Mutual Benefit in Cognitive Radio Networks: A Coalitional Game Framework

Project Summary

Cognitive radio (CR) is a revolutionary wireless communication paradigm in which cognitive users are able to observe, learn, optimize, and intelligently adapt in order to improve utilization of spectrum without interfering with traditionally licensed users. Yet major technical challenges remain in order to make this vision a reality. *First*, to avoid interfering with primary users, the cognitive users must explore and sense the spectrum opportunities to determine whether there are ongoing activities before data transmission. *Second*, a critical issue is dynamic and opportunistic resource allocation over time-varying heterogeneous interfering environments. *Third*, due to hardware limitation, each cognitive user should distributively choose the candidate channels to either sense or access (i.e., exploration and exploitation).

Due to the distributed nature, the future network and protocol architectures for cognitive radio networks should be self-organized, distributed, and collaborative to overcome the above challenges. Game theory is a powerful and flexible mathematical tool to study how the autonomous users interact and cooperate with each other. Motivated by these facts, this proposed research constructs a framework to investigate the cooperative and competitive relations among individual distributed cognitive users, based on a variety of approaches to cope with the time-varying channel/traffic conditions, heterogenous user profiles, different QoS requirements, and security.

Intellectual Merit: The proposed five-year activities are primarily targeted at uncovering the fundamental design challenges/tradeoffs, proposing distributed solutions based on the game theory, and constructing hardware/software platforms with easy online access to other researchers.

- *Identify Major Problems in CR Networks.* The PI investigates *Spectrum Sensing* aspects such as collaborative sensing and its inherent tradeoff between false-alarm and detection probabilities; *Dynamic Spectrum Access* aiming at maximizing utilization of the limited radio bandwidth while accommodating the increasing amount of services and applications in wireless networks; and *Exploration & Exploitation* for balancing between spectrum sensing and spectrum accessing with consideration of channel variation, the licensed users' presence, and other cognitive users' activities.
- *Propose Coalitional Game Theory Approaches.* The PI proposes to employ the novel cooperative game theory that emphasizes mutual benefit management with simple distributed solutions. In the literature, only a small number of work has investigated the applications of the strong analytical tools of cooperative games in cognitive radio networks. The PI proposes solutions based on three categories of cooperative games: Canonical Coalitional Game, Coalitional Formation Game, and Coalitional Graph Game.
- *Hardware Implementation and Software Protocol Development.* The proposed schemes and frameworks will be implemented using the hardware/software platform in the newly established Wireless Networking, Signal Processing, and Security Lab at the University of Houston. The research outcomes will be shared and publicly available for other researchers worldwide.

Broader Impact: The proposed program is interdisciplinary and combines concepts from signal processing, economics, decision theory, optimization, information theory, communications, networking, and control theory. The results and design philosophy are transformative and can potentially be applied to other research areas. The results will be publicly available through publications and over the Internet for hardware/software platforms. Ultimately, the proposed framework will provide a blueprint for building new perspectives on future cognitive radio design. The research results will be integrated into the existing combined education and research effort at the University of Houston. Furthermore, the education component will equip both graduate and undergraduate students with the skills needed to contribute to the field of wireless networks partially based on the PI's three textbooks. Outreach activities will be directed to middle school and high school students and teachers, and will emphasize increasing the participation of women and minorities in science and engineering. As such, the broader impact resulting from the proposed activities is also reflected through the integration of research and education for the training of the future engineering workforce.

Section C: Project Description

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1 Introduction

The Federal Communications Commission (FCC) allows predetermined users the right to transmit at a given frequency. Under the traditional command-and-control spectrum licensing schemes, non-licensed users are regarded as harmful interference and are not allowed to transmit within certain frequency bands. As demands for wireless communication become more and more pervasive, wireless devices must find a way to transmit within the extremely limited radio bands. However, there exist a large number of frequency bands that have considerable, and sometimes periodic, dormant time intervals. In the literature, these frequency bands are referred to as spectrum holes [1, 2]. This creates a dilemma: on the one hand the mobile users have no spectrum to transmit, while on the other hand other spectrums are controlled, but not fully utilized.

In order to cope with this dilemma, the FCC has recently investigated management options providing efficient spectrum usage for cognitive radios. This is a novel paradigm that improves spectrum utilization by allowing secondary (unlicensed) users to borrow unused radio spectrum from primary licensed users or to share the spectrum with the primary users. As intelligent wireless communication systems, cognitive radios are aware of the radio frequency environment, can select the communication parameters (such as carrier frequency, bandwidth and transmission power) to optimize spectrum usage, and adapt transmission and reception accordingly. The emergence of cognitive radios can revolutionize the whole area of wireless communication and will significantly improve spectrum efficiency of wireless communication systems. The cognitive process is first to sense the available spectrum, gain spectrum access, utilize the available spectrum, and finally release the spectrum. Recently, a significant amount of research has been devoted to study the different aspects and challenges of cognitive radio networks.

In this proposal, the PI aims to develop a unified framework to provide a new perspective based on coalitional game theory for cognitive radio network design. To construct this framework, the PI focuses on the research topics and proposes the research objectives as follows.

1. The PI will identify the major and important research topics in CR networks. The research topics are unique and different from other traditional wireless networks.

- *Spectrum Sensing* has the objective of detecting the presence of transmissions from licensed (primary) users. Traditionally, spectrum sensing is performed by an individual CR user. In recently proposed collaborative sensing approaches [102, 108, 136], spectrum sensing information from multiple unlicensed users is exchanged in order to efficiently detect the presence of licensed users. This collaborative scheme increases the probability of detection but at the same time increases the false-alarm probability. Moreover, spectrum sensing in multichannel and multiuser networks is also a challenging task.

- *Dynamic Spectrum Access* is a mechanism to adjust spectrum resource usage in the near-real-time manner in response to changes in the users' objectives, changes of radio state, and changes in the environment and external constraints. The PI will concentrate on the design challenges and tradeoffs such as random access vs. coordinated access, noncooperative scheme vs. cooperative scheme, and social optimum vs. fairness.

- *Tradeoff Between Exploration and Exploitation* is as follows: Exploitation refers to the immediate benefit gained from accessing the channel with the estimated highest reward, whereas exploration is the process by which the cognitive users tend to probe more channels to discover better channel opportunities. The goal of the cognitive sensing strategy is to distributively and intelligently choose the channel(s) each cognitive user should probe at different time slots in order to maximize the expected throughput.

2. Novel resource allocation with an emphasis on micro-economics based approaches will be proposed. The behaviors of distributed cognitive radios range from complete autonomy to full compliance. For example, for the noncooperative approaches in the literature, the CR users are rivals and compete for the limited resources available. As a result, system performance and fairness are often very poor. To overcome these problems, the PI proposes coalitional game theoretical approaches. The basic idea is that cooperation can bring mutual benefits. In particular, the PI proposes the following three schemes for different network scenarios:

- *Canonical Coalitional Game* can bring mutual benefits whenever a number of CRs form a coalition. The main objectives are to analyze the stability of the grand coalition (the coalition of all users) and to achieve fairness of dividing the benefits. Different problem formulations and fairness criteria will be proposed for CR networks.
- *Coalition Formation Game* considers the case in which the clustered network is preferred to the grand coalition. The key goals are to identify which coalitions will form, what the optimal coalition size is, and how to assess the network structure's characteristics. Two main rules are proposed for forming and breaking coalitions, namely, the so-called merge and split rule.
- *Coalitional Graph Game* studies the case in which the players need to communicate with each other inside every coalition. The PI proposes to construct a low-complexity and stable algorithm to form a graph for the structure of such communication. Myopic and far-sighted approaches are constructed and analyzed.

3. The PI plans to implement hardware platforms and software protocols for the proposed research in the newly established Wireless Networking, Signal Processing, and Security Lab at the University of Houston. Solid plans will be elaborated so as to facilitate the proposed and future research. If funded, the lab facilities will also benefit other research activities being conducted in other departments such as computer science and mechanical engineering.

Broader Impact: The impact of the proposed research will be to improve the design methodology by providing the new perspectives and solution concepts using the framework of coalitional games. The unique angle of mutual benefit management for distributed CR users fills a significant gap in current research. In addition, novel schemes will be proposed and implemented by linking economic models to the engineering problems. The theoretical and practical implications of the proposed schemes can significantly push the research frontier of cognitive radios. The proposed program is interdisciplinary and transformative, combining concepts in signal processing, economics, decision theory, optimization, information theory, communications, networking, and control theory. The proposed research can also significantly boost the quality of the Ph.D. program, not only by impacting curriculum development but also through engaging undergraduate and graduate students in related research. The outreach activities will encourage high school students, especially female and minority students, to pursue science and engineering careers.

2 Background and Related Works

2.1 Cognitive Radio Network Infrastructure

Cognitive radio is a new wireless communication paradigm in which the transmission or reception parameters can be changed to achieve efficient communication without interfering with licensed users. This alteration of parameters is based on the active monitoring of several external and internal radio parameters, such as radio frequency spectrums, user behaviors, and network states. Cognitive radios can be designed as an enhancement layer on top of the Software Defined Radio (SDR) concept. An SDR system is a radio communication system that can tune to any frequency band and receive any modulation across a large frequency spectrum by means of programmable hardware that is controlled by software. By sensing the available spectrum, cognitive radios can adapt to the most suitable available communication links. As an analogy, consider the spectrum to be a typical freeway. On the freeway, high occupancy vehicles (HOV) can drive in the HOV lanes, but, the HOV lanes are infrequently occupied. A more efficient management system may be to reserve the HOV lanes for rush-hour traffic, and allow other vehicles to access the HOV lanes during lower-demand periods. In this sense, cognitive radios are similar to other non-HOV vehicles.

Cognitive radios can bring a variety of benefits. For a regulator, cognitive radios can significantly increase spectrum availability for new and existing applications. For a license holder, cognitive radios can reduce the complexity of frequency planning, facilitate secondary spectrum market agreements, increase system capacity, and reduce interference. For equipment manufacturers, cognitive radios can increase demands for wireless devices. Finally, for an individual user, cognitive radios can bring more capacity per user, enhance inter-operability and bandwidth-on-demand, and provide ubiquitous mobility with a single user device across disparate spectrum-access environments.

2.2 Current State of the Art

There has been an increasing research interest in cognitive radio networks during the last few years. Due to page limitation, only a few works are briefly explained here. Some other existing researches in the area are referred to in [3]-[135]. For *Spectrum Sensing* researches supported by the recent NSF-funded programs, D. Roberson in IIT constructs Spectrum Observatory System; Q. Zhao in UC Davis constructs learning algorithms; H. Dai at NCSU and H. Li at the University of Tennessee propose the quickest detection for spectrum sensing. In [47], the CRs collaborate by sharing their sensing decisions through a centralized fusion center that combines the CRs sensing bits using the OR-rule for data fusion. A similar approach is used in [48] using different decision-combining methods. In [49], spatial diversity techniques are proposed for improving the performance of collaborative spectrum sensing by combating the error probability due to fading on the reporting channel between the CRs and the central fusion center. Other performance aspects of collaborative spectrum sensing are studied in [50, 51, 52].

A lot of important work focuses on *Dynamic Spectrum Access*. Virginia Tech has a group of faculties working on dynamic spectrum access for cognitive radio [56, 57, 58, 59, 66, 68, 71]. H. Zheng at UC Santa Barbara employs cooperative game theory, auction theory, and graph theory [7, 8, 67]. X. Liu at UC Davis investigates smart-radio-technology-enabled opportunistic spectrum utilization [3, 4]. N. Mandayam at Rutgers develops game theoretic approaches for open access to spectrum of cognitive radios [28, 29, 30]. A. Lippman and D. P. Reed at MIT Media Laboratory propose viral radio. D. A. Roberson and X. Li at IIT study the interferences with WiFi in [53] and routing in [70], respectively. P. Cosman at UC San Diego proposes video coding for cognitive radios [61]. Joint works from J. Andrews at UT Austin, N. Jindal at the University of Minnesota, and S. Weber at Drexel target capacity optimization through local adaptation [62]. R. R. Rao at UC San Diego constructs the CogNet (Cognitive Complete Knowledge Network) System [63]. Q. Zhao at UC Davis proposes an integrated approach to opportunistic spectrum access [64]. M. Krunz at the University of Arizona applies resource management and distributed protocols for heterogeneous cognitive-radio networks [74]. L. Swindlehurst at UC Irvine investigates the cognitive radio in sensor network [69]. I. Akyildiz at Georgia Tech studies the cognitive radio in OFDM networks [72]. A. Yener at Pennstate and S. Kishore at Lehigh University develop protocols for opportunistic and collaborative cognitive radio networks [73]. J. Ren at Michigan State University investigates the security

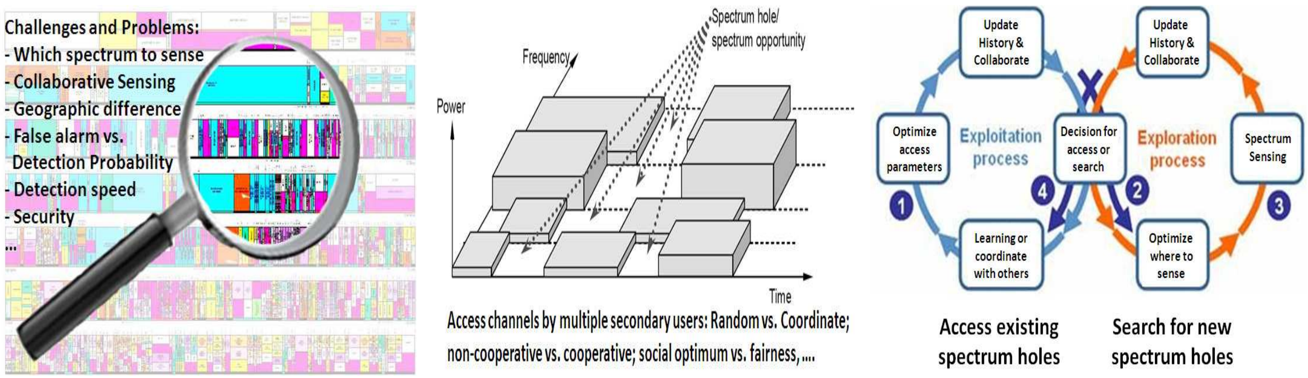

Figure 1: Major Identified Tasks for Cognitive Radio Networks (a) Spectrum Sensing (b) Dynamic Spectrum Access (c) Exploration and Exploitation

aspect of the cognitive radio networks [75]. Some other related works funded by the US government can be found in [76]-[98]. The PI recently published a book on this subject, entitled "Dynamic Spectrum Access in Cognitive Radio Networks" [99], by Cambridge University Press.

Some cognitive radio *Platforms* are supported by NSF or other institutions, such as Wright State University's Broadband, Mobile, Wireless Networking Research Laboratory [41]; San Diego State University's Multimedia and Wireless Networks Research Group [42]; Virginia Tech's Center for Wireless Telecommunications [43]; a COgnitive Radio approach for usage of Virtual Unlicensed Spectrum (CORVUS) at Berkeley [44]; Dynamic Intelligent Management of Spectrum for Ubiquitous Mobile-access Networks (DIMSUMnet) at Lucent-Bell Labs [45]; the DRiVE project at Ericsson Research; the OFDM-based Cognitive Radio (OCRA) network at GaTech [46]; the programmable/versatile radio platform for wireless networking research community at UCLA [44] and UC Irvine; the high-performance cognitive radio platform at Rutgers University; the programmable radio platforms for highly dynamic networks at the Stevens Institute of Technology; the programmable wireless platform for spectral, temporal and spatial spectrum management at the University of Colorado, Boulder; the CogNet platform to investigate architectural issues at the University of Kansas, and the GNU Radio as a collection of software to combine with minimal hardware for cognitive radios.

The PI has already had some publications [146]-[157] related to the coalitional game theoretical approaches for other wireless networks. Compared with the current state of the art, the proposed activities in the next section advance the research frontier by exploring the economic concepts, and fill the gap by investigating the mutual benefits brought by cooperation using coalitional games in CR networks.

3 Proposed Research Activity

In this section, first and foremost, the main problems and challenges in cognitive radio network are discussed. Then the PI proposes the coalitional game-based approaches to provide mutual benefits among the cooperative CR users. Finally, the PI explains the software/hardware platform implementation plan.

3.1 Identified Research and Problem Statement

Among many important technical challenges, the PI focuses on three major tasks: spectrum sensing, dynamic spectrum access, and exploration & exploitation, as shown in Figure 1, which are related to one another and different from the problems of the traditional wireless networks.

1. *Spectrum Sensing*: The objective of spectrum sensing is to detect the presence of transmissions from licensed (primary) users. Spectrum sensing can be either noncooperative or collaborative. Noncooperative spectrum sensing is employed by an unlicensed user (note that the terms unlicensed user, cognitive user, and secondary user are hereinafter used interchangeably.) to detect the primary user by using local measurements. The signal detection at time t can be described as:

$$x(t) = \begin{cases} n(t), & H_0; \\ h \times s(t) + n(t), & H_1; \end{cases} \tag{1}$$

where $x(t)$ is the received signal of an unlicensed user, $s(t)$ is the transmitted signal of the licensed user, $n(t)$ is the additive white Gaussian noise (AWGN), and h is the channel gain. Here, H_0 and H_1 are defined as the hypotheses of not having and having a signal from a licensed user in the target frequency band, respectively. The performance of spectrum sensing is generally measured in terms of probability of correct detection (P_d = Prob(decision = $H_1|H_1$)) and probability of false alarm (P_f = Prob (decision = $H_1|H_0$)).

In collaborative sensing, spectrum-sensing information from multiple unlicensed users is exchanged in order to detect the presence of licensed users. Suppose there are N secondary users. An OR-rule decision rule is made for H_1, if any secondary user decides H_1. The probability of detection and false-alarm for collaborative sensing can be written as:

$$Q_d = 1 - (1 - P_d)^N \quad \text{and} \quad Q_f = 1 - (1 - P_f)^N, \tag{2}$$

respectively. Compared with noncooperative sensing, the collaborative scheme increases the probability of detection but at the same time increases the false-alarm probability.

Spectrum sensing gives rise to several physical and MAC-layer research issues such as:

- Sensing Performance Limit: detection speed; low signal-to-noise ratio; interference.
- Spectrum Sensing in Multichannel Networks: which channel is more likely to be vacant and how often should the spectrum sensing be performed?
- Spectrum Sensing in Multiuser Networks: decision discrepancy due to geographical difference; tradeoff between false-alarm and detection probabilities.

2. *Dynamic Spectrum Access (DSA)*: A mechanism to adjust the spectrum resource usage in a near-real-time manner in response to the changing radio environment and objective (e.g., available channel and type of applications), changes in radio state (e.g., transmission mode, battery status, and location), and changes in radio environment and external constraint (e.g., radio propagation, operational policy). DSA can be based on common-use (spectrum is open for everybody), shared-use (secondary users opportunistically access when primary users are idle), and exclusive-use (primary users grant access to secondary users) models. There are two approaches for dynamic spectrum access: spectrum underlay (which restricts the interference temperature to primary users so that the transmission can coexist) and spectrum overlay (in which there is no such restriction and transmission of primary users and secondary users cannot coexist). The PI will concentrate on the following tradeoffs of DSA:

   - Noncooperative Scheme vs. Cooperative Scheme: Each individual secondary user can maximize its own performance by non-cooperatively utilizing the network resources such as power and bandwidth. Alternatively, they can cooperate to achieve mutual benefits by bargaining and forming contracts or agreements for resource allocation.

- Social Optimum vs. Fairness: Due to the nature of wireless networks, the network resources would be allocated to the few secondary users with the best channels to achieve social optimum (e.g., the highest overall transmission rate). However, this is not fair for the other CR users that might not be able to transmit. Some criteria can be investigated such as proportional fairness and maximin fairness.

3. *Exploration and Exploitation*: As previously mentioned, exploitation refers to the immediate benefit resulting from accessing the channel with the estimated highest reward; whereas exploration is the process by which the cognitive users tend to probe more channels to discover better channel opportunities. The goal of the cognitive sensing strategy is to distributively choose which channel(s) each cognitive user should probe intelligently at different time slots in order to maximize the expected throughput. A fully distributed strategy is proposed based on the adversarial bandit problem that addresses the fundamental tradeoff between exploration and exploitation. Learning algorithms such as non-regret learning and Q-learning are usually used, especially for time-varying scenarios. This research field is still completely open. The cooperation among users can surely improve their performance.

The above issues are the major problems that the PI proposes to investigate in this proposal. To solve these problems, we can use the centralized schemes in which all secondary users are coordinated, or we can employ distributed and noncooperative schemes in which they compete with one another. For the centralized schemes, the bottlenecks are signalling and scalability, which prevent the schemes from being utilized in large networks. For the noncooperative scheme, network performance can be very low due to the inefficient usage of the wireless resources. To overcome these challenges, the PI proposes the coalitional game framework in the following sections for a smaller amount of signalling, better scalability, and higher performance.

3.2 Proposed Coalitional Game: Cooperation Provides Mutual Benefits

In this section, the PI proposes three classes of novel coalitional games as shown in Figure 2, based on the different game properties. The key idea is that cooperation can provide mutual benefits. The formation of coalitions can occur in three different forms as discussed in the previous section. Moreover, coalitions can be formed in different layers for different resource sharing arrangements.

3.2.1 Basic Definitions of a Coalitional Game

In essence, coalitional games involve a set of players, denoted by $\mathcal{N} = \{1, \ldots, N\}$ who seek to form cooperative groups (i.e., coalitions) in order to strengthen their position in the game. Any coalition $S \subseteq \mathcal{N}$ represents an agreement among the players in S to act as a single entity. The second fundamental concept of a coalitional game is the coalition *value*. Mainly, the coalition value, denoted by v, quantifies the worth of a coalition in a game. The definition of the coalition value determines the *form* and *type* of the game. Nonetheless, independent of the definition of the value, a coalitional game can be uniquely defined by the pair $(\mathcal{N}, v)$. It must be noted that the value v is, in many instances, referred to as *the game*, since for every v a different game can be defined.

The most common form of a coalitional game is the *characteristic form*, where the value of a coalition S depends *solely* on the members of that coalition, and not on how the players in $\mathcal{N} \setminus S$ are structured. The characteristic form was introduced, along with a category of coalitional games known as games with *transferable utility* (TU) [137]. The value of a game in characteristic form with TU is a function over the real line defined as $v : 2^N \to \mathbb{R}$ (characteristic function). This characteristic function associates with every coalition $S \subseteq \mathcal{N}$ a real number quantifying the gains of S. The TU property implies that the total utility represented by this real number can be divided in any manner among the coalition members. The

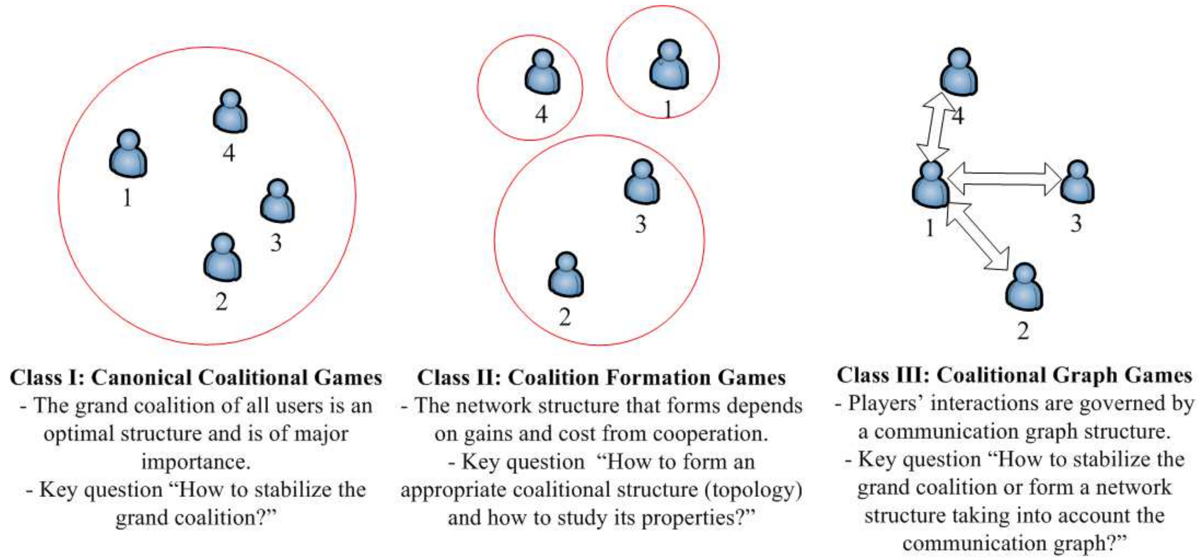

Figure 2: Three Proposed Coalitional Games.

values in TU games can be thought of as monetary values that the members in a coalition can divide among themselves using an appropriate *fairness* rule (e.g., an equal division). The amount of utility that a player $i \in S$ receives from the division of $v(S)$ constitutes the player's *payoff* and is denoted by x_i hereinafter. The vector $\boldsymbol{x} \in \mathbb{R}^S$ with each element x_i being the payoff of player $i \in S$ constitutes a *payoff allocation*.

Although the TU characteristic function can model a broad range of games, many scenarios exist in which the coalition value cannot be assigned a single real number or rigid restrictions exist on the division of the utility. These games are known as coalitional games with non-transferable utility (NTU) [138, 139]. In an NTU game, the payoff that each player in a coalition S receives depends upon the joint actions that the players of coalition S select. The value of a coalition S in an NTU game, $v(S)$, is no longer a function over the real line, but a set of payoff vectors, $v(S) \subseteq \mathbb{R}^S$, where each element x_i of a vector $\boldsymbol{x} \in v(S)$ represents a payoff that player $i \in S$ can obtain within coalition S given a certain strategy. Given this definition, a TU game can be seen as a special case of the NTU framework [139]. Coalitional games in characteristic form with TU or NTU constitute one of the most important types of games, and their solutions are illustrated in Figure 2 class I and explored in details in Section 3.2.2.

Recently, there has been an increasing interest in coalitional games in which the value of a coalition depends upon the partition of $\mathcal{N}$ that is in place at any time during the game. In such games, unlike the characteristic form, the value of a coalition S will have a strong dependence upon how the players in $\mathcal{N} \setminus S$ are structured. The concept of games in *partition form* is introduced in [140]. In these games, given a *coalitional structure* $\mathcal{B}$, defined as a *partition* of $\mathcal{N}$ (i.e., a collection of coalitions $\mathcal{B} = \{B_1, \dots, B_l\}$, such that $\forall\ i \neq j,\ B_i \cap B_j = \emptyset$, and $\cup_{i=1}^{l} B_i = \mathcal{N}$), the value of a coalition $S \in \mathcal{B}$ is defined as $v(S, \mathcal{B})$. This definition imposes a dependence upon the coalitional structure when the value of S is evaluated. Coalitional games in partition form are inherently complex to solve, but the potential of these games is interesting and, thus, we will provide insights on the usage of these games as shown in Figure 2 class II and in Section 3.2.3.

In many coalitional games, the players are interconnected and communicate through pairwise links in a graph. In such scenarios, both the characteristic form and the partition form may be unsuitable since, in both forms, the value of a coalition S is independent of how the members of S are connected. For modeling the interconnection graphs, coalitional games in *graph form* were introduced in [141] where *connected* graphs were mapped into coalitions. This work was generalized in [142] by making the value of each coalition $S \subseteq \mathcal{N}$ a function of the graph structure connecting the members of S. Hence, given a coalitional game $(\mathcal{N}, v)$ and a graph G_S (directed or undirected) with vertices the members of a coalition $S \subseteq \mathcal{N}$, the value of S in *graph form* is given by $v(G_S)$. For games in graph form, the value can also depend upon the graph $G_{\mathcal{N}\setminus S}$ interconnecting the players in $\mathcal{N} \setminus S$. The PI will investigate these types of games as shown in Figure 2 class III in Section 3.2.4.

3.2.2 Canonical Coalitional Game

The canonical games pertain to the most famous and popular tools of coalitional game theory. The coalitional game is in *characteristic* form (TU or NTU). Cooperation (i.e., the formation of large coalitions) is *always* beneficial. Hence, in canonical games no group of players can do worse by cooperating (i.e., joining a coalition) than by acting noncooperatively. This pertains to the mathematical property of *superadditivity*. The main objectives of a canonical game are: (1) to study the properties and stability of the *grand coalition* (i.e., the coalition of all the players in the game), and (2) to study the gains resulting from cooperation with negligible or no cost, as well as the distribution of these gains in a manner that is *fair* to all of the users. One major concept is the *core*, which is the set of allocations in which the grand coalition is stable. In other words, no one has the incentive to leave the grand coalition. If the core is not empty, the next question is how to divide the benefits among different players. Fairness concepts have been proposed, such as *Shapley value* and *Nucleolus*. In summary, canonical games are an important tool for studying cooperation and fairness in communication networks, notably when cooperation is always beneficial. With regard to cognitive radio system, the PI proposes the following research directions:

1. For collaborative spectrum sensing, depending upon the different users' remaining energy, power consumption for transmission, and channel estimation accuracy, smart-fusing algorithms can be developed so as to maximize the network lifetime, ensure fairness among CR users, and optimize sensing efficiency.

2. For dynamic spectrum access, under the interference channel, the coalition can coordinate different CR users' transmissions so that both the overall performance and individual performance can be improved, while fairness among CR users is maintained.

3. For exploration & exploitation, using the canonical coalitional game, CR users are coordinated for sensing and accessing under the limited available spectrum. The coalition can limit competition among CR users and explore more available spectrum.

4. The method will be investigated for checking the extra benefit (such as decreased experienced delay or multimedia quality - PSNR) brought to the coalition when new network nodes are deployed or some nodes leave.

5. Different fairness rules (such as the Proportional Bargaining Fairness (PBS), the Shapley value and the nucleus) will be investigated to see if they lie inside the core of the game. Allocate the resources (such as time slot) for different users forming the grand coalition by the fairness criterion.

In brief, whenever a cooperative scheme, that yields significant gains at any layer, is devised, one can utilize canonical coalitional games for assessing the stability of the grand coalition and identifying fairness criteria in allocating the gains that result from cooperation.

3.2.3 Coalition Formation Game

The coalition formation game encompasses coalitional games in which, unlike the canonical class in the previous subsubsection, *network structure* and *cost* for cooperation play a major role. Forming a coalition brings gains to its members, but the gains are limited by a *cost* for forming the coalition, and hence the grand coalition is seldom the optimal structure. The objective is to study the *network coalitional structure*, i.e., answering questions such as which coalitions will form, what the optimal coalition size is and how we can assess the structure's characteristics, and so on. Coalition formation games also provide tools to cope with radio environment changes such as a variation in the number of players, a change in the strength of each player, or other factors that can affect the network's topology.

To play the network formation game, we propose two main rules for forming or breaking coalitions, referred to as *merge* and *split*. The basic idea behind the rules is that, given a set of players $\mathcal{N}$, any collection of disjoint coalitions $\{S_1, \ldots, S_l\}$, $S_i \subset \mathcal{N}$ can agree to *merge* into a single coalition $G = \cup_{i=1}^{l} S_i$, if this new coalition G is preferred by the players over the previous state, depending upon the selected comparison order. Similarly, a coalition S *splits* into smaller coalitions if the resulting collection $\{S_1, \ldots, S_l\}$ is preferred by the players over S. Independent of the selected order, any arbitrary sequence of these two rules is shown to converge into a final partition of $\mathcal{N}$ [143].

For assessing the stability of the final partition, one can assess whether, in a given partition $\mathcal{T}$ of $\mathcal{N}$, there is an incentive for the players to deviate and form other partitions or collections. A first notion of stability is a weak equilibrium-like stability, known as $\mathbb{D}_{hp}$ stability. A $\mathbb{D}_{hp}$-stable partition simply implies that, in this partition, no group of players has an interest in performing a merge or a split operation. This type of stability can be thought of as merge-and-split proofness of a partition, or a kind of equilibrium with respect to merge-and-split. Another important type of stability inspected in [143] is $\mathbb{D}_c$-stability, which is stricter and has the properties of uniqueness, social welfare maximization, and group rationality. These stability concepts will improve the network robustness. For example, if the allocation is in the core, the network will have stable coalitions, which will lead to increased robustness for transmission.

For cognitive radio systems, the PI proposes the following research directions:

1. For spectrum sensing, due to the different locations of the CR users, their views of spectrum holes might be different. As a result, it is natural to employ a coalition formation game and shape the network into clusters in which the neighboring CR users can form coalitions and share the view of primary users' activities.
2. For dynamic spectrum access, if the interference is less severe, it would be optimal to group the less interfering CR users as coalitions to transmit simultaneously. Consequently, the interference can be limited. This is similar to the frequency reuse in the cellular system. Some other QoS metrics such as delay performance and video quality can also be investigated.
3. For exploration and exploitation, because of the facts that a) different users have different views of the channels and b) frequency-selective channels are different for different CR users, it can be beneficial for groups of users to coordinate sensing and access within every coalition.

3.2.4 Coalitional Graph Game

In certain scenarios, the *underlying communication structure* among the players in a coalitional game can have a significant impact on the utility and other characteristics of the game [141, 144]. By underlying communication structure, we imply the graph representing the connectivity of the players to each other, i.e., which player communicates with which inside each coalition. We propose network formation games, in which the main theme is the presence of a graph for communication among the players. There are two objectives for coalitional graph games. The first and most important objective is to provide low-complexity algorithms for building a network graph to connect the players. A second objective is to study the properties and stability of the formed network graph.

In network formation games, there is a need to form a network graph as well as to ensure the stability of this graph, through concepts analogous to those used in canonical coalitional games. For forming the graph, a broad range of approaches exists, and it is grouped into two types: *myopic* and *far sighted*. The main difference between these two types is that, in a myopic approach, the players play their strategies given the current state of the network, while in a far-sighted approach, the players adapt their strategy by learning and predicting the future strategies of the other players. One approach to solve the game is to play a *best-response dynamics*, whereby each player selects the strategy (i.e., to form or to break the link(s)) in order to maximize utility. The stability concepts, such as *pairwise stability* and *coalitional stability* [145], depend upon deviations by a group of players instead of the unilateral deviations allowed by the Nash equilibrium.

In cognitive radio systems, the PI proposes the following research directions:

1. For collaborative sensing, different levels of fusion centers can be formed so that the network has a tree structure, which can balance between the false-alarm and missing probabilities. Moreover, the delay can be reduced due to the tree structure.
2. For dynamic spectrum access, cognitive routing can be formulated so that the routes can avoid the primary users and the costs, such as delay, can be optimally reduced.
3. For exploration & exploitation, the order of sensing and access might have to be taken into account. As a result, the tree structure might be formed so as to decide who will sense or access first.

3.2.5 Preliminary Result

The PI has some extensive work [146, 147, 148, 149, 150, 151, 152, 153, 154, 155, 156, 157] to apply the coalitional game theoretical approaches to a variety of resource allocation problems in different wireless networks. Next, we show a preliminary result for the application of the coalitional game to cognitive radio networks. Collaborative spectrum sensing (CSS) has been proposed for improving the sensing performance of the CR users, in terms of reducing the probability of missing the detection of the primary user (PU) (probability of miss), and hence decreasing the interference on the PU. Although CSS decreases the probability of miss for primary users, it also increases the false-alarm probability (i.e., the probability of falsely detecting that the PU is transmitting). Hence, CSS presents an inherent tradeoff between reducing the probability of miss (reducing interference to the PU) and maintaining a good false alarm probability, which corresponds to a good spectrum utilization. We consider a network of CR users, that interact for improving their sensing performance, while taking into account the false alarm cost. For performing CSS, every group of CR users forms a coalition, and within each coalition, a CR user selected as coalition head, will gather the sensing bit from the coalition members. By using well-known decision-fusion rules, the coalition head can decide on the presence or the absence of the PU. Using this CSS scheme, each coalition reduces the probability of miss of its CR users. However, this reduction is accompanied by an increase in the false-alarm probability. This tradeoff between the probability of miss and the false alarm, impacts the coalitional structure that forms in the network.

Consequently, the CSS problem can be modeled as a dynamic coalition formation game among the CR users ($\mathcal{N}$ is the set of CR users in this game). The utility $v(S)$ of each coalition S is a decreasing function of the probability of miss $Q_{m,S}$ within coalition S and a decreasing function of the false-alarm probability $Q_{f,S}$. Here, we have a maximum tolerable false-alarm probability (i.e., an upper bound constraint α on the false alarm) that cannot be exceeded by any CR user. The proposed coalitional formation algorithm consists of three phases: in the first phase the CR users perform their local sensing, in the second phase the CR users engage in an adaptive coalitional formation algorithm based on the merge and split rules, and in the third phase, once the coalitions have formed, CR users report their sensing bits to the coalition head who makes a decision as to whether or not the PU is present.

In Figure 3 (a), we show an example of a coalitional structure that the CR users form for CSS in a cognitive network of 10 CR users with a false-alarm probability constraint of $\alpha = 0.1$. Clearly, the proposed algorithm allows the CR users to structure themselves into disjoint independent coalitions for the purpose of spectrum sensing. By forming such topologies, the CR users can significantly improve their

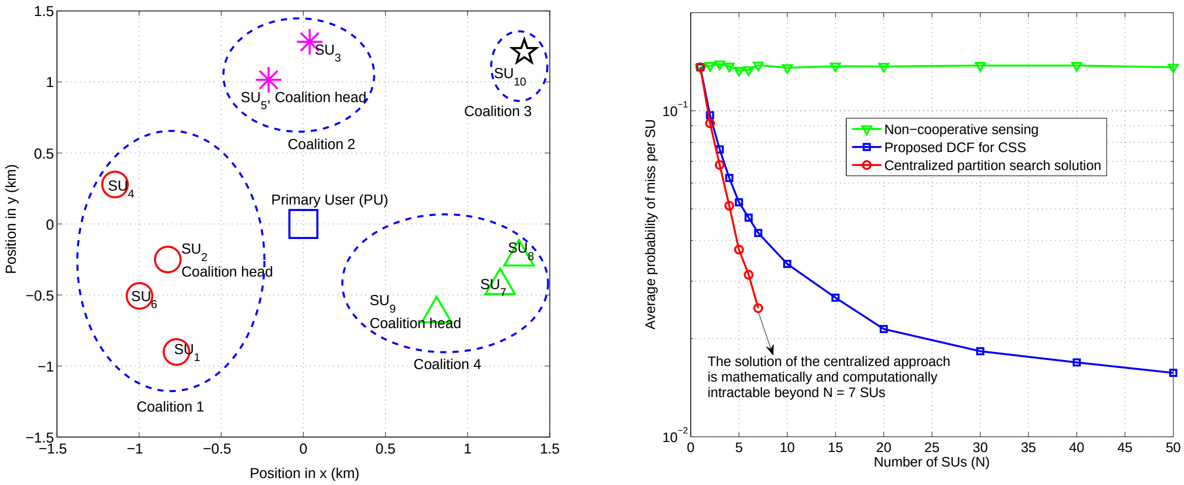

Figure 3: Preliminary Results (a) Topology resulting from coalition formation in collaborative spectrum sensing for 10 CR users. (b) Average probabilities of miss (average over locations of CR users and non-cooperative false-alarm range $P_f \leq \alpha$) versus number of CR users achieved by the proposed algorithm and a centralized solution that finds the partition that minimizes the average probability of miss per CR user subject to the false-alarm constraint α.

performance, in terms of probability of miss, relative to the noncooperative sensing case, while maintaining the desired false-alarm level of α [136]. Figure 3 (b) shows the average missing probability achieved per CR user for different network sizes. The probability is averaged over random locations of the CR users as well as a range of energy-detection thresholds λ that do not violate the false-alarm constraint; this in turn, maps into an average over the non-cooperative false-alarm range $P_f \leq \alpha$ (obviously, for $P_f > \alpha$ no cooperation is possible). We show that the proposed algorithm yields a significant improvement in the average probability of miss reaching up to 88.45% reduction (at $N = 50$) relative to the non-cooperative case. This advantage is increasing with the network size N. In this figure, we also show the results of a centralized exhaustive search solution that minimizes the average probability of miss per CR user, subject to the false-alarm constraint α. This solution is shown for up to $N = 7$ because it is mathematically intractable for larger networks. Compared with the centralized solution, there exists a gap in the performance of the proposed algorithm stemming mainly from the individual choices of the CR users when they act in a distributed manner, i.e., selecting their partners based on a balance between gains and costs as opposed to a centralized approach that does not capture these individual incentives. Although the proposed algorithm yields a performance gap in terms of miss probability, the individual decisions of the CR users force a false-alarm probability for the distributed case smaller than that of the centralized solution. Overall, dynamic coalition formation provides novel collaboration strategies for CR users in a CR network who are seeking to improve their sensing performance, while maintaining a desired spectrum utilization (false-alarm level). The framework of dynamic coalition formation games yields a significant performance improvement and enables stable network topology.

3.3 Software and Hardware Cognitive Radio Platform

The technical approaches for the cognitive radio architecture mentioned in the previous sections will be implemented in the newly established *Wireless Networking, Signal Processing, and Security Laboratory* at the University of Houston. The PI will develop a working system that bridges the gap between promising techniques and practical working solutions. Specifically, the PI plans first to construct a CR network simulator, then to develop prototyping and device driver, and finally to deploy a testbed as well as conduct field experiments. The proposed hardware implementation would also be incorporated with the existing infrastructure at the University of Houston.

3.3.1 Implementation of CR Network Simulator

The proposed research tackles a suite of fundamental technical issues in sensing, learning, and resource allocation in distributed CR networks. Extensive testing is essential for proof of the proposed coalitional game framework and will be carried out via simulations. The MATLAB tool and NS2 provide the convenient platforms for generating various realistic network topologies and traffic patterns, based on which the proposed coalitional game algorithms will be tested. The PI will enhance the performance evaluator to add new functionalities pertinent to CR networks, such as an energy detector, interference temperature at licensed nodes, and QoS measures. The PI will also compare the performance of the proposed approach with other existing schemes using extensive simulation studies. A variety of MATLAB and NS2 functions also provide guidance to develop the prototyping and device driver, and eventually benefit the hardware testbed deployment. The CR-enhanced toolboxes will be disseminated as shareware to allow researchers in this field to test and compare performances of their cognitive algorithms. The toolboxes will be available via the Internet at the lab or on the math-network Web sites.

3.3.2 Hardware, Prototyping and Device Driver

Based on the insights obtained from the software platform, the PI plans to develop a prototype implementation. The available wireless hardware platforms are listed as follows:

1. The open-source GnuRadio software package, paired with the USRP (or USRP 2) hardware peripheral by Ettus Research (*http://www.ettus.com/*), is a popular choice. All of the baseband signal processing is done by the general-purpose processor on the PC. The advantage is that reconfiguring the transceiver at the PHY layer is straightforward. However, the latency and computation power are the issues. In the proposed platform, GnuRadio can be used as the simple distributed CR users for sensing and accessing.
2. Rice University has a platform called the WARP (*http://warp.rice.edu/*). It is significantly more expensive than the USRP, but it can be run untethered from a PC. It has a powerful FPGA and has strong configurability. So this hardware can be implemented for the nodes (e.g., cluster heads) that need to perform heavy computations. In the proposed platform, WARP can be employed as the cluster heads, fusion centers, or mini base stations to perform more complicated control and computation than those in GnuRadio.
3. Some other available hardware platforms are considered as a tradeoff between GnuRadio and WARP, including Lyrtech Small form factor SDR development platforms, Wavefront for RF from Red River, FlexRadio PowerSDR, DRM Software Radio, Programmable Digital Radio Receiver DCM, Spectra SDR, FlexComm SDR-3000, WinRadio, and the DARPA Wireless Network after Next (WNaN).

Based on the available hardware, the design can be classified as device driver, micro-controller or field programmable gated array (FPGA). The device driver such as those open-source Linux drivers is easy to program but has limited control over the hardware. The FPGA design can control most details in the Physical layer and the MAC layer, but programming can be time consuming. The micro-controller provides a tradeoff between complexity and capability.

3.3.3 Testbed Deployment and Field Experiment

The proposed proof-of-concept testbed deployment and field experiment will be conducted in three phases. First, in-lab baseline tests will be conducted for a few nodes to show cooperation together. The PI plans to modify 802.11 devices as the legacy device (PU), and test the interaction of the PU with multiple CRs to evaluate the performance of the proposed research.

Once the baseline tests are completed, multiple CRs can be configured to emulate a distributed heterogeneous broadband environment. The PI plans to use a set consisting of a signal generator and a channel simulator to further test the interaction of CRs with more sophisticated PU systems. In particular, the signal generator can generate the signals and upconvert them to ISM band(s). This allows us to evaluate the effectiveness of the proposed strategy by sending the upconverted signals through an indoor multipath environment and feeding back CR signals to the PU receivers. The signal generator has a BER (Bit Error Rate) mode that allows us to test the impact of CR transmission on the PU. This test emulates the complex wireless signals and wireless environments.

Finally, the PI plans to incorporate the testbed with other infrastructures at the University of Houston. Specifically, the proposed testbed can help the Wireless System Research Group in the Computer Science Department in doing robust resource management in ISM bands, wireless structure health monitoring, and collaborative in-network processing in wireless vision sensor networks. Moreover, the Interoperable Smart Sensors and Networking Lab in the College of Technology can potentially be beneficial for biomedical instrument networking.

4 Education and Outreach Plan

The goals are to improve curriculum development at the University of Houston; to expose graduate, undergraduate, and high school students to the excitement of wireless network technologies; and to disseminate research to current and future engineers and scientists.

Curriculum and Educational Technology Development: The PI has developed the graduate course *Advanced Telecommunications* and the undergraduate course *Introduction to Telecommunication Engineering.* In addition to teaching the traditional curricula, the PI would like to introduce new special-topic courses about the foundations of resource allocation, game theory and cognitive technique for wireless networks. These courses are based on three textbooks by the PI:

1. Zhu Han and K. J. Ray Liu, *Resource Allocation for Wireless Networks: Basics, Techniques, and Applications*, Cambridge University Press, April 2008.
2. Ekram Hossain, Dusit Niyato, and Zhu Han, *Dynamic Spectrum Access in Cognitive Radio Networks*, Cambridge University Press, June 2009.
3. Zhu Han, Dusit Niyato, Walid Saad, Tamer Basar, and Are Hjørungnes, *Game Theory in Wireless and Communication Networks: Theory, Models and Applications*, Cambridge University Press, estimated to be published in December 2010.

The word "educate" comes from the Latin "educare", which means "to draw out" the student into the world of knowledge. Teaching is an opportunity to empower and inspire others as well as the teacher himself/herself. As an educator, it is the PI's goal to enhance student learning as a transformative experience. The PI wants to maintain a very lively and interactive atmosphere for the students. Teaching is not about lecturing to students; instead, it is about presenting theories, concepts, and empirical materials to students in such a way that encourages them to willingly integrate this information into their own life experiences. Ultimately, they would be able to become professionals who have comprehensive understandings of principles, have universal views of the development trends, and can overcome challenges in their future work. On the other hand, student-teacher interactions can also foster development of creativity, independence, and discipline to pursue advanced research. So, it is also a great opportunity for the PI to be a student advisor and mentor to promote these interactions.

If funded, the PI would like to propose the following essential philosophies for successful teaching: 1. Put the course material into perspective to provide students with the wider topical picture. 2. Maximize intuition with sufficient maths. 3. Understand students' perspectives in developing pedagogical content. Organize the subjects for students according to the students' experiential backgrounds. Try to build new knowledge on what students have previously learned. 4. Assist students in becoming self-sustaining and life-long learners. 5. Help students to be organized, so that they know when, where, and why to use their knowledge. Encourage students to explore the course-related areas to have a sense of how a specific method works by inquiry-based instruction.

Reaching Out to Under-represented Groups: Over the last 20 years, the percentage of college students choosing engineering majors has been gradually declining. This trend has become even more marked in the last 6 years [165]. In order to encourage more high school students to pursue careers in engineering, the PI has designed and implemented special sessions for three existing outreach programs in June 2007, June 2009 and July 2009, respectively, to give presentations and conduct experiments for wireless communication for the 9th and 10th grade students. Specifically, the PI taught the basics of network security, and then high school students, mentored by female college engineering students, worked in teams to test the security of wireless connections via wireless connections. The PI used hands-on activities involving self discovery, cooperative learning, critical thinking, and problem solving. If the proposal is funded, the PI plans to attend other possible outreach activities.

The PI will extend outreach to include programs targeted specifically towards high school girls. Significant effort has been dedicated to determining why women are under-represented in engineering fields [158, 159, 160, 161, 162, 163, 164]. Some of the reasons for fewer women entering the area of engineering are: a lack of self-confidence in terms of engineering skills, a lack of encouragement, few female role models [163], and lack of understanding by girls and people in general about the personal relevance, rewards and benefits of an engineering career [164]. The PI has three female students in his research lab and can use their success as examples for the planned outreach, which has the potential to attract young women to engineering as a college major and career option.

Another proposed outreach component is a *group mentoring program.* During the special sessions, the PI will recruit female students as well as students from other under-represented groups who are interested in engineering, to participate in a group mentoring program. Different from traditional mentoring programs that emphasize one-to-one relationship between a mentor and a mentee, this group mentor program will enable both group communication and one-to-one communication. Inspired by the success of Google Groups, and with the cooperation of Dr. Yan Sun at the University of Rhode Island, the PI plans to establish a Google group containing 4∼7 mentors and 20∼40 mentees. The mentees and mentors can post and answer questions, initiate discussions, share interesting articles or experiences, and conduct one-to-one communication if necessary. It is well known that *multicast* is more efficient than *multiple unicast.* Similarly, group mentoring is expected to suppress redundant questions, reduce the workload of mentors, and allow mentees from different geographical locations to learn from one another.

Engaging High School Teachers, Undergraduates and Graduates in Research: The PI participated in the Research Experiences for Teachers (RET) program funded by NSF in June 2009, and has tried to understand into high school students' backgrounds and expectations by communicating with high school teachers during the one-month event held by the University of Houston. The PI also has worked directly with undergraduates in his current research activities. For example, a student funded by NSF Research Experiences for Undergraduates (REU) worked in the Wireless Networking, Signal Processing and Security Lab of the University of Houston for three months. The student's major task is to help the outreach events and develop the lab Web site for broader impact. If this proposal is funded, the PI plans to recruit several undergraduates from the senior class every year to conduct research, working with a Ph.D.-level graduate student or the PI directly. Graduate students will be involved in all aspects of the proposed research. They will present their work at international conferences, publish papers in premier journals, and develop the hardware/software platform to test the proposed protocols.

5 Industrial Support and Broader Impact

The proposed research also attracts much interest from industrial companies. For example, Qualcomm Research Lab in San Diego showed great interest and enthusiasm in the game theoretical approaches for cognitive radio during the PI's visit in Summer 2009. The company also hosts Qualcomm's Research Center University Open House that provides the opportunity to learn about on-going Qualcomm research, and it has held informal one-on-one discussions with our engineers about further university collaboration opportunities. Cognitive radio topic has been discussed with regard to the latest research applications and engineering design challenges. The Qualcomm collaborator is Dr. Ahmed Sadek (*asadek@qualcomm.com*), Senior Systems Engineer of the Qualcomm Research Center, who has been very active in CR research during the last few years. Dr. Sadek and the PI will work closely, and the insights obtained from this project will be brought into the Qualcomm research lab. The PI also plans to work closely with other industrial companies so that the research results can benefit more consumers faster and more efficiently. If funded, the PI also plans to pay summer visits to different companies to understand the industrial needs better.

The proposed project will also have *broad impacts* for the students who participate directly in the research, for students at the University of Houston, for the research community, and more generally for those affected by the outreach programs. The department's vision is to become a nationally recognized department that engages in the highest-quality teaching and research, benefiting the students, the faculty, the University, the Houston region, the State of Texas, the nation, and society at large. The results generated through the proposed work will be published and presented in appropriate journals and conferences. Moreover, the PI proposes the research to be made available on the Internet, so that other researchers in the community can conduct their investigations on the same platform. The proposed program is transformative and can potentially be applied to other research areas. The results will be used as teaching tools by instructors at high school and college levels. The PI will continue to participate in outreach programs for high school students, RET and REU programs.

6 PIs' Qualifications and Time Line

The successful completion of the proposed research requires the PI's expertise. Dr. Han has extensive experiences in wireless networking, signal processing and security. He has published about 40 journal and 80 conference articles in these areas. Moreover, Dr. Han has worked in a US company (JDSU) for three years to develop firmware by FPGA, micro-controller, and software driver for telecommunication equipment. Dr. Han is actively involved in outreach events and is deeply committed to broadening participation in engineering. Finally, if the proposal is funded, the *time line* of the proposed research and education activities in the next five years is shown in Figure 4. The key milestones include: 1. continues publication of results in prestigious journals and presentations at conferences; 2. Ph.D. graduation for the future wireless engineering force; 3. software platform and its connection to the Internet; 4. small-scale hardware platform within the lab; 5. large-scale testbed such as on campus; 6. integration with the existing infrastructure at the University of Houston; and 7. new graduate courses development.

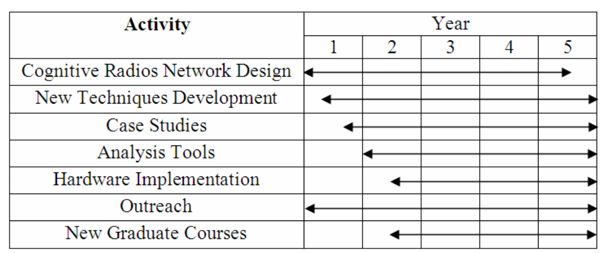

Figure 4: Time Line of the Proposed Activities

7 Results from Prior NSF Support

Zhu Han: "Collaborative Research: Trusted Cooperative Transmission: Turning a Security Weakness into a Security Enhancement", (10/08-9/10). This collaborative project has involved a total of two Ph.D. students to the completion of their degrees. One book chapter, two journal articles and two conference publications have already resulted from this grant are [166, 167, 168, 169, 170].

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