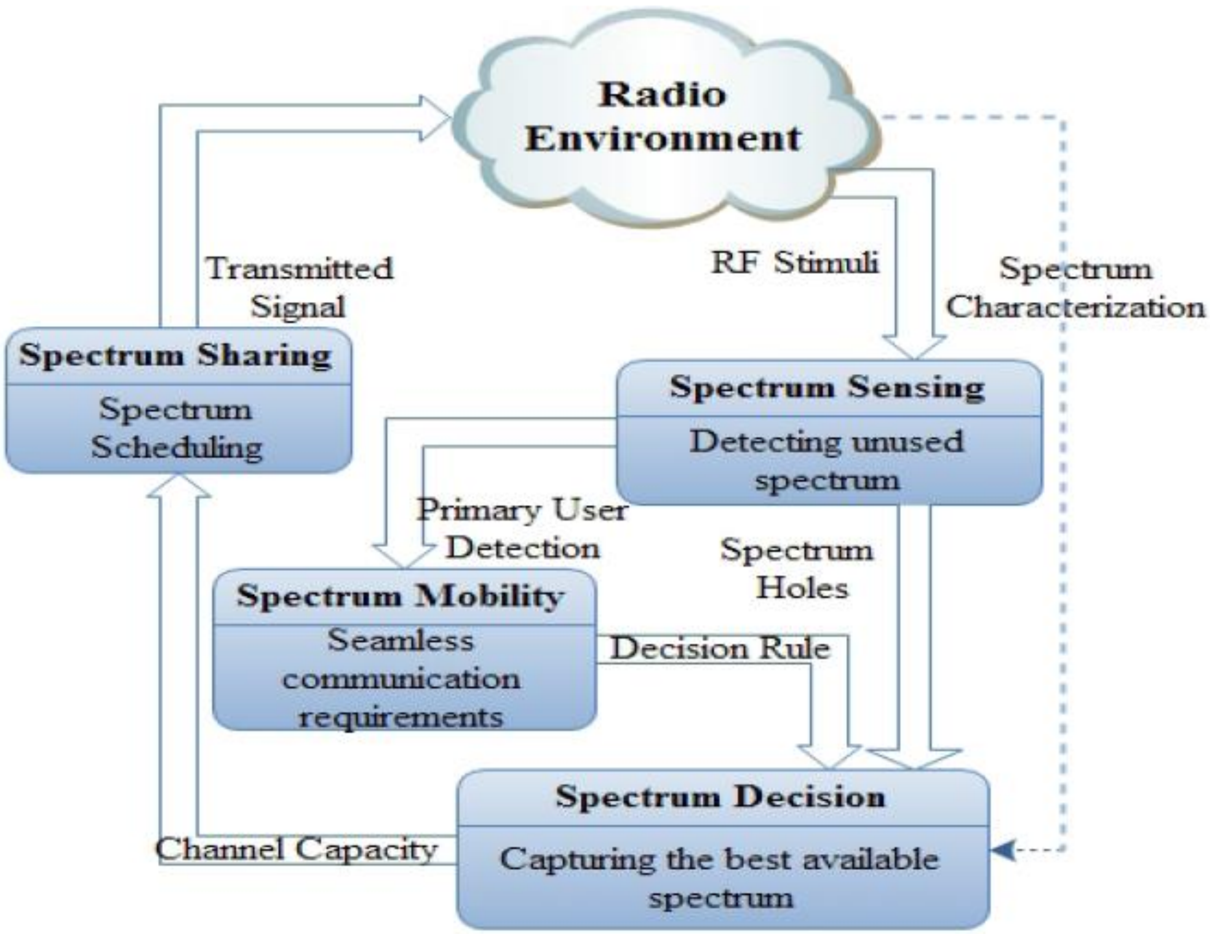

Figure 3: The Cognition Cycle as Defined by [18]

In CRNs, nodes are distinguished as either primary or secondary users. Primary users (PUs) are those that have current license agreements with the FCC which have yet to expire. Secondary users (SUs), also referred to as cognitive users (CUs), communicate only in those frequencies in which the primary users are inactive [17]. According to [16], primary users intend to find a network path with a higher bit rate and a lower delay. On the other hand, a secondary user's objective is to gain channel access and, therefore, a higher throughput for itself, while simultaneously preserving energy consumption as it

transmits primary traffic. Cooperative communication exploits this mutually beneficial relationship.

There are various application data types that are transmitted during the normal operations of a wireless device. These types vary by user and function. Each of these applications has unique performance characteristics that affect their normal operations. Not only are the application-specific network handling requirements varied, but the impact to the overall network is varied. The network must be able to effortlessly support this diversity. The concept of associating application-specific design requirements with the network dynamics of the frequency spectrum lends itself to a quality-of-service (QoS) methodology [2].

The dynamic nature of cognitive radio networks imposes unique challenges on network setup. Cooperative transmissions are essential to the efficient operation of such networks. Most existing research focuses on the single-hop relay selection of a primary transmitter-receiver pair. This research models multi-hop scenarios as a network formation game using a reputation-based infrastructure and transmit power control. Models of trust are maintained about neighboring users, forming a reputation mechanism. Additionally, an interference temperature threshold is enforced to protect primary users and to provide a method for imposing punishment on users who violate the network policy.

2.1.4. Software Defined Radios

As mentioned earlier, CRs extend Software Defined Radio as a means to enable communication in cognitive radio networks. SDR technologies can provide reconfigurable radios with the flexibility, cost efficiency, and power essential for them to maximize their potential, the benefits of which can help to increase system efficiencies realized by both service providers and end users.

The SDR Forum, along with the Institute of Electrical and Electronic Engineers (IEEE) P1900.1 group, has formed a definition of Software Defined Radio as "radio in which some or all of the physical layer functions are software defined". Simply, a radio is any kind of device that wirelessly transmits or receives signals in the radio frequency (RF) part of the electromagnetic spectrum to facilitate the transfer of information [24]. Radios exist in computers, mobile phones, garage door openers, televisions, and many other commonly used devices.

With the tremendous growth in communication methods, traditional hardware based radio devices are limited in that they can only be modified through physical revision. As demand increases, SDR offers a more affordable solution through reconfigurable operating software that allows multi-mode, multi-band, and/or multi-functional wireless devices the ability to perform software upgrades. This is accomplished through modifiable software or firmware operating on programmable processing technologies.

This research proposes a technique that serves as an add-on component to the existing primary network and is opportunistically harvested. It does not

call for major change in the existing primary infrastructure, and therefore is of great practical interest.

2.2. Cooperative Communication in Cognitive Radio Networks

In an exhaustive search of literature for studies related to relay selection in cognitive radio networks, a variety of articles were uncovered that investigated the phenomenon of cooperative relay selection in centralized and distributed networks, single-hop and multi-hop infrastructures, reputation-based approaches, and power control methods. The following section identifies articles relevant to the research.

Jing et al. in [15] addressed the challenge of efficiently selecting an appropriate relay node in order to satisfy the quality-of-service needs of the primary transmitter. Because cognitive radio networks have the potential to have a large number of secondary users, it may not be feasible to observe all neighboring nodes. [15] introduced an optimal stopping rule to the selection process that compares the instantaneous reward and the expected reward of future observations. The channel quality of the "candidate relay" represents the instantaneous reward, and the expected reward of future observations is the reward the primary user can obtain if it continues observing the subsequent candidate relays. They studied the impacts of their algorithm in terms of the number of observation steps and the average reward for the PU pair. They discovered that the number of SU candidate relays influences the relay selection performance and that the primary user should stop observation quickly to avoid generating a large cost. Additionally, Jing et al. found that the

size of the network was directly related to the number of observation steps, because the PU pair has more relay options. Here, secondary users are also used to enhance the performance of primary users; however, the focus is strictly on single hop relaying.

In [5], Huang, Han, Chiang, and Poor describe two auction mechanisms that determine relay selection and relay power allocation by maximizing total rate increase. This study seeks to determine when a user should relay, based on a threshold policy, and how a user should select a relay and allocate its resources. It provides a distributed algorithm using auction theory, tested on a single relay network, to address the challenge of efficient resource allocation in cognitive radio networks. This study does not investigate its benefit to primary users. Its results are isolated to the performance of secondary users, as does this research.

The solution provided in [6] explored trust as related to network layer functions in a cognitive radio network. The network layer functions include location management, handoff management, and security. The framework to model trust is computed as a function of the routing path. The overall trust is determined by multiplying the reputation value at each segment along the path. In this model, trust is irreversible, and the trust through an intermediate node cannot be higher than the originating node. [6] does not consider trust for cooperative relay selection to improve the payoff of primary users.

[12] concentrated on the property-rights model as an approach to grant spectrum access to secondary users. In the property-rights model, primary

users own the spectral resource and have the authority to lease part of it to cognitive users in exchange for compensation. The proposed solution is modeled as a Stackelberg game where secondary nodes have the option to cooperate or not. It has a hierarchical structure, where the primary transmitter's goal is to enhance its quality-of-service in terms of rate and probability of outage. Although [12] employs the cooperation of secondary users and utilizes a distributed power control method, its primary goal is toward spectrum sharing and identifying spectrum holes, instead of relay selection. Also, it does not consider trust as a metric.

A game theoretic model is also provided in [16]. Here the network setup problem is modeled as a Stackelberg game, as in [12]. Although both solutions are applied to multi-hop scenarios, [16] devised a cooperation framework in which the primary traffic and the secondary traffic are separated in the frequency domain and the relays share the leased sub-channel in the time domain, in an attempt to alleviate interference and reduce delay in the network. This research found that a larger transmit power can enlarge the transmission range, resulting in more cooperation opportunities for both the primary and secondary users. It also reported that larger transmit power could reduce user payoffs, if no more relays can be invited to participate in the cooperative transmissions. Different from our research, [16] considers the existence of more than one primary transmitter and primary receiver pair, competing over a single set of secondary users. Its algorithm allows secondary users to accept or reject an offer from a primary transmitter based its payoff,

even if it is currently in cooperation with another primary transmitter. This research does not consider power control nor trust as metrics for cooperation.

[13] discusses the application of the Prisoner's Dilemma to the IEEE (Institute of Electrical and Electronics Engineers) 802.11 standard, specifically in the distributed coordination function (DCF). In this game, each player (node) has two strategies: *Transmit* or *Not Transmit*. Users choose a strategy based on the probability of a function determined by payoffs of a successful transmission, an idle node, and a failed transmission. [13] focuses on the under-utilization of the electromagnetic spectrum and provides an original technique to identify spectrum holes.

[4] presented a reputation mechanism that applies the Prisoner's Dilemma to relay selection. In this mechanism, a centralized authority keeps records of the cooperative behavior and punishes non-cooperating nodes. Each node is a player and the strategy is whether to cooperate or not. This paper emphases the various techniques available to provide incentives to cooperate in cooperative communication.

[28] focuses on secondary communication where transmitters and receivers are located in different areas of primary users with varying spectrum diversity. It proposes a cooperative relay scheme to "improve spectrum utilization and increase the SINR of secondary communication". This study focuses on the Interference Power Constraint as a general scheme of power control. It exploits a single relay node to improve the received SINR, based on the relay's location between the transmitter and receiver nodes. The emphasis

here is determining whether or not to employ the use of a relay node strictly for improved utility for secondary users, as opposed to primary users.

A noncooperative power control game is presented in [54]. Similar to [28], Jia and Zhang present a framework for spectrum sharing in [54] that concentrates on an interference temperature limit, in only one effective communication area. This research uses an exclusive user model for spectrum sharing. Here, a primary user has “exclusive and transferable rights to the user of a specified spectrum within a defined geographic area, with flexible spectrum use rights that are governed primarily by technical rules to protect spectrum against interference” [54]. In this model, users’ transmissions are backed off if they violate the interference temperature limit. This backing off technique affects their quality-of-service and overall payoff function. [54] only focuses on secondary communication. Its game does not involve secondary users assisting with primary user communication. Additionally, this use of power control is geared toward spectrum sharing instead of relay selection. In contrast to [54], the original technique presented in this research uses power control to evaluate trustworthiness of neighboring nodes and provides a forgiveness mechanism that allows users to re-enter game play after violation of any constraints.

2.3. Social Networking Theories and Social Capital

The review of literature in the previous section discussed specific protocols for relay selection, transmit power control, and trust in a cognitive radio network. This section focuses on defining social network theory and

social capital and explaining how it is applicable to relay selection in cognitive radio networks.

2.3.1. Social Network Theory

Social network theory (SNT) explains how information and connections develop in the framework of active social groups in self organizational communities. Social interaction has been studied in sociology, psychology, communication, and economics, with recent studies in computer networks. Hammond and Glenn relate social network theory to complexity theory in [52] because "it seeks to explain nonlinear phenomena by focusing on the flow of information through relationships". Note the similarity of this definition to that of cognitive radio networks presented in Section 2.1.3.

Let's use a Chinese marketplace to relate SNT to cognitive radio networks. In this real social network, traders, farmers, and craftsmen sell their products and services in a highly interactive environment that constantly changes. People broadcast their desire to conduct business and willingness to negotiate by shouting in the air. Often times, regular customers receive a better deal. Friends gossip, spreading important economic and political information. Trading is preferred, although money may be exchanged. The marketplace is a place of exchange, where trust is gained and lost and where trade skills and established relationships are essential to survival.

In CRNs, the traders, farmers, and craftsmen may be related to the primary users and secondary users. Transmission rate, channel availability, delay, and energy conservation are resources that may be considered products

and services, as in the marketplace. Users broadcast their desire to route information to their neighbors, and network state information is exchanged among users. A history of interactions can provide information pertinent to the reputation of neighboring users. Additionally, virtual currency may be exchanged in cognitive radio networks as an incentive to cooperate.

Three important overlapping conceptualizations may be noted between social network theory and cognitive radio networks. They include information and sustainability, change and emergence, and order and chaos. First, information exchange is key to CRNs as a social system. Information allows the individual to adapt to changes in the environment sensed by other parts of the network and foster sustainability [52]. Competition and collaboration in the network creates various trust levels among users.

In SNT, there are strong ties and weak ties. Strong ties consist of links to individuals or groups with whom you have regular and direct contact. For humans, individuals have strong ties with parents and siblings. Analogously, cognitive users have strong ties with one-hop neighbors. Weak ties are the nodes in the network that reach beyond immediate friends and family. That is, two-hop and three-hop neighbors. Both category of ties are critical to communication and sustainability.

Secondly, the ability to adapt to change in the emergence of unique situations is inherent, as cognitive users must adjust reception parameters based on outside stimuli. They must also alternate their role in

communication, serving as both senders and receivers of information. The roles of the primary transmitter and primary receiver pair remain consistent.

Order can be defined as "an emergent rhythm" [52]. This may be displayed in CRNs as nodes replicate their relay selections in subsequent communications based on an established history of trust, that is, a predictable set of strong and weak ties. Chaos may be easily related to a network failure, caused by either an individual or cluster failure.

2.3.2. Social Capital

Social capital is defined as the "value of the relationships we create and maintain within our social networks to gain access to and mobilize needed resources" by Smith in [41]. Social capital is dependent on initial positions in the social hierarchies, as well as, on the range of social ties, according to Lin in [36]. Research has shown that social capital is higher when members of a community are linked and cooperating with each other.

In terms of sociology, it may be categorized as personal resources or social resources. Lin's differentiation of the two are as follows:

> Personal resources belong to an individual who can use and dispose them with freedom and without much concern for compensation. Social resources are resources accessible through one's direct and indirect ties. The access to and use of these resources are temporary and borrowed. For example, a friend's occupational or authority position, or such positions of this friend's friends, may be ego's [an individual's] social resource. The friend may use his/her position or network to help ego to find a job. These resources are borrowed and useful to achieve ego's certain goal, but they remain the property of the friend or his/her friends. [36]

Both strong and weak ties play important roles in social capital as they foster reciprocity, coordination, communication, and collaboration. Behavior of

such ties in cognitive radio networks affords achievement of the ultimate goal, packet-forwarding from the primary transmitter to the primary receiver. Intuitively, the primary transmitter and receiver pair benefit from increased bit rate and decreased delay by utilizing the shared affiliations or activities of secondary users.

Studies of the actual dynamic behavior of social entities has been applied to examining the compensation of CEOs and investigating how interpersonal channels affect individuals' ability to secure more satisfactory jobs. Research has led to the discovery of patterns in behavior that will be exploited here in the relay selection process of cognitive radio networks.

Qin et al. view trustworthiness as social capital in cognitive radio networks. It is used by the community of nodes to encourage good behavior and facilitate dynamic spectrum access. This research uses a similar approach, as it views trustworthiness as social capital in CRNs to encourage positive interactions and facilitate relay selection.

This leads to a need to define trust as it relates to both social network analysis and cognitive radio networks. In both areas, trust is a measure of uncertainty. In social network analysis, behavior is judged through interactions among linked entities and trust measurements are made as a function of these interactions [39]. Similarly, in cognitive radio networks, it is a measure of the confidence of a network node on the ability of other nodes to transmit data, while preserving the veracity of the data [39].

2.3.3.Applications of Social Network Theory in CRNs

As previously mentioned, Qin et al. in [40] proposed a trust-aware resource allocation scheme in a cognitive radio network with a system-level trust model in which trustworthiness is used as social capital to gain system resources. Its focus is to improve radio spectrum utilization in a centralized CRN. The proposed scheme has two parts which include trust-aware collaborative sensing and resource allocation. In trust-aware collaborative sensing, a secondary user performs a sensing operation to determine the activity state of a primary user and reports its observation to a base station. Here, a trustworthiness score is calculated for each SU. The next step, resource allocation, is to maximize the total bit rate for all chosen SUs subject to "total transmit power, trustworthiness, and PU interference constraints".

Wang and Chen develop a trust-based data aggregation scheme to cope with malicious secondary user attacks in cooperative spectrum sensing in [43]. The objectives of the aggregation scheme are: too provide no incentive for malicious SUs to report fake sensing capabilities; to minimize the cost endured by the "Data Fusion Center"; and to maximize the success decision rate for the data fusion outcome matching the ground truth channel availability. In this research, the Data Fusion Center is a centralized authority that has an overarching view of PU channel occupancy for the network. A game-theoretic design is employed as an incentive for secondary users to accurately and honestly relay sensing capabilities and sensing results.

[39] develops a relationship between the trust concepts in the social network theory and wireless ad hoc networks. It examines trust in the context of routing and reliable forwarding of data in these networks. It proposes a scheme that uses balance theory to predict bidirectional ties. Modeled in terms of signed graphs, the nodes of the graph represent users and the positive/negative edges represent their friendly/hostile relationships. The potential source of tensions are formed from three agents in a clique that create a cycle. Local density measurements are used to set thresholds for direct trust for nodes. In other words, there is a correlation between the number of direct ties a node has and the number of mutual local neighbors. This trust scheme incorporates indirect observations to calculate direct trust values and utilizes dynamic thresholds.

The ergodicity of the dynamics of cognitive radio networks, having a grid topology and random deployment, by using the model of interacting particles in nonequilibrium statistical mechanics is studied by Li et al. in [35]. The ergodicity of the social behavior dynamics means "whether the dynamics will converge to a single equilibrium or may have multiple equilibria" [35]. This is a study of the social behavior propagation in cognitive radio networks, particularly the propagation of channel preference in the recommendation system using a social networks framework. Spin systems are used to model cognitive radio networks. These types of systems consist of a finite number of elements, each represented by either state 0 or state 1. The overall system state is the collection of the individual states in continuous time, and a

nonnegative function can be given that displays the rate at which any given element flips its current state.

In [29], Gunasekaran and Nagarajan use social network theory to propose a mobility model to detect the movement of the nodes within a mobile ad hoc network. They introduce a Unified Relationship Matrix (URM) to represent relationships from multiple and heterogeneous groups. Input to this mobility model is a social network matrix, which has the connections of individuals carrying the mobile devices. Relationships may be intra-type (belonging to the same group) or inter-type (belonging to different groups).

2.4. Social Network Model

An exhaustive search of literature for studies related to predicting relay selection in cognitive radio networks using social network theory has shown a scarcity of research in this area. As seen in the previous section, research has been conducted on using SNT in CRNs related to discovering dynamic spectrum access, behavior propagation, bidirectional ties, and mobility. To my best knowledge, this research is the first to study the use of social network models to predict relay selection in cognitive radio networks.

Social network models study the actual dynamics of social network formation and evolution, leading to the discovery of relationships and behavior patterns [41]. These models were originally developed to test for factors influencing social relationships among individuals. [44] uses social network models in social psychological experiments to analyze the mean proportion of time spent speaking by doctors to different types of patients. They have also

been applied to social status attainment in [36], where studies were conducted to determine the relationship of social capital to socioeconomic attainment.

In contrast, Fletcher et al. applied social network models to infer connectivity across landscapes in areas relevant to ecology and conservation biology in [27]. This technique was used because the statistical models of social networks have the ability to reveal complex, emergent patterns with limited data to predict linkages. In ecology and conservation, network analysis is increasingly being used to assess population connectivity across landscapes.

[27] considers two types of social network models, a sender-receiver model [31] and a latent space model [32] to predict landscape connectivity of "within-field movements of cactus-feeding insect (Chelindea vittiger) on patchy Opuntia cactus and breeding-season movements of the endangered Everglades snail kite (Rostrhamus sociabilis plumbeus) across wetlands in peninsular Florida". These models require empirical data on movement. The study found that the sender-receiver models provided the highest predictive accuracy in both networks and was the only model that could account for the observed directionality in movement, although it predicted a higher level of exchange in movement than what was actually observed. The next section discusses the latent space model used by Fletcher et al. in [27] and its relevance to relay prediction in cognitive radio networks.

2.4.1. Latent Space Model

Social network data, just as cognitive radio network data, typically consists of a set of entities, often called users, along with the links that connect

them. Hoff, Raftery, and Handcock related these links as ordered pairs of actors in [32]. This model is described by a set of n actors and a relational tie $y_{i,j}$, measured on each ordered pair of actors i, j = 1, …, n. In the simplest cases, $y_{i,j}$ is a "dichotomous variable indicating the presence or absence of some relation of interest, such as friendship, collaboration, transmission of information or disease, and so forth" [32].

The data is modeled as an $n \times n$ sociomatrix Y, with entries $y_{i,j}$ denoting the value of the relation from actor i to actor j. In the binary case, $y_{i,j} = 1$ indicates the presence of an edge (direct tie) in a graph, and $y_{i,j} = 0$ indicates the absence of a direct tie. Cognitive radio networks may also be represented in this fashion, where $y_{i,j} = 1$ represents one-hop neighbors (direct ties).

Hoff et al. take a conditional, independent approach to modeling by assuming that the presence or absence of an edge between two individuals is independent of all other edges in the system. They provide a probability measure over unobserved characteristics of a social network in which the presence of a tie between two individuals is dependent on the presence of other ties. In other words, the observation of $i \rightarrow j$ and $j \rightarrow k$ suggests that i and k are not too far apart in social space. [32] gives a logistic regression model ($n_{i,j}$ = log odds($y_{i,j} = 1 \mid z_i, z_j, x_{i,j}, \alpha, \beta$)) in which the probability of a tie depends on the Euclidean distance between z_i and z_j.

The results from [32] showed that this model may be used to improve the statistical uncertainty in the social space to be quantified, to generalize

multiple relationships with varying strengths, to leverage limited data, and to apply transitive characteristics to models lacking such structure.

CHAPTER 3
RESEARCH PROPOSITIONS

3.1. Introduction

This chapter reiterates the research questions and puts forth the propositions for this study. The research questions were generated from literature related to cognitive radio networks and social networking theory. As seen in the Emergency Management Survey [48], 40 percent of emergency respondents use ham radio and fixed radio to communicate during emergency operations. With additional applications in military operations and other sentient spaces, there is a need for reliable relay selection in cognitive radio networks. Because these situations are dynamic, emergent, and often chaotic, they require reciprocity, coordination, communication, and collaboration among users. This lends social network models as a tool to perform network analysis where limited data is available yet a quick response is demanded.

3.2. Research Questions

The primary research questions of this study are listed below. It is important to note that the focus of this study is not purely on the use of social network theory in cognitive radio networks, but also on the multi-hop network setup problem. As seen in [29], [35], [39], [40], and [43], research has been conducted on using SNT in CRNs related to discovering dynamic spectrum access, behavior propagation, bidirectional ties, and mobility. Therefore, the shift in use is to the effectiveness of a social network model to predict relay selection in the network setup problem experienced by CRNs. Chapter 4

discusses the methodologies employed to assess the effectiveness of the newly proposed reputation-based, power control model, as well as, to evaluate the effectiveness of social network models in predicting relay selection.

1. Is the newly proposed reputation-based model comparable to existing trust schemes?
2. How is the quality-of-service (QoS) for primary users affected by incorporating the proposed game-theoretic approach to network formation?
3. Can network constructions derived from social network models predict actual linkages in a cooperative multi-hop relaying network?
4. What is the current use of social networking theory and social capital to predict relay selection in cognitive radio networks?

3.3. Research Propositions

The above mentioned research questions can be broken down into four areas of discovery:

Proposition 1: The new distributed, game-theoretic approach to relay selection in CRNs, using trustworthiness as social capital, is comparable to existing trust schemes.

Proposition 2: The QoS enjoyed by primary users is improved by using secondary users to transmit primary data.

Proposition 3: The latent space model [32] may be applied in CRNs to predict multi-hop relay selection.

Proposition 4: This research presents the first solution to using social networking theories in relay selection for cognitive radio networks.

The newly proposed algorithm for relay selection in cognitive radio networks is of great interest in this study. The average trustworthiness of users that have implemented the new trust scheme should be comparable to existing schemes. (**Proposition 1)**

The cooperation framework presented by the RBPCG considers relay selection in which the multi-hop relay path is computed by performing the players' strategies in the form of link operations. It must be determined if a Nash Equilibrium exists for the network formation game that maximizes the payoff received by primary users that are able to get into cooperation with relays. (**Proposition 2)**

Due to the overlapping conceptualizations between cognitive radio networks and social network theory, this research contends that a social network model may be applied to the relay selection problem, with modifications directly related to inherent characteristics of CRNs.

Fletcher et al. reported that the sender-receiver models presented in [31] provided the highest predictive accuracy in both of its empirical, mark-recapture datasets and was the only model that could account for the observed directionality in movement, although it predicted a higher level of exchange in movement than what was actually observed. It is reasonable to hypothesize

that these techniques will have a similar effect on relay selection in cognitive radio networks. (**Proposition 3**)

One of the main goals of this research is to determine the use of social networking theories and social capital for relay selection in cognitive radio networks. A comprehensive review of literature may support that this research is uncharted territory in this field of study. (**Proposition 4**)

3.4. Theoretical Research Model

This section details the algorithm that provides the framework to test the above propositions. It begins with a brief overview of game theory and cooperation incentives.

3.4.1. Game Theory Overview

Game theory is the study that analyzes the dynamic strategies of rational individuals who are engaged in competitive interactions. It provides a mechanism to predict future moves of an opponent who may have conflicting interests. Game theory has been applied to contexts in war, economics, and networks.

As mentioned earlier, cognitive users must be aware of the changes in their environment and be capable of adapting their transmission parameters accordingly. These users have the ability to observe, learn and act to optimize their total performance, unlike conventional spectrum sharing where it is generally assumed that all users cooperate in a static environment [13]. Within this context, game theory can be appropriately applied to the network setup

problem because cognitive users are autonomous, opportunistic agents seeking to maximize benefits.

The main components of any game are the set of players, the set of strategies, and the utility function. The set of players are the finite set of decision makers. Each player has a set of strategies. These are the actions that they may choose during game play. The series of actions performed by each player will determine the outcome of the overall game. The utility function associates a numerical payoff for every outcome product of an action taken by a player.

Generally, games may be divided into noncooperative games and cooperative games. In cooperative games, players compete and cooperate to form coalitions in unstructured interactions to create and obtain specific payoffs. Cooperative games are out of the scope of this paper. On the other hand, noncooperative games are modeled under the basis that all players make choices or play strategies considering only their own selfish interests – their final objective is to maximize their own total utility [16]. Noncooperative games have various categories that pertain to players' strategies and the availability of information.

1. Static game: players make decisions simultaneously, or in isolation, with no information about other players' past or present decisions.
2. Dynamic game: occurs when there is a strict order of turns that the players must obey.

3. Complete information game: all players are conscious of the number of players, the strategies, and the utility function of the rest.
4. Incomplete information game: one or more of the components (the number of players, the strategies, and the utility function) of the game must be estimated or assumed.

3.4.2. Cooperation Incentives

Cooperative communication has great potential in wireless communication, especially when paired with game theory. A main obstacle blocking the widespread use of it is the lack of incentives for users to participate in cooperative communication. There are three primary mechanisms designed to provide such incentives: reputation-based mechanism, resource-exchange-based mechanism, and pricing-based mechanism.

In a reputation-based mechanism, a centralized authority maintains history of the cooperative behavior and punishes noncooperative nodes. Here, each node is considered to be a player, and its strategy is whether to cooperate with another node. In general, all players are assumed to play the best strategy that yields the best utility. Cooperative nodes may be awarded permission to transmit at a higher power, while noncooperative nodes will be punished and not afforded this opportunity.

The source node exploits relays for cooperative communication in the resource-exchange-based mechanism. As an award, the source node provides

its own resource to help the relay nodes achieve certain objectives [4]. For example, in cognitive radio networks, primary users may use secondary users as relays. If the secondary users choose to cooperate, they will obtain access to the wireless channel for their own transmissions in return.

In the pricing-based mechanism, virtual currency or tokens are assumed in the network. Relay nodes sell their resources (e.g. bandwidth, power, time) for a certain price. According to [4], source nodes make payments to relay nodes for using their resources. Often times, a game using this mechanism will form either a buyer's or seller's market.

3.4.3. Introduction to the Reputation-Based Power Control Game

This work will focus on the study of relay selection in cognitive radio networks using a reputation-based power control game (RBPCG). This model will be a dynamic, incomplete information game. There is a strict order of play, and all players are aware of the number of players and the utility function of the players. Each player does not share their strategies, although some path information is shared.

It considers the case where secondary users coexist with primary users to conduct data transmissions. Primary users are those that have current license agreements with the Federal Communications Commission (FCC) which have yet to expire. Secondary (cognitive) users communicate only in those frequencies in which primary users are inactive, and operate based on agreements/etiquettes imposed by primary users of the spectrum.

An interference temperature is established to protect the primary users. The power control problem is one of the most critical issues in such a model. It is formulated in cooperative cognitive radio networks to maximize energy efficiency of secondary users and guarantee the quality-of-service (QoS) of both primary and secondary users. The secondary users, equipped as transmitter and receiver pairs, sharing a licensed frequency have to regulate their transmission power so that the interference temperature limit at a specified measurement point is not violated. The QoS of elastic traffic is directly related to signal-to-interference-plus-noise ratio (SINR) at the receivers, which is a result of the transmission power of secondary users. Secondary users have elastic-data applications in which throughput of each user is determined by the SINR at its receiver [54].

Measurement points are nodes that monitor the real-time interference temperature of a given frequency band at their locations. There is interaction among the measurement points, primary users, and secondary users. We assume that a measurement point maintains a history of secondary users who violate the maximum received power at its location, as well as, monitors the interference temperature. As long as the interference temperature threshold (ITT) is not violated, the measurement point will not interfere in the secondary users' operation. As in [54], if the limit is exceeded, the measurement point will notify the secondary users generating the highest interference. These secondary users will back off their data transmissions, upon receiving such a notification. When there are several secondary users generating the same

highest interference, the user with the lowest trust will be used to break the tie. (Trust will be discussed in future sections.) If the ITT is still violated, the next highest user will be notified to back off. This process will continue until the interference temperature threshold is no longer violated.

Additionally, this model defines interaction between the primary users and the secondary users. Interaction occurs during relay selection and when a defect occurs. A defect occurs when the measurement point notifies the secondary user who is generating the highest received power that the interference limit has been violated, when a secondary user chooses to defect for selfish reasons (i.e. inefficient power supply), or when a secondary user fails to respond to a relay request. A primary user may notified of a defect by secondary users and the measurement point.

Considering the selfishness of secondary users, this project will be modeled as a noncooperative game where all players make choices or play strategies considering only their own selfish interests – their final objective is to maximize their total utility. Under the assumption that each user is rational, it must be determined if a unique Nash equilibrium can be identified in this game.

This model follows an exclusive use model in which “a licensee (primary user) has exclusive and transferable rights to the user of a specified spectrum within a defined geographic area, with flexible spectrum use rights that are governed primarily by technical rules to protect spectrum against interference” [54]. The defined geographic area is the effective communication area (ECA).

The exclusive use model introduces a metric called interference temperature to quantify and manage the interference in the ECA and provide protection to primary users. Based on such a metric, a primary user sets up an interference temperature threshold under which secondary users can coexist with primary users. The ITT must not be violated at the primary user's receiver. According to the FCC, interference temperature threshold ITT is specified in Kelvin and is defined as

$$\mathrm{ITT}(\mathrm{m},\, \mathrm{W}) = \frac{P_I(m,W)}{kW} \qquad (1)$$

where P_I is the average interference power in Watts centered at m, covering bandwidth W measured in Hertz, and the Boltzmann's constant k is $1.38\mathrm{x}10^{-23}$ Joules per Kelvin degree. The FCC would establish an interference temperature threshold (ITT) for a given geographic area. This is the highest tolerable interference for a given bandwidth in a particular location. Any unlicensed user utilizing this bandwidth must guarantee that their transmissions, added to the existing interference, must not surpass the interference temperature threshold at a licensed receiver.

3.4.4.System Model

The system model we study is an IEEE 802.16 Broadband Wireless Access System (WiMAX). The primary wireless network is OFDMA-based. We focus on relay selection in multi-hop communication between primary transmitter-receiver pairs that maximizes energy efficiency of secondary users and guarantees the quality-of-service (QoS) of both primary and secondary users. The system model is provided in Figure 4. There is one primary

transmitter (PT), primary receiver (PR) pair. The PT owns the license for PU Band 1, and the PR owns the license for PU Band 2. The effective communication areas (ECA) are denoted by *a* and *b*, for PU Band 1 and PU Band 2 respectively. The other nodes are secondary users. They are either located in communication area *a* or *b*.

There are two measurement points, x_a and x_b. These measurement points monitor the interference temperature thresholds of the effective communication areas and maintain a history of user violations. x_a and x_b are located on the boundary of *a* and *b*, respectively, with the shortest distance to *a* or *b*.

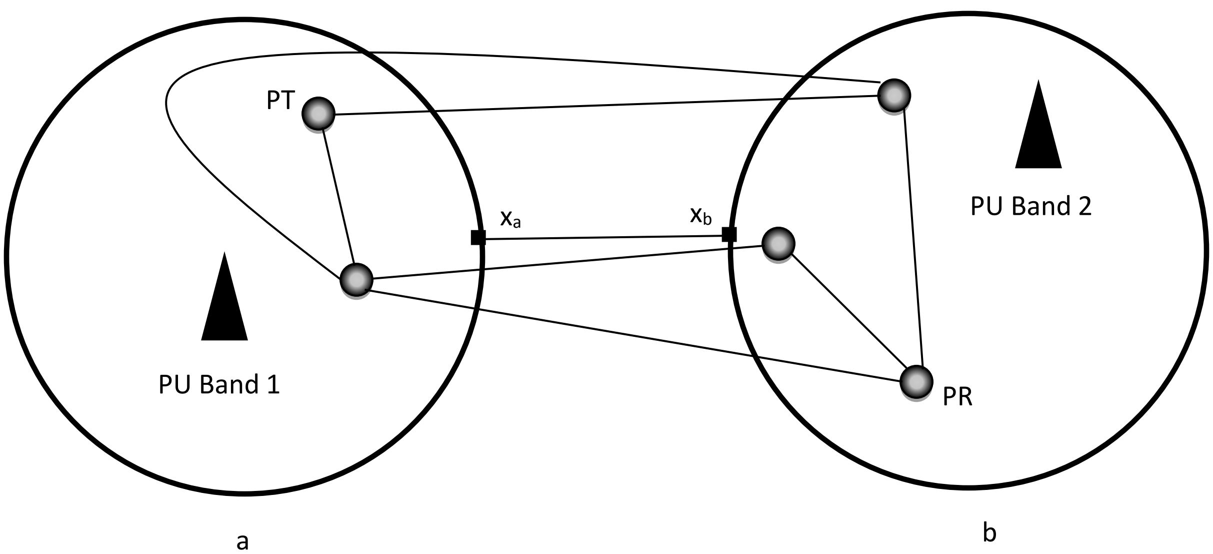

Figure 4: RBPCG System Model

3.4.5.Utility Functions

We make the following assumptions with respect to the communication network. We assume at an ECA a primary user offers a portion of its frequency

spectrum to be shared among a set of secondary users. Each secondary user is a transmitter-receiver pair. All secondary users use decode-and-forward multi-hopping to relay primary data.

The interference temperature threshold is interpreted as a threshold of the total receiver power at a specified measurement point. This is denoted by T_a and T_b, for each licensee's designated geographic area. Following [54] and [57], we denote the transmit power for user i by p_i and $p_i \in P_i = \left[p_i^{min}, p_i^{max}\right]$.

$$p_i^{min} \leq p_i \leq p_i^{max}, \forall i \in N \qquad (2)$$

We let $P_i = (0, +\infty)$, which is interpreted as the achievable power of secondary users can generate interference much higher than the power threshold at the measurement point [54]. N is the total number of secondary users.

The link gain from user i's transmitter to user j's receiver is g_{ij} and the link gain from i's transmitter to a measurement point is g_{im}, where m is either x_a or x_b. Then the ITT for the designated geographic areas are denoted by

$$\sum_{i=1}^{n} p_i g_{ix_a} \leq T_a \qquad (3)$$

$$\sum_{i=n+1}^{N} p_i g_{ix_b} \leq T_b \quad (4)$$

where n is the number of secondary users interfering with the primary transmitter and N-n denotes the number of secondary users interfering with the primary receiver. Similar functions are used in [28] and [54].

First, we consider the case when no relays are employed for communication. For direct communications, the SINR, denoted by $\gamma(PT)$, is

$$\frac{p_{PT}\, g_{PT,PR}}{\sigma^2} \quad (5)$$

(5) is used in [5], [28], [54], and [57], with some variations.

As stated earlier, secondary users produce elastic traffic in which throughput of each user is determined by the SINR at its receiver. When user i is not backed off by the measurement point, the quality of service (QoS) enjoyed by user i in a specified effective communication area is characterized by a function $u_i(\gamma_i)$, where γ_i is the SINR at user i's receiver,

$$\gamma_i(\boldsymbol{p}) = \frac{p_i g_{ij}}{\sum_{j=u, j\neq i}^{v} p_i g_{jm} + \sigma^2}, \forall i \in N \qquad (6)$$

where σ^2 is the background noise at secondary receiver j, $\{u, \ldots, v\}$ is the set of secondary users that interfere with each other in a given ECA, and $\boldsymbol{p}$ is the transmit power vector of a given ECA.

The efficiency function u_i defined for this project

$$u_i(\gamma_i) = \ln(\gamma_i) \qquad (7)$$

presents the throughput of communication systems in the high SINR regime. This efficiency function is also used in [54] and [57].

If user i is backed off, then its utility is 0. B denotes the set of secondary users that have backed off their transmissions. B includes the users with the largest interference at a measurement point. B is set to null after a designated number of data transmissions, in order to allow those users to re-enter play. $\boldsymbol{p}^*$ is the transmit power vector after the backing off process. U_i denotes user i's utility.

$$U_i(\boldsymbol{p}) = \begin{cases} u_i(\boldsymbol{p}), if\ \sum_{i=u}^{v} p_i g_{im} \leq T\ and\ i \notin B \\ u_i(\boldsymbol{p}^*), if\ \sum_{i=u}^{v} p_i\, g_{im} > T\ and\ i \notin B \\ \quad 0, if\ \sum_{i=u}^{v} p_i g_{im} > T\ and\ i \in B \\ \quad 0, if\ \sum_{i=u}^{v} p_i g_{im} \leq T\ and\ i \in B \end{cases} \quad (8)$$

where T is the interference temperature threshold for a certain effective communication area, denoted by T_a or T_b. The above utility function U_i ($\boldsymbol{p}$) follows that of [54]. However, [54] only considers a single effective communication area.

Also, the existing utility function does not embody the effect of trust in relay selection. However, we can introduce pricing as an effective tool to qualify such effects. An efficient pricing mechanism will encourage secondary users to share resources in order to maximize their utility. The pricing function is denoted by τ.

A pricing function is used for incorporating direct trust and reputation into a probabilistic formulation. This mechanism provides not only a trust measure about a neighbor, but also a level of confidence (C) that must be maintained in order to forward network traffic. The approach incorporates both positive (α) and negative (β) vectors to calculate the belief against the required level of confidence.

Each user maintains a set of α and β vectors that represent the histories of interactions with other users. If a user is sent a request to forward network traffic and they do not respond, this is considered a β observation. A non-response may indicate a node failure and the primary transmitter is notified. A response may be either positive or negative. All users are initially trusted.

Each time a user receives a request from another user, it will evaluate the trust model to determine whether to participate. The trust model provides the mean probability that a user can be trusted, based on its own observations (direct trust) and those from all one-hop neighbors shared by both users (reputation). The user will not be trusted if the trust value is less than the confidence level. A user is considered to be on punishment once its confidence level drops below the minimum. In repeated play, a succession of positive observations can move an untrusted neighbor back to being trusted again.

Initially, $\alpha = 1$ and $\beta = 0$. H is the set of one-hop neighbors for a specified user. A user i's measure of trust (direct trust) for any given one-hop neighbor is computed by a function $t_i(h)$. The value of $t_i(h)$ is expected to be

$$t_i(h) = \frac{\alpha+1}{(\alpha+\beta)+1} \qquad (9)$$

where $h \in H$, α is the number of successful interactions at a given time, and β is the number of unsuccessful interactions at a given time between i and h, with respect to i.

The trust value of a requester (reputation), τ, is expected to be:

$$\tau_L = \frac{\sum_{y=1}^{s} t_y(L) + t_i(L)}{s+1}, \forall y \in S \qquad (10)$$

where S is the set of shared neighbors between user i, that has received a request, and the requester, L. The number of shared neighbors is denoted by s. The requesting node uses the same scheme to determine the trust of its one-hop neighbors. Both the primary transmitters and primary receivers are always trusted.

In this game, each user must decide between two strategies: cooperate or defect. The primary transmitters and primary receivers always cooperate. It is assumed that the player initiating a move has agreed to cooperate and will continue play.

Taking the pricing function into consideration, the utility function U_i is

$$U_i(\boldsymbol{p}) = \begin{cases} u_i(\boldsymbol{p}), if \ \sum_{i=u}^{v} p_i g_{im} \le T \ and \ \tau_i \ge C \ and \ i \notin B \\ u_i(\boldsymbol{p}^*), if \ \sum_{i=u}^{v} p_i g_{im} > T \ and \ \tau_i \ge C \ and \ i \notin B \\ 0, if \ \sum_{i=u}^{v} p_i g_{im} > T \ and \ (\tau_i < C \ or \ i \in B) \\ 0, if \ \sum_{i=u}^{v} p_i g_{im} \le T \ and \ (\tau_i < C \ or \ i \in B) \end{cases} \quad (11)$$

3.4.6.Relay Selection Game Formulation

This model produces empirical evidence that can be used to predict if a PT-PR pair will be able to get into cooperation with a set of relays (i.e. the probability of establishing a path) that improve its SINR. Initially, the primary transmitter will perform direct transmission to the primary receiver in order to establish the baseline SINR. Once the baseline SINR has been determined, the PT-PR pair will resend the signal by employing the help of secondary users.

In this relay selection game, the players consist of the transmitters and the receivers of the primary communication pairs and the secondary users, which are denoted as primary players and secondary players, respectively. The players are connected according to some network relationship summarized by an undirected graph *G(V, E)*, with *V* being the players and *E* being the set of links connecting two interacting players in the game.

Definition 1: (Path) A path, *D*, of the PT-PR pair is defined as a subset of *E* consisting of a sequence of players, i.e. $D = \{(\upsilon_k, \upsilon_{k+1}) \in E \mid k = 1, 2, \ldots, k\text{-}1, \upsilon_1 =$

PT, υ_k = PR}, and (υ_k, υ_{k+1}) is a directed link from υ_k to υ_{k+1} and k is the number of players on the path.

In this game, the action of each player is reflected by the operation on links. The action space contains two operations: add a link or back-off a link. The primary players, specifically the PT, initiate the cooperation. Secondary users may accept or reject a request for cooperation. The PR does not play any strategies. The measurement point monitors communication links.

Definition 2: (Action Space) The action space of PT is defined as $\boldsymbol{S} = \{s(i) = [+(\upsilon_k, SU_i), -(\upsilon_k, SU_i)] \mid SU_i \in (N \cap V) \setminus V_D, \upsilon_k \in V_D\}$.

In other words, a strategy is a sequence of actions that form communication links by adding a link, $+(\upsilon_k, SU_i)$, or backing off a link, $-(\upsilon_k, SU_i)$. $D+s(i)$ denotes the modified path after an action is taken.

Definition 3: (Beneficial Action) An action $s(i) \in \mathbf{S}$ is a beneficial action for PT if and only if $u_i(\gamma_i) > u_{PT}(\gamma_{PT})$ and $\tau_i \geq C$.

Definition 4: (Action Preference List) An action preference list $\bar{S}$ is the set of all its beneficial actions sorted in increasing order of distance from the PT.

The action preference list is limited to one-hop neighbors. According to the simple path loss model in [28], link gain is a strictly decreasing function of the distance between the transmitter and the receiver, so the following inequations are satisfied in our system model of Figure 4.

$$g_{PT,1} > g_{PT,PR}, g_{PT,3} > g_{PT,PR} \qquad (12)$$

Definition 5: (Best Action) An action s(i*) $\in$ **S** is the best action of PT if and only if s(i*) is in the first place of the action preference list $\bar{S}$.

3.4.7. Algorithm

We assume that each player wants to maximize their own utility. Players want to use large transmission power to obtain high SINR at the receiver. Initially, $D = \emptyset$. During the distributed relay selection process, the PT exploits the measurement point to determine the next-hop relay. The PT selects the next-hop relay according to the following steps:

1. QoS Arbitration

   PT announces its cooperation information to its one-hop neighbors, identified by the measurement point. Then each neighbor determines its QoS ($u_i(\gamma_i)$) obtained from PT and feedbacks the cooperation information, including its transmit power from P_i.

2. Handover Request

   After receiving the replies from all one-hop neighbors, PT computes the payoff ($U_i(\boldsymbol{p})$) for the add action in S and makes the corresponding action preference list $\bar{S}$. If $\bar{S} = \emptyset$, PT does not have any incentive to cooperate. Otherwise, it sends an offer to SU_{i^*}, which corresponds to the best action $s(i^*)$, and then removes $s(i^*)$ from $\bar{S}$. With this removal, the best action of PT changes after each handover request and an SU receives the offer from PT at most once during each round.

3. Cooperation Agreement

   PT gets into cooperation with SU_{i^*} if its offer is accepted, and it is out of cooperation if it is rejected by SU_{i^*}. At this point, the measurement point

determines the allowable QoS of each secondary player in the given ECA, using an inverse linear distribution that affords *s(i*)* the greatest gain.

Algorithm 1 Reputation-Based Power Control Game
Initialization: the network graph *G(V, E)*, $D = \emptyset$, k = 0
repeat
k = k + 1
PT announces cooperation information to *H*
for all SU_i : *H*
Compute $u_i(\gamma_i)$
Send PT cooperation information
PT computes $U_i(\boldsymbol{p})$ for all *H*
if $\bar{S} \neq \emptyset$
Remove *s(i*)* associated with SU_{i^*} from $\bar{S}$
SU_{i^*} accepts PT
Measurement point broadcasts allowable QoS
else
PT sends direct transmission to PR
until v_k = PR

3.4.8.Game Model

We consider a game in strategic form. Let RBPCG = $[K, \{P_i\}, \{U_i\}]$ denote the noncooperative reputation-based, power control game. Here *K* are the set of players on a path from PT to PR. Each player picks a transmit power from the strategy space P_i which is continuous and receives a payoff $U_i(\boldsymbol{p})$.

Theorem: There exists a unique Nash equilibrium (NE) for the RBPCG, a path profile (strategy profile), which is

$$d^* = (d_1^*, d_2^*, \dots, d_k^*) \quad (13)$$

Proof: In the case of cooperative communication, the received SINR from PT to PR will be the smallest of the multi-hop relaying. An effective SINR (γ_e) is defined to describe this.

$$\gamma_e = \min(\gamma_{v_2}, \dots, \gamma_{v_k}) \quad (14)$$

By definition, the best action $s(i^*)$ has a utility that is greater than that of a direct transmission. If $\gamma_{v_i} > \gamma_{PT}$ $\forall i \in K$ and $u_i(\gamma_i) > u_{PT}(\gamma_{PT})$ $\forall i \in K$, then $\gamma_e > \gamma_{PT}$ and $u_e(\gamma_e) > u_{PT}(\gamma_{PT})$. Therefore, a path profile d^* is a NE if it is a fixed point of the best responses, i.e.

$$u_i(d_i^*, d_{-i}^*) \geq u_i(d_i', d_{-i}^*) \quad (15)$$

for any d_{-i}^* and any user i. Here, $d_{-i}^* = (d_1^*, \dots, d_{i-1}^*, d_{i+1}^*, \dots, d_K^*)$. In a Nash equilibrium, none of the players can improve its utility function by unilaterally changing its next-hop relay. Therefore, a NE is a stable outcome of the game.

Lemma 1: The NE for the RBPCG maximizes the payoff U_i (***p***) when each player is afforded a QoS allocation at the measurement point by using an inverse linear distribution of the received interference temperature threshold, i.e.

$$p_i g_{im} = \frac{T}{nA - \boldsymbol{E}}(A - e_i) \quad (16)$$

Proof: The reason this maximizes the utility function for a given path profile is explained as follows.

According to Definition 4, players in the action preference list are ranked according to the simple path loss model. Let e_i for $i = 1, 2, \dots, n$ be the distance of each player in a given effective communication area. The set of nodes e_i $\forall i \in n$ consists of the players in $\bar{S}$ (listed first) followed by the remaining nodes in the ECA (sorted in increasing order of distance from PT). $A = \max e_i$ is the distance of the player with the largest distance from the PT. An inverse linear distribution can be identified using the variable $x_i = A - e_i$, where each f_i $(p_i g_{im})$ is proportional to x_i.

$$f_i = \alpha x_i$$

$$\sum_{i=1}^{n} f_i = T$$

After substitutions of f_i and x_i, the formula becomes

$$\alpha \sum_{i=1}^{n} A - e_i = T$$

Further simplification, results in

$$\alpha(nA - \sum_{i=1}^{n} e_i) = T$$

Solving for α yields

$$\alpha = \frac{T}{nA - \boldsymbol{E}}$$

where **E** is the sum of all distances.

So, the SINR of each player in the given ECA is expected to be

$$f_i = \frac{T}{nA - \boldsymbol{E}}(A - e_i)$$

$$p_i g_{im} = \frac{T}{nA - \boldsymbol{E}}(A - e_i)$$

Therefore, d_i^* is afforded the highest transmit power in order to maximize U_i (***p***).

The outcome for a given game is Pareto optimal if it is not possible for all the players to improve their payoffs by collectively agreeing to choose a strategy different from the Nash equilibrium. In other words, one player's payoff cannot be improved without making another player's payoff less.

Lemma 2: The Nash equilibrium is Pareto optimal if and only if the power threshold is reached at any given link along the path.

Proof: Suppose there exists a path D = (v_1, …, v_i, …, v_k). If the power constraint is not tight at each link (v_k, v_{k+1}), then any player may choose to deviate from such a cooperatively agreed-upon strategy in order to improve their payoff at the group's expense. That is, at each link there exists a power vector $\mathbf{p}$ = (p_1, …, p_i, …, p_n). If any player chooses to increase its transmit power by some factor θ, its SINR will also be increased. This would also result in a new power vector $\mathbf{p}'$ = $(p_1', \dots, p_i', \dots, p_n')$ and a new path D′. However, this increase by a single player causes

$$\sum_{i=1}^{n} p_i g_{im} = T + \theta \quad (17)$$

which violates the ITT and causes the player with the highest power (i.e. the player chosen to establish a link based on the inverse linear distribution) to be backed off. This Pareto optimal outcome describes a social optimal in the sense that no individual player can improve its payoff without making at least one other player worse off.

3.4.9. Performance of Nash Equilibrium

Now, let's consider the performance of the Nash equilibrium. Pareto optimal implies social optimal in our system which in turn results in a tight power constraint. Therefore,

$$U_i(p_i) = ln \frac{p_i g_{im}}{T - p_i g_{im} + \sigma_m}.$$

Denote $f_i = p_i g_{im}$, the system optimization problem can be presented by a constrained maximization problem. We want to maximize $\sum_{i=1}^{n} U_i(f_i)$, constrained by $\sum_{i=1}^{n} f_i = T$. Using the Lagrangian multiplier, we have the following equations:

$$L(f_i, \lambda) = \sum_{i=1}^{n} U_i(f_i) - \lambda(\sum_{i=1}^{n} f_i - T) = \sum_{i=1}^{n} ln \frac{f_i}{T - f_i - \sigma_m} - \lambda(\sum_{i=1}^{n} f_i - T).$$

The first order derivative of the optimal point

$$\frac{dL(f_i, \lambda)}{df_i} = \sum_{i=1}^{n} \frac{(T - f_i + \sigma_m)(T - 2f_i + \sigma_m)}{f_i(T - f_i + \sigma_m)^2} - \lambda n = 0.$$

Since an inverse linear distribution is used here, it is immediate to see that $f_i = \frac{T}{nA-E}(A - e_i)$, because $\sum_{i=1}^{n} f_i = T$. Based on the first order condition, the system utility is obviously continuous. The second order derivative satisfies

$$\frac{d^2L(f_i, \lambda)}{d(f_i)^2} < 0;$$

therefore, $U_i(p_i)$ is concave.

CHAPTER 4
METHODOLOGY

4.1. Introduction

This chapter reports the research methodology that was employed to address the research questions and to test the research propositions. The simulation environment is described here in detail. This dissertation focuses on a need to understand the social networking aspect of relay selection in cognitive radio networks. It aims to determine if humanistic behavior patterns may be applied to forming a successful communication chain in CRNs.

4.2. Research Methodology

In order to address the first research question, **"Is the newly proposed reputation-based model comparable to existing trust schemes?"**, the average trust values of randomly chosen nodes using the RBPCG are compared to the existing CONFIDANT and Information Theoretic schemes presented in [39].

To address the second research question, **"How is the quality-of-service (QoS) for primary users affected by incorporating the proposed game-theoretic approach to network formation?"**, a number of simulations were conducted to analyze the probability that a PT-PR pair will be able to get into cooperation with a set of relays (i.e. the probability of establishing a path) that improves its SINR. The details of the simulation environment are outlined in the next sections.

For the third research question, **“Can network constructions derived from social network models predict actual linkages in a cooperative multi-hop relaying network?”**, a number of simulations were conducted to analyze the use of the Latent Space in predicting relay selection. The details of the simulation environment are outlined in the next section.

Transition matrices were generated for each scenario conducted during simulation that identify probability measures that a given user will be chosen during any given round of play, based on observations from 100 rounds of play. In the n x n matrix, senders are represented as rows, and one-hop neighbors are represented as columns, for any given network. The grand mean frequency for each sender’s one-hop neighbors is an entry in the transition matrix. Output from the simulations was analyzed by overlay plots.

For the final research question, **“What is the current use of social networking theory and social capital to predict relay selection in cognitive radio networks?”**, a comprehensive review of literature is performed. Detailed comparisons and contrasts will be provided of the findings.

4.3. Simulation Environment

We consider a multi-channel primary wireless network based on WiMAX (Worldwide Interoperability for Microwave Access), with multiple SUs assisting PUs on the uplink. This research proposes a technique that serves as an add-on component to the existing primary network and is opportunistically

harvested. It does not call for major change in the existing primary infrastructure, and therefore is of great practical interest.

WiMAX (Worldwide Interoperability for Microwave Access) refers to the interoperable implementations of a wireless communications standard (IEEE 802.16). WiMAX is similar to WiFi, but on a much larger scale and at faster speeds. 802.11 has ranges up to about 820ft and 54Mbps, while 802.16 has ranges up to about 40 miles and 70Mbps. 802.16's primary application is broadband wireless access. In contrast, 802.11 is intended for wireless local area networks (LANs). The bandwidth and range of WiMAX make it suitable for providing "portable mobile broadband connectivity across cities and countries through a variety of devices" [58]. WiMAX has the potential to do to broadband Internet access what cell phones have done to phone access. It operates on the same general principle as WiFi, sending data from one computer to another using radio signals. [59]

The WiMAX module provided by ns-3 provides a MAC and PHY level implementation of the 802.16 standard with point-to-multipoint mode and a wirelessMAN-OFDMA PHY layer. The figure below shows the WiMAX architecture.

In this infrastructure, the uplink scheduler at the base station decides which of the secondary users will be assigned uplink allocations based on the QoS parameters associated with the RBPCG. When a service flow is created, the uplink schedule calculates necessary parameters based on the QoS requirements.

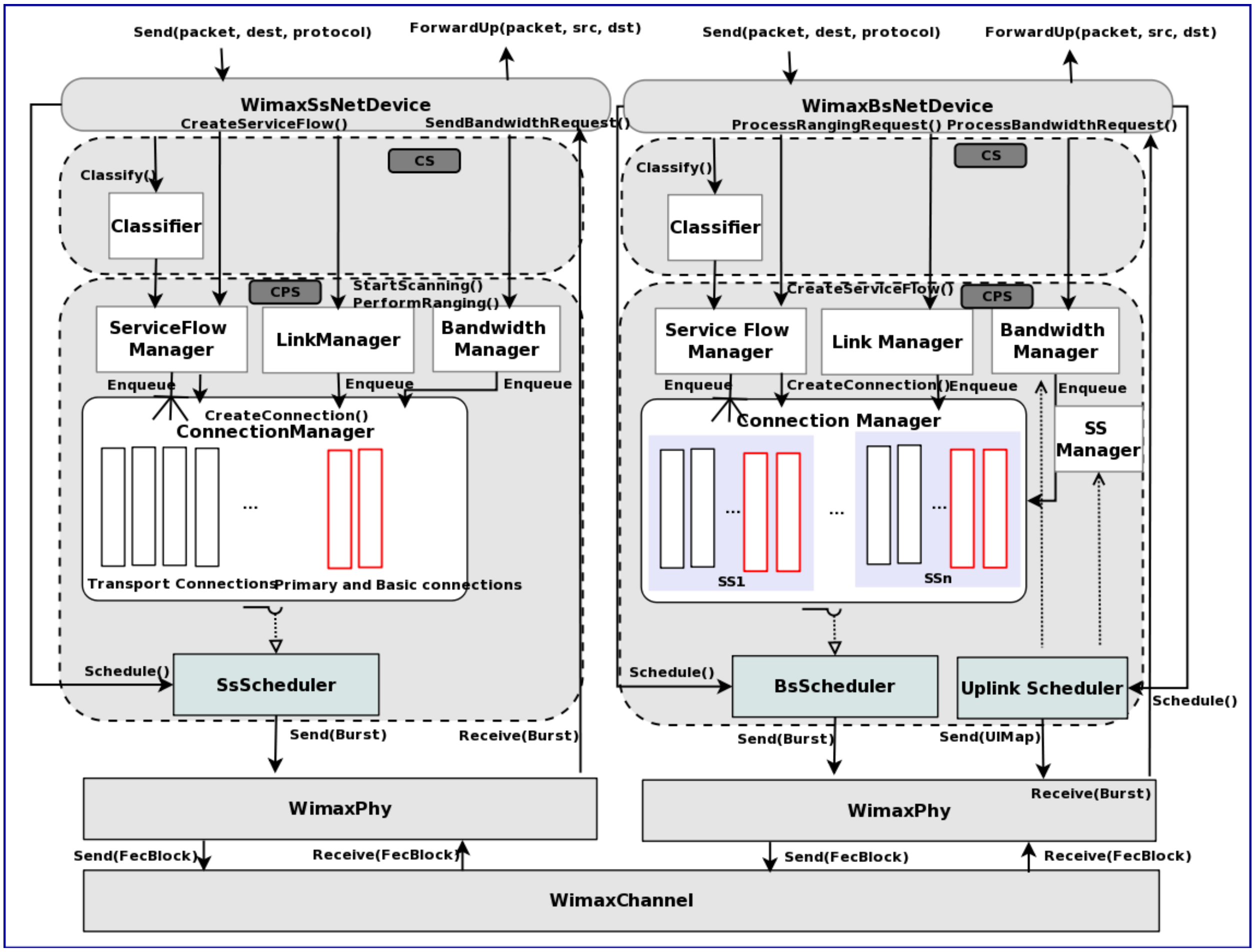

Figure 5: WiMAX Architecture [60]

4.4. Simulation Parameters

The existing WiMAX module in ns-3 will be used as the control group. There will be two primary base stations. To check the impact of the number of relays, we will uniformly deploy 5, 20, 100, 200, 500, and 1000 secondary users within the network. A network graph G is randomly generated for each scenario. This network graph identifies each user's one-hop neighbors and their distances from each other, along with the primary base station that it is in the vicinity of. The interference temperature threshold (ITT) is 11dB for a

network on the 2.5GHz frequency band, using 16QAM (1/2) modulation. The threshold of the number of rounds of plays for each network is 100.

We investigate the performance of the RBPCG based on the following performance metrics:

- the average packet loss,
- the ratio of transmissions with improved SINR from cooperative communication,
- the average SINR of direct transmissions compared to the average effective SINR,
- the minimum edit distances,
- the average path length, and
- the standard deviations of the mean SINR .

CHAPTER 5
RESEARCH RESULTS AND FINDINGS

5.1. Introduction

This chapter reports the findings and statistical results for the dissertation. Various analyses were performed in this study. JMP® 11.2.0 statistical software was used in the numerical experiments.

5.2. Analysis of Research Question 1

Let's consider the first proposition: "The new distributed, game-theoretic approach to relay selection in CRNs, using trustworthiness as social capital, is comparable to existing trust schemes". In [39], Pai et al. discussed the Information Theoretic scheme and the CONFIDANT scheme. Both of these trust mechanisms have been proposed in wireless ad hoc networks. In these schemes, a trust value, also called a direct trust value, is assigned by node i to node j as a function of a history of positive and negative interactions with that node. The Information Theoretic scheme using the binary entropy function $\sum_x p(x)\log p(x)$ to update the direct trust values. The CONFIDANT scheme uses a beta probability function $\frac{\alpha}{\alpha+\beta}$ to update the direct trust values.

The reputation-based trust model for the RBPCG also uses a beta probability function; however, it takes into account both alpha and beta vectors, along with consideration of ITT violations. In order to compare the RBPCG scheme with the Information Theoretic and CONFIDANT schemes, the trust value of nodes was observed and recorded after the 100 rounds of game play. Various confidence levels were used in order to aid in the comparison.

The subjects of one such comparison are listed below.

- node 2 from the 5-node network
- node 13 from the 20-node network
- node 24 from the 100-node network
- node 99 from the 200-node network
- node 200 from the 500-node network
- node 682 from the 1000-node network

The table below offers a visual comparison of the subjects' final trust value. These values are based on observations from all one-hop neighbors.

It is evident from this table that the trust values assigned using the Information Theoretic scheme, decrease much slower than both the CONFIDANT and RBPCG schemes. The RBPCG trust model is comparable to the CONFIDANT trust mechanism with average trust values differing from 0.0001 to 0.02. This theoretical trust model is the framework used to analyze the research questions and propositions.

5.3. Analysis of Research Question 2

The research question, "How is the quality-of-service (QoS) for primary users affected by incorporating the proposed game-theoretic approach to network formation?", was investigated by comparing various network metrics.

Table 1: Trust Scheme Comparisons

# Nodes	Trust Threshold	0.3	0.5	0.7
5	CONFIDANT	0.7011	0.7014	0.7014
	Information Theoretic	0.9144	0.9144	0.9144
	New Scheme	0.7010	0.7011	0.7011
20	CONFIDANT	0.8736	0.8736	0.8736
	Information Theoretic	0.9090	0.9090	0.9090
	New Scheme	0.8527	0.8527	0.8527
100	CONFIDANT	0.6881	0.6882	0.6882
	Information Theoretic	0.7215	0.7215	0.7215
	New Scheme	0.6867	0.6867	0.6867
200	CONFIDANT	0.7477	0.7477	0.7477
	Information Theoretic	0.8220	0.8221	0.8221
	New Scheme	0.7333	0.7333	0.7333
500	CONFIDANT	0.8961	0.8961	0.8961
	Information Theoretic	0.9722	0.9722	0.9722
	New Scheme	0.8880	0.8880	0.8880
1000	CONFIDANT	0.8419	0.8420	0.8420
	Information Theoretic	0.9254	0.9254	0.9254
	New Scheme	0.8363	0.8363	0.8363

A number of simulations were conducted to determine if the newly proposed algorithm is comparable in performance to the existing infrastructure and to analyze the probability that a PT-PR pair will be able to get into cooperation with a set of relays (i.e. the probability of establishing a path) that improve its SINR.

The figure below describes the ratio of packet loss. Packet loss varies based on details of the data transmission including, but not limited to,

modulation and coding. The red line represents the system without RBPCG, and the blue line represents with RBPCG. There is a slight decrease in packet loss with the RBPCG. This may be attributed to the cooperative communication employed by RBPCG that affords higher SINR to relays agreeing to assist the primary users. Higher SINR guarantees a better signal at the receiver.

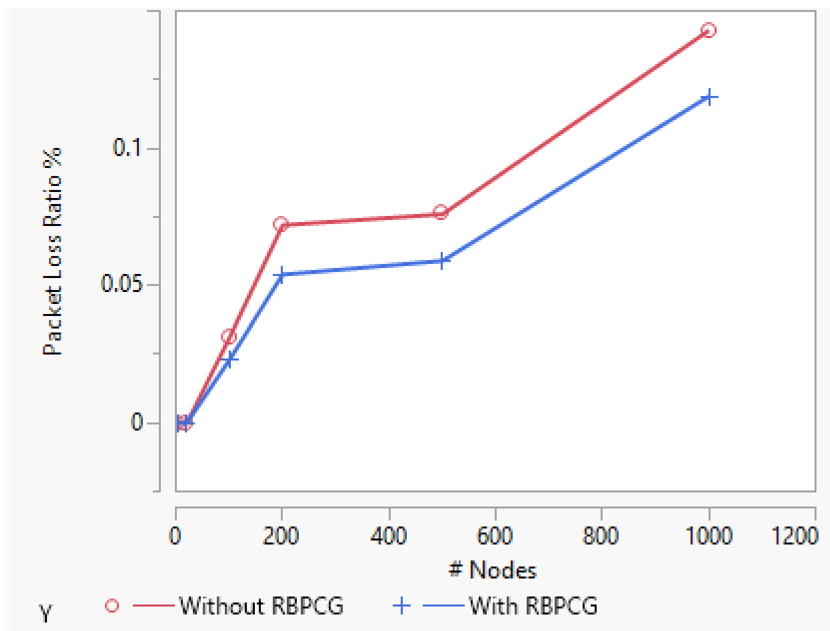

Figure 6: Packet Loss Without RBPCG versus With RBPCG

The next figure demonstrates the percent of transmissions (i.e. rounds of game play) that utilized cooperative communication and, therefore, the primary users enjoyed a higher payoff. It is evident from the research that this improvement decreases as the number of nodes increases.

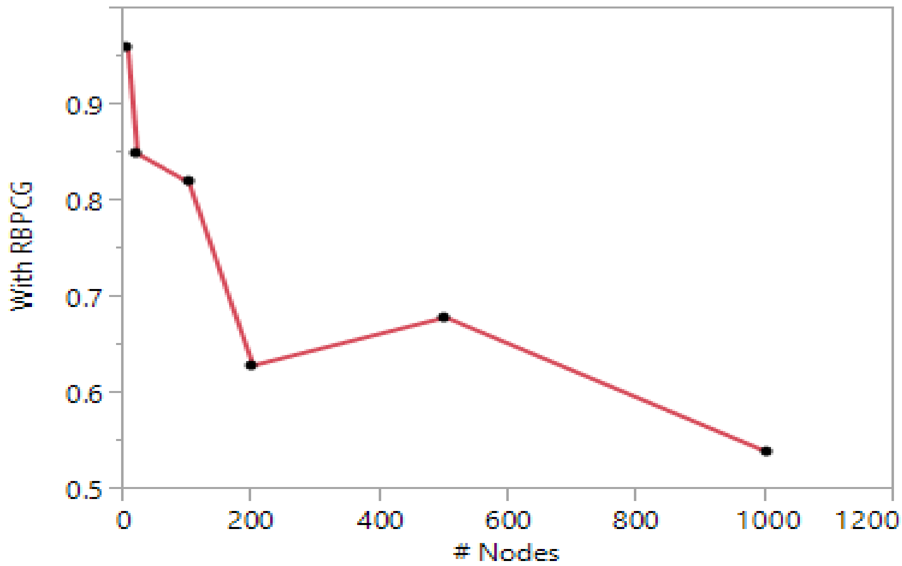

Figure 7: Ratio of Transmissions with Improved SINR

Consider Figure 8. Here, the bilinear model, fitted to a cubic polynomial function with Rsquare of 0.918, appears to show that the average SINR enjoyed by primary users in direct transmissions is a good predictor of the effective SINR enjoyed by the same users using cooperative communication. However, the average effective SINR is slightly lower than that of direct transmissions.

5.4. Analysis of Research Question 3

Due to the overlapping conceptualizations between cognitive radio networks and social network theory, a social network model was applied to the relay selection problem. The third proposition states “The latent space model [32] may be applied in CRNs to predict relay selection”. Logistic regression analysis was used to explore the applicability of the Latent Space model to relay selection in cognitive radio networks.

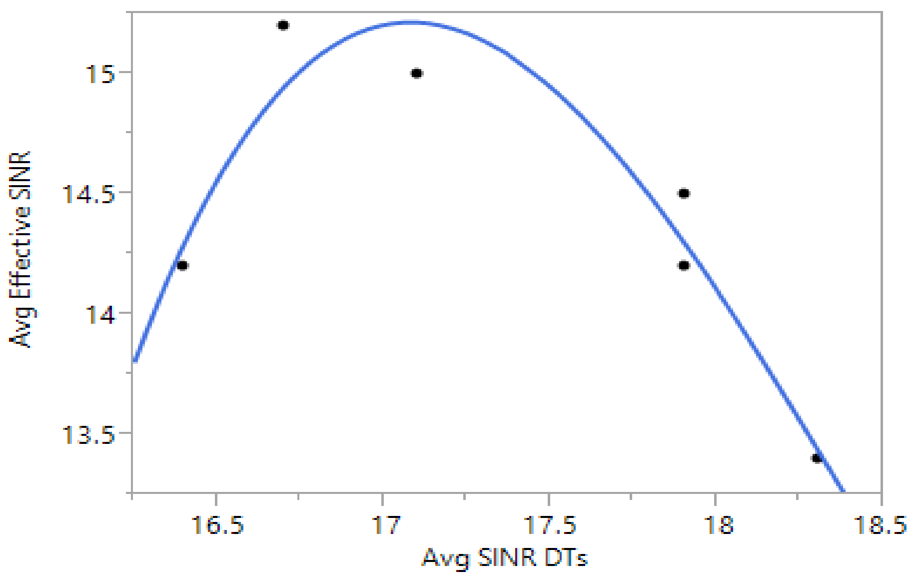

Figure 8: Average SINR of DTs Compared to Average Effective SINR

In this social network model, Hoff et al. provide a probability measure over unobserved characteristics of a social network in which the presence of a tie between two individuals is dependent on the presence of other ties. In other words, the observation of $i \to j$ and $j \to k$ suggests that i and k are not too far apart in social space.

[32] uses the log odds function to estimate unobserved ties. In the cognitive radio network scenario, the log odds model can be used to construct a Markov chain. A Markov chain can be described as a set of states $Z = \{Z_0, Z_1, \ldots, Z_r\}$, where Z_0 is the start state. $\hat{Z} = \{Z_i, \ldots, Z_h\}$ is the set of states where the Euclidean distance from the current state is 1, and h is the number of one-hop neighbors for a given user. The basic algorithm is to reiterate the steps below. The process described is initiated by the primary transmitter.

1. Using $Z_0 = \hat{Z}$ as a starting state. Construct a Markov chain over model parameters as follows:

a. for all $i : h$

i. $Z' = \arg\max Q(i, a)$

b. Accept Z' with probability $\mathbb{P}(R_{i|a})$, where $\mathbb{P}(R_{i|a})$ is the value from the transition matrix.

2. Repeat this process using the node selected in step 2.

Here, Q is the value of the log odds function with i and a providing indexes into the corresponding transition matrix.

In each case, the Latent Space model [32] can eventually predict the actual path for each network with 100% accuracy. Table 2 provides the minimum edit distance (Levenshtein distance) between the actual path and the predicted path for each network. The minimum edit distance is a way of quantifying how different two strings are to one another by counting the minimum number of operations (insert, delete, and substitute) required to transform one string into the other. The prediction is 100% accurate to the stable path at the completion of the 100th round. In other words, the minimum edit distance is zero at the end of each game. This is true in all scenarios, across all networks.

The figure that demonstrates the average path length clearly shows that the average path length increases as the number of nodes in the network increases. This can be expected as the density of users increases in a given effective communication area. Therefore, a growth in the number of secondary users willing to cooperate with primary users is demonstrated.

Table 2: Minimum Edit Distances for All Games

Set	5 Nodes	20 Nodes	100 Nodes	200 Nodes	500 Nodes	1000 Nodes
1	2	4	12	15	8	10
2	1	5	10	10	8	10
3	2	3	6	6	4	7
4	1	5	6	4	1	3
5	0	4	2	4	0	0
6	0	4	0	2	0	0
7	0	0	0	0	0	0
8	0	0	0	0	0	0
9	0	0	0	0	0	0
10	0	0	0	0	0	0

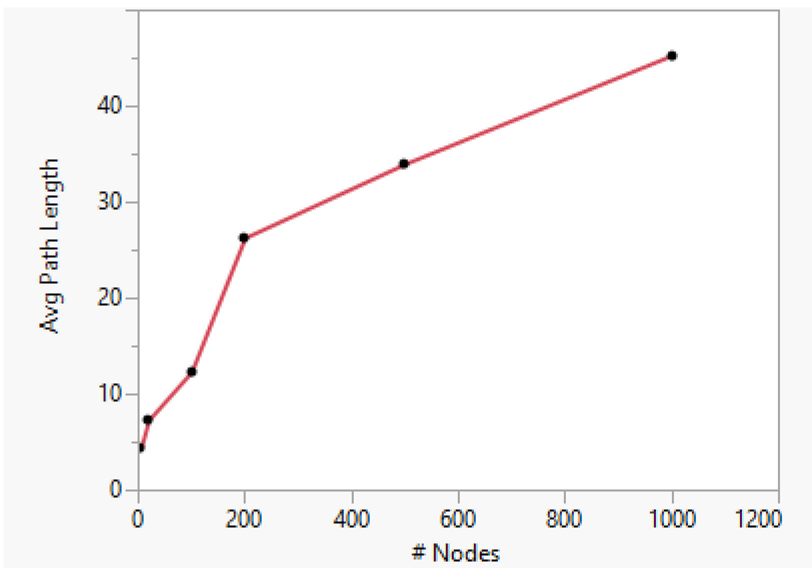

Figure 9: Average Path Length

The next figure shows the standard deviation of the average SINR of each network scenario. The mean comparisons are between the network scenarios with and without the reputation-based power control game. It's obvious that there is little variation in the data sets.

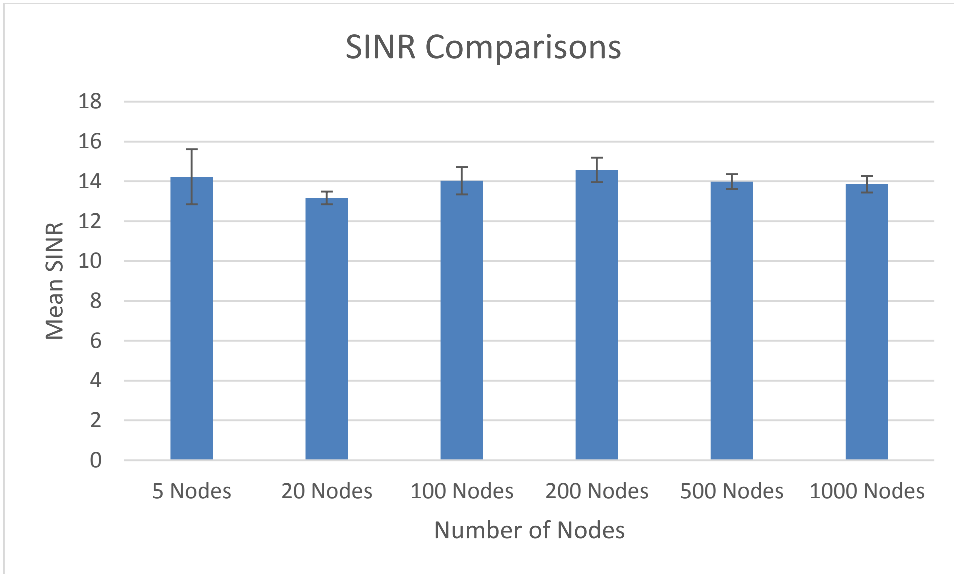

Figure 10: SINR Comparisons

5.5. Analysis of Research Question 4

To address the last research question, "What is the current use of social networking theory and social capital to predict relay selection in cognitive radio networks?", an exhaustive review of literature was conducted for research related to using social network models as a tool to predict relay selection in CRNs. This search has shown a severe inadequacy of research in this area. As noted in Section 2.3.3, [29], [35], [39], [40], and [43] have conducted research on using SNT in CRNs related to discovering dynamic spectrum access, behavior propagation, bidirectional ties, and mobility. To my best knowledge, this research is the first to study the use of social network models to predict relay selection in cognitive radio networks. This is one of the major contributions of this dissertation.

The table below identifies the literature discovered that is relevant to social network theory and social capital in cognitive radio networks.

Table 3: SNT and CRNs Literature Review

Title	Date of Publication	Authors	SNT and CRN Research?	Relay Selection?	Contributions
Behavior Propagation in Cognitive Radio Networks: A Social Network Approach	2014	Li, Song, Chen, Lai, Qiu	Yes	No	Studied social behavior propagation in CRNs by applying the model of interacting particles
Improving the Community Behavior of Social Network Theory Based Mobility Model for MANET	2008	Gunasekaran, Nagarajan	Yes	No	Proposed a mobility model to detect the movement of nodes
Trust-aware Resource Allocation in a Cognitive Radio System	2012	Qin, Leung, Miao, Chen	Yes	No	Developed a mechanism where trustworthiness is used as social capital to improve radio spectrum utilization
Trust-based Data Fusion Mechanism Design in Cognitive Radio Networks	2014	Wang and Chen	Yes	No	Developed a trust-based data aggregation scheme to enhance spectrum sensing capabilities
Using Social Network Theory Towards Development of Wireless Ad hoc Network Trust	2007	Pai, Roosta, Wicker, Sastry	Yes	No	Proposed a trust-based scheme that uses balance theory to predict bidirectional ties among users

CHAPTER 6
CONCLUSIONS

This research examined the applicability of social networking and social capital theories in the context of cognitive radio networks' ability to predict users' intentions in network formation, a technique that could be utilized in many real world scenarios. A major concern in CRNs is relay selection in a distributed, multi-hop environment. The cooperation between the primary and secondary users is critical to accomplish this. Cognitive users are similar to humans in social networks as they can sense their environment, make decisions based on observations, and act on these decisions.

These similarities allow cognitive radio networks to be likened to online communities. The social phenomena underlying online communities can be directly related to network formation. Research in building, discovering and analyzing online communities is increasingly important as the Internet becomes the largest collection of ideas, personalities, and cultures in history. These communities represent groups of individuals connected by some social relation, such as a trusted contact link in a business network, a family relationship, or a collegiate organization.

In this dissertation, a novel network formation game is applied to form a multi-hop path between a primary transmitter and its receiver, employing secondary users as relays. It also focused on a need to understand the social networking aspect of relay selection in cognitive radio networks. One of its main contributions is that it provides empirical data showing that a social

network model may be applied to predicting relay selection in cognitive radio networks.

This research has shown that this technique has not been applied previously to relay selection in cognitive radio networks. Table 3 shows evidence of studies that applied social network theory to cognitive radio networks. None of these studies used it in relay selection.

Table 4 provides a summary of the results of the research propositions. As with all research, the current study has certain limitations. They include the following:

- Small sample size,
- Theoretical study as opposed to field study, and
- Use of a social network model not specifically designed to evaluate the field of cognitive radio networks.

An overall recommendation is to continue research that leads to the improvement of the RBPCG algorithm and tests the applicability of more social network models to relay selection in cognitive radio networks.

Table 4: Summary of Results

Propositions	**Results**
P1: The new distributed, game-theoretic approach to relay selection in CRNs, using trustworthiness as social capital, is comparable to current trust schemes.	The reputation-based technique introduced here decreases at a faster rate than the Information Theoretic scheme and the CONFIDANT schemes.
P2: The QoS enjoyed by primary users is improved by using secondary users to transmit primary data.	The rate of packet loss is slightly lower after the RBPCG is introduced. The average effective SINR of cooperative communication is slightly lower than that of direct transmissions.
P3: The latent space model [32] may be applied in CRNs to predict relay selection.	The latent space model [32] may be applied to relay selection and provided 100% accuracy of prediction to stable paths.
P4: This research presents the first solution to using social networking theories in relay selection for cognitive radio networks.	This is the first study of the applicability of social networking theories in relay selection for CRNs.

REFERENCES

[1] Adams, Doug. *Cognitive Radio: Advantages and Challenges*. 11 June 2012. <http://large.stanford.edu/courses/2012/ph250/adams2/>.

[2] al., U. Wiggins et. "Data-Centric Prioritization in a Cognitive Radio Network: a Quality-of-Service based Design and Integration." *IEEE* (2008).

[3] Christensen, C. Pippin and H. "Incentive Based Cooperation in Multi-Agent Auctions." *Association for the Advancement of Artificial Intelligence* (2012): 61-68.

[4] D. Yang, X. Fang, and G. Xue. "Game Theory in Cooperative Communications." 2012.

[5] J. Huang, Z. Chiang, H. Poor. "Auction-Based Resource Allocation for Cooperative Communications." *IEEE* (2008): 1226-1237.

[6] K. Chen, Y. Peng, N. Prasad, Y. Liang, S. Sun. *Cognitive Radio Network Architecture: Part II - Trusted Network Layer Structure*. 10 March 2008. <http://santos.ee.ntu.edu.tw/Publication/Cognitive_radio_network_architecture_part_II_trusted_network_layer_structure.pdf>.

[7] L. Cottatellucci, X. Mestre, E. Larsson, and A. Ribeiro. "Cooperative Communications in Wireless Networks." *EURASIP Journal on Wireless Communications and Networking 2009* (2009).

[8] Lane, Bill. *Topic 8: Cognitive Radio for Public Safety*. n.d. <http://transition.fcc.gov/pshs/techtopics/techtopic8.html>.

[9] Lee. *Introduction to Cognitive Radio and Dynamic Spectrum Access*. 25 November 2009. <http://www.wirelessinnovation.org/assets/documents/Introduction%20to%20CR%20and%20DSA.pdf>.

[10] M. Cesana, F. Cuomo, and E. Ekici. "Routing in cognitive radio networks: Challenges and solutions." *Ad Hoc Networks* (2010).

[11] Nalebuff, A. Dixit and B. *Prisoner's Dilemma*. 2008. <http://www.econlib.org/library/Enc/PrisonersDilemma.html >.

[12] O. Simeone, I. Stanojev, S. Savazzi, Y. Bar-Ness, U. Spagnolini, and R. Pickholtz. "Spectrum Leasing to Cooperating Secondary Ad Hoc Networks." *IEEE* (2008): 203-213.

[13] Rodriguez, O. *Spectrum Sensing and Multiple Access Schemes for Cognitive Radio Networks*. Ontario, 2013.

[14] Stephanie. *Software Defined Radio*. 20 May 2008. <http://www.wirelessinnovation.org/assets/documents/SoftwareDefinedRadio.pdf>.

[15] T. Jing, S. Zhu, H. Li, X. Cheng, and Y. Huo. "Cooperative Relay Selection in Cognitive Radio." *IEEE* (2013): 175- 179.

[16] W. Li, X. Cheng, T. Jing, and X. Xing. "Cooperative Multi-hop Relaying via Network Formation Games in Cognitive Radio Networks." *IEEE* (2013): 971-979.

[17] Y. Kondareddy, P. Agrawal, and K. Sivalingam. "Cognitive Radio Network Setup without a Common Control Channel." *IEEE* (2008).

[18] Chouhan, L. 1 September 2011. *http://www.trai.gov.in/WriteReadData/Events/Presentation/PPT/201111230248091562500Lokesh_Chauhan.pdf*. 8 July 2014.

[19] J. Mitola, G. Q., Jr. "Cognitive Radio: Making Software Radios More Personal." *IEEE* (1999): 13 - 18.

[20] J. Perez-Romero, L. Doyle, M. C. Vuran. "Applications of Cognitive Radio Networks." *Vehicular Technology Magazine, IEEE* 2012.

[21] K. Chen, Y. Peng, N. Prasad, Y. Liang, S. Sun. "Cognitive Radio Network Architecture: Part I - General Structure." 10 March 2008. *http://fcom.ee.ntu.edu.tw/papers/Cognitive_radio_network_architecture_part_I_general_structure.pdf*. 7 July 2014.

[22] M. Felice, R. Doost-Mohammady, K. R. Chowdhury, L. Bononi. "Smart Radios for Smart Vehicles: Cognitive Vehicular Networks." *Vehicular Teechnology Magazine, IEEE* 2012.

[23] Mitola, J. "Cognitive Radio Architecture Evolution." *Proceedings of the IEEE* (2009): 626 - 641.

[24] "Wireless Innovation Forum." 20 May 2008. *http://www.wirelessinnovation.org/what_is_sdr*. 4 April 2014.

[25] Borgatti, S. (2006). Identifying sets of key players in a social network. *Comput Math Organiz Theor*, 21 - 34.

[26] Fanfan, Y. (2011). Insights into Social Network Theory and Entreprenurship. *2011 International Conference on Management and Service Science*, 1 - 4.

[27] Fletcher, R. e. (2011). Social network models predict movement and connectivity in ecological landscapes. *PNAS*, 19282- 19287.

[28] Gong, X. e. (2008). A Cooperative Relay Scheme for Secondary Communication in Cognitive Radio Networks. *IEEE GLOBECOM 2008 Proceedings*, 1 - 6.

[29] Gunasekeran, S. a. (2008). Improving the Community Behaviour of Social Network Theory Based Mobility Model for MANET. *International Conference on Computing, Communication and Networking*, 1- 7.

[30] Hanaoka, S. e. (2007). Simulation Results of Inter Radio System Handover For Cognitive Radio. *Taiwan-Japan Joint Conference on Communications Technology* , 89 - 92.

[31] Hoff, P. (2003). Bilinear Mixed Effects Models for Dyadic Data. *J Am Stat Assoc 100*, 286 - 295.

[32] Hoff, P. e. (2002). Latent Space Approaches to Social Network Analysis. *American Statistical Association*, 1090 - 1098.

[33] Khan, S. e. (2012). Distributed Resource Map: A Database-driven Network Support Architecture for Cognitive Radio Ad hoc Networks. *IEEE IV International Congree on Ultra Modern Telecommunications and Control Systems*, 188 - 194.

[34] Li, H. a.-f. (n.d.). *Collaborative Research: Design, Analysis and Implementation in Cognitive Radio Networks.* Retrieved from National Science Foundation: http://www.nsf.gov/mps/ast/ears/1247834Li_pres.pdf

[35] Li, H. e. (2014). Behavior Propagation in Cognitive Radio Networks: A Social Network Approach. *IEEE Transactions on Wireless Communications*, 646 - 657.

[36] Lin, N. (1999). Social Networks and Status Attainment. *Annual Reviews*, 467 - 487.

[37] Lugo, H. a. (2006). Incentives to Cooperate in Network Formation. *Computational Economics*, 15 - 27.

[38] Meng, Q. a. (2012). Determining the number of clusters in co-authorship networks using social network theory. *Second International Conference on Cloud and Green Computing*, 337 - 343.

[39] Pai, S. e. (2007). Using Social Network Theory Towards Development of Wireless Ad hoc Network Trust. *Advanced Information Networking and Applications Workshops*, 443 - 450.

[40] Qin, T. e. (2012). Trust-aware Resource Allocation in a Cognitive Radio System. *2012 IEEE International Conference on Computer Science and Automation Engineering*, 797 - 801.

[41] Smith, M. (2008). Social Capital in Online Communities. *Proceedings of the 2nd PhD workshop on Information and knowledge management* , 17 - 24.

[42] Teacy, W. T. (2006). TRAVOS: Trust and Reputation in the Context of Inaccurate Information Sources. *Auton Agent Multi-Agent Sys*, 183 - 198.

[43] Wang, J. a.-R. (n.d.). Trust-based Data Fusion Mechanism Design in Cognitive Radio Networks.

[44] Warner, R. e. (1979). A New Round Robin Analysis for Variance for Social Interaction Data. *Journal of Personality and Social Psychology*, 1742 - 1757.

[45] Xin, C. a. (2009). A Cognitive Radio Network Architecture Without Control Channel. *IEEE GLOBECOM 2009 Proceedings*, 1 - 6. (Zhou)

[46] Bachman, Jonathan. *Reuters*. 13 June 2013. http://www.reuters.com/article/2013/06/13/us-chemicals-fire-idUSBRE95C0P120130613. 17 September 2014.

[47] Mangal, Varun. "Systems Theory and Social Networking: Investigation of Systems Theory principles in Web 2.0 Social Network Systems." *International Journal of Business and Commerce* (2013): 117 - 135.

[48] Vesely, Rebecca, and Suzanna Hoppszallern. *Health Facilities Management*. 2 July 2014. http://www.hfmmagazine.com/display/HFM-news-article.dhtml?dcrPath=/templatedata/HF_Common/NewsArticle/data/HFM/Magazine/2014/July/special-report-emergency-management-survey. 17 September 2014.

[49] xG Technology. n.d. http://www.xgtechnology.com/resources/presentations/cognitive-radio-for-public-safety-applications/. 17 September 2014.

[50] Brown, Michael, and M. Alkadry. "Social Networking and Individual Perceptions: Examining Predictors of Participation." *Springer Science* (2014): 285- 304.

[51] Chena, Rui, and S. Sharma. "Understanding Member Use of Social Networking Sites from a Risk Perspective." *Procedia Technology* (2013): 331- 339.

[52] Hammond, Scott, and L. Glenn. "The ancient practice of Chinese social networking: Guanxi and social network theory." *E:CO Special Double Issue* (2004): 24 - 31.

[53] Facchetti, G., et al. "Computing global structural balance in large-scale signed social networks." *PNAS* (2011): 20953 -20958.

[54] Jia, Juncheng and Q. Zhang. "A Non-Cooperative Power Control Game for Secondary Spectrum Sharing." *IEEE* (2007): 5933 - 5938.

[55] Xu, Hong, and B. Li. "Efficient Resource Allocation with Flexible Channel Cooperation in OFDMA Cognitive Radio Networks." *INFOCOM* (2010): 1 - 9.

[56] Zhang, Jin, and Q. Zhang. "Stackelberg Game for Utility-Based Cooperative Cognitive Radio Networks." *ACM* (2009): 23 - 31.

[57] Zhou, P., et al. "Joint Power and Rate Control in Cognitive Radio Networks: A Game-Theoretical Approach." *IEEE* (2008): 3296 - 3301.

[58] *http://en.wikipedia.org/wiki/WiMAX*. n.d. 3 May 2015.

[59] *http://computer.howstuffworks.com/wimax2.htm*. n.d. 2 May 2015.

[60] *https://www.nsnam.org/docs/models/html/wimax.html*. n.d. 11 January 2015.

VITA

Brandy Michelle Tyson-Polk, a native of Baton Rouge, Louisiana, was born on May 20th, to Robert and Mildred Tyson. After receiving her high school diploma from Tara High School, she continued on to Southern University and A&M College at Baton Rouge, Louisiana. She received her Bachelor of Science and Master of Science degrees in Computer Science in December 2001 and December 2003, respectively.

Thereafter, she obtained full time employment at Baton Rouge Community College where she taught Computer Science courses. As her interest in higher education grew, she began pursuing administrative positions at the community college and returned to school to pursue her doctorate.

She is a candidate for the degree of Doctor of Philosophy in Computer Science, which will be awarded in August 2015.