



Game Theory and Cognitive Radio Based Wireless Networks

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Abstract. The ability to model individual, independent decision makers whose actions potentially affect all other decision makers renders game theory particularly attractive to apply to various fields of Information technology, especially, to analyze the performance of wireless networks. In this paper, we discuss how various interactions in cognitive radio based wireless networks can be modeled as a game at different levels of protocol stack. This allows the analysis of existing protocols and resource management schemes, as well as the design of equilibrium-inducing mechanisms that provide incentives for individual users to behave in socially-constructive ways. **In nutshell, this paper serves two main objectives; first, to model some of the fundamental questions on cognitive radio based wireless networks as interactive games between the nodes and second, to gain our understanding on inter-discipline research issues.**

Keywords: Cognitive Radio, Wireless Networks, Game Theory, Cross-layer Design, Mechanism Design.

1 Introduction

The modern information society will continue to emerge, and demand for wireless communication services will grow. Future generation wireless networks are considered necessary for the support of emerging services with their increasing requirements. Significant amounts of radio spectrum will be needed at dynamically changing times and locations. **However, this need for radio spectrum is a problem, that is, the spectrum scarcity.** The electromagnetic radio spectrum is a precious natural resource. Despite the recent advancements in communication technology such as Multiple Input Multiple Output (MIMO) antennas, third generation cellular networks and their integration with wireless Local Area Network (LAN) IEEE 802.11, it is difficult to foresee how a truly connected information society can be established, given today's regulation of radio spectrum.

Cognitive radio (CR) is a revolutionary technology that aims for remarkable improvements in efficiency of spectrum usage. **Basically, cognitive radios are radio systems that continuously perform spectrum sensing, dynamically identify unused ("white") spectrum, and then operate in this spectrum at times when it is not used by incumbent radio systems.** It will change the way the radio spectrum is regulated, but also requires new enabling techniques such as improved spectrum sensing, dynamic spectrum assignment, and cross layer design[1].

Table 1. Cognitive radio based wireless networking game

Components of a game	Elements of a wireless network
Players	Nodes in the wireless network
A set of actions	A modulation scheme, Coding rate, transmit power level, etc.
A set of preferences	Performance metrics (e.g. Throughput, Delay, SNR, etc.)

We want to propose a concept of cognitive radio based network (CRN) that can be intelligent about spectrum usage and network performance and thus have great flexibility and security. In order to develop the CRN, we shall use some analyzing tools that can control the CRN and optimize the performance of the whole protocol stack. We believe that techniques originated from game theory can be used to create a toolset for the analysis of CRNs.

Game theory provides a mathematical basis for the analysis of interactive decision-making process between the rational players. It provides tools for predicting what might happen when nodes (players) with conflicting interests interact. Game theory is a collection of modeling tools that aid in the understanding of interactive decision problems. In the past several years, the application of game theory to problems in communication and networking has become popular and productive. Specifically, game theoretic models have been developed to better understand congestion control, routing, power control, topology control, trust management, and other issues in wired and wireless communication systems.

A game is made up of three basic components: a set of players, a set of actions, and a set of preferences. The players are the decision makers in the modeled scenario. The actions are the alternatives available to each player. In a wireless system, actions may include the choice of a modulation scheme, coding rate, protocol, flow control parameter, transmit power level, or any other factor that is under the control of the node. When each player chooses an action, the resulting “action profile” determines the outcome of the game. Finally, a preference relationship for each player represents that player’s evaluation of all possible outcomes. Table 1. shows typical components of a cognitive radio based wireless networking game.

Appropriately modeling these preferences relationships is one of the most challenging aspects of the application of game theory. A clear distinction should be drawn, however, between a game, which must involve multiple decision makers, and an optimization problem, which involves only a single decision maker. A model is usually appropriate only in scenarios where we can reasonably expect the decision of each node to impact the outcomes relevant to other nodes. For example, a single car navigating a road way in an attempt to reach a destination as quickly as possible performs an optimization. When the roadway is shared, though, the drivers are engaged in a game in which each attempts to reach his/her destination as quickly as possible without getting in an accident or receiving a traffic ticket.

A CRN is a self-configuring, multihop network in which there is no central authority. Thus, every aspect of the configuration and operation of a CRN must be completely distributed. Furthermore, nodes in a CRN often severely energy and power constrained. Game theory, as we have discussed, offers a suite of tools that may be used effectively in modeling the interaction among independent nodes in a CRN.

2 Necessity

In the CRN, it is essential for CR devices to perform **spectrum sensing / sharing tasks in order to co-exist with other types of networks**. However, this device-level design would inevitably have high complexities and costs. Also, only CR devices themselves could not deal with the distributed spectrum allocation effectively, therefore additional aids from other aspects should be necessary. So, a new spectrum-sharing strategy with the aid from network level is to be designed and developed. This strategy can solve the coexistence problem of CRNs and simplify the design of CR devices. In fact, it is a cross-layer design strategy that integrates useful information obtained from the physical, MAC and network layers, in order to fully exploit available spectrum resources without introducing interference to existing users.

In the CRN, **each node running a distributed protocol must make its own decisions, possibly relaying on information from other nodes**. These decisions may be constrained by the rules or algorithms of a protocol, but ultimately each node will have some freeway in setting parameters or changing the mode of operation. These nodes, then, are independent agents, making decisions about spectrum usage, interference level, radio parameters, node position, network status, transmit power, packet forwarding, backoff time, and so on. Now, important question here is “what does the node seek to optimize?” while making these decisions. In some cases, nodes may seek the “greater good” of the network as a whole. In other cases, nodes may behave selfishly, looking out only their own user’s interests. In a final case, nodes may behave maliciously, seeking to ruin network performance for other users. In second and third cases, the application of game theory may be straightforward, as game theory traditionally analyzes situations in which player objectives are in conflict. In the first case, node objectives may be aligned with the network main objective, but still game theory may offer useful insights. Even when nodes have shared objectives, they will each have a unique perspective on the current network state, and leading to possible conflicts regarding the best course of action. Game theory allows us to model CRNs in which there is no centralized entity with full information of network conditions.

3 CRN Challenges

The main problem of a CRN is the coexistence with the **Licensed Incumbent Users (LIU)**, which are the owners of licensed spectrum and have higher priorities. A practical CR device, or in other words, **Customer Premise Equipment (CPE)**, shall not interfere with the existing LIUs. The definitions and requirements are listed below[2].

Licensed Incumbents

- TV Broadcasters: NTSC (US/Canada/Japan analog TV), ATSC (US, Canada DTV), PAL (Europe analog TV), SECAM (France analog TV), DVB-T (Europe/worldwide DTV).
- Land Mobile Radio Networks:
- Public Safety (police, fire, etc.), Commercial (cabs, towing services, etc.)
- Wireless Microphones and other TV broadcast related devices (in the US, FCC rules, Part 74 Low Power Auxiliary Station devices).

Customer Premise Equipments

- Avoid operating on Land Mobile Radio channels.
- Use planning, GPS, databases for Base Station planning, licensing.
- Use Base Station authorization/control and distributed sensing, in BS and CPE's, to avoid unintentional operation on TV channels.
- Use sensing to mitigate interference to Part 74 devices.

It is a challenge to construct an efficient spectrum allocation scheme, which can dynamically manage radio resources in a real-time pattern according to the environment. The channel allocation scheme **should at least satisfy two basic requirements: 1) it can exploit as many as possible available frequency bands; 2) it must NOT produce more interference to LIUs than before.** However, there are some tradeoffs between these two requirements.

Beyond the traditional spectrum sensing method, there would be chances for CPEs to exploit more frequency bands, if more information concerned with spectrum usage of LIU, interference level, positions etc. can be obtained. It is also implied that in the CR network asymmetric links among CPEs could be set up, depending on their specific surroundings. Therefore, the channel allocation scheme should take into account various factors of different layers in order to satisfy the requirements of CPEs. As shown in the figure 1 game theory can be applied to the modeling of a CRN at the physical layer, link layer, and network layer. **Applications at the transport layer and above exist also, but we restrict our research up to network layer.** A research issue of interest in all those cases is that of **how to provide the appropriate incentives to discourage selfish behavior.** Selfishness is generally dangerous to overall network performance; **examples include a node's increasing its power without regard for interference it may cause on its neighbors (layer 1), a node's immediately retransmitting a frame in case of collisions without going through a backoff phase (layer 2), or a node's refusing to forward packets for its neighbors (layer 3).**



3.1 Physical Layer (PHY)

In the PHY case, it needs to offer **high performance** while keeping the complexity **low**. In addition, it needs to **exploit the available frequency in an efficient** manner to provide adequate performance, coverage and data rate requirements of the service. The PHY has also to provide **high flexibility in terms of modulation and coding.**

The physical layer can perform basic frequency detection and spectrum sensing tasks, in order to find available empty frequency bands. In our considerations, not only

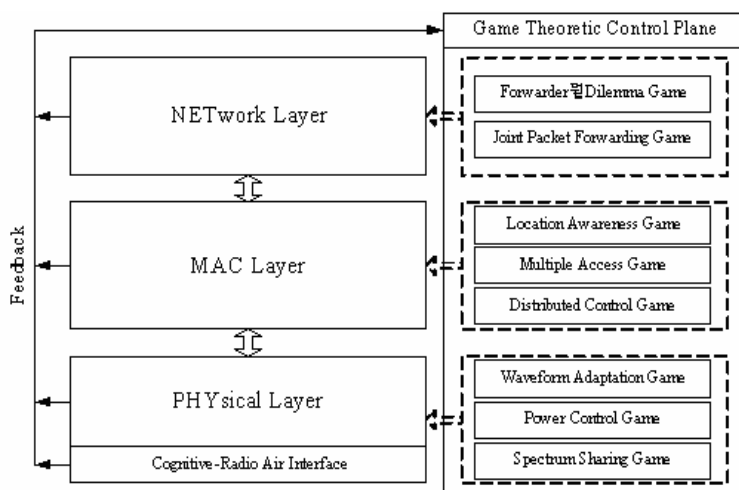


Fig. 1. The classification of the games according to protocol layers

can the empty bands be utilized, but also the on-the-air frequency bands can be exploited under some conditions. This will be a great improvement in the PHY design.

Power control, though closely associated with cellular networks, could be implemented in CRNs due to the potentially significant performance gains achieved when nodes limit their power level. In wireless communication systems, mobile terminals respond to the time varying nature of the channel (short term and long term fading) by regulating their transmitter powers. Specifically, in a CDMA system, where signals of other terminals can be modeled as interfering noise signals, the major goal of this regulation is to achieve a certain signal to interference (SIR) ratio regardless of the channel conditions while minimizing the interference due to terminal transmit power level. Hence, there are two major reasons for a terminal to perform power control; the first one is the limit on the energy available to the mobile node, and the second reason is the increase in quality of service (QoS) by minimizing the interference. In the CRN, a kind of distributed power control can be performed, that means, not only can the node adjust its power according to its own status, but also the distributed networking function can determine the proper power limit to optimize the performance of the whole network.

Finally, Waveform adaptation in CRNs involves the selection of a waveform by a node such that the interference at its receiver is reduced. The interference at the receiver is a function of the correlation of a user's waveform with the waveforms of the other users in the network. Also, in general, the individual nodes involved in transmission have no or very little information about the receiver's interference environment. Hence to minimize the adaptation overhead, distributed waveform adaptation algorithms that require a minimal amount of feedback between receivers and transmitters need to be developed for these networks. Game theory can provide useful insights to this scenario.

3.2 MAC Layer

Beacon Enhancement: If the CPE has the knowledge of which channel the neighboring LIU (typically, TV set) is currently being tuned on, it could have chance to use the bandwidth of the rest on-the-air TV channels at the same time. The local beacon is a good method of identifying the LIU, that is, the LIU itself or a special beacon transmitter periodically broadcasts signals in order to actively announce the existence of the LIU to the surroundings. It becomes easier for the CPE to find neighboring LIUs and act correspondingly. For example, the CPE can estimate the distance from the LIU according to the received beacon signal strength. In addition, if we add more information elements (IE) in the beacon frame, the CPE will benefit from them. For example, in the beacon frame, the position of LIU, the beacon transmit power, the total received interference level can be included. After decoding these IEs, the CPE can calculate the path loss, estimate its possible interference level to the LIU and then decide which potential bands can be available. All beacon transmitters should use the same frequency band to broadcast beacon frames. This common beacon band could be an unlicensed frequency band, or a dedicated channel that is not occupied by LIUs, or just a spare gap between TV channels.

Positioning: The location information of neighboring nodes is important for CPEs to estimate interference to and from the existing LIU devices. Also, the location information can help the CPE decide if a link can be set up with the other CPE. The Global Position System is a mature positioning method suitable for CR networks, since the distance between nodes would be relative large. If the CPE uses some specific radio techniques, such as impulse-radio ultra wideband, the CPE can measure distances and positions by itself.

The position of the LIU could be obtained by reading the beacon frames. Then the location information could be exchanged among CPEs with an ad hoc manner. In the central-controlled structure, the base station of the CR network could broadcast the position information to all CPEs. In this case, the feedback mechanism from the CPE to the base station should be defined.

Interference Estimation: The purpose of interference estimation is to tell if the potential channels of a CPE can be really used or not. At first, based on the position information, the path loss model, its maximum transmit power etc., the CPE could estimate its interference to the LIUs nearby if its potential channels were deployed. For example, if the estimated interference level does not exceed a predefined threshold, the corresponding potential channel for transmission can be regarded as “available”.

The interference estimation is also necessary for a receiving CPE that is shadowed by the TV transmitter. Besides some possible interference mitigation technique, the shadowed CPE can estimate its signal-to-interference-and-noise ratio (SINR), according to the total interference level from TV signals, the distance to the transmitting CPE and the transmit power of CPE etc. If the estimated SINR exceeds a predefined threshold, the corresponding potential channel for reception can be regarded as “available”.

Medium Access Games-The Slotted Aloha and DCF Games: The medium access control problem, with many users contending for access to a shared communications medium, lends itself naturally to a game theoretic formulation. In these medium access control games, selfish users seek to maximize their utility by obtaining an unfair share of access to the channel. This action, though, decreases the ability of other users to access the channel.

3.3 Network Layer

Update and Exchange Band Information: Each CPE in a CRN shall be continuously in charge of sensing and measuring its surroundings, determining its available transmission and reception channels, and sending relevant information to other CPEs. If there are some events occurred, for example, a neighboring LIU is powered on or off, a LIU is tuning its working channels, or the position of a LIU is changed, the CPE should be able to detect these changes quickly, adjust its available channels, update its frequency usage database and let other CPEs know about it.

In a CRN, all CPEs shall have the consistent consensus about the common set of empty channels (not occupied by TV transmitters or other transceivers), which should be a minimal intersection of all spectrum sensing results from CPEs. This common set of empty channels can be adopted to realize some network control functions and provide seamless data delivery throughout the network. On the other hand, the potential channels of a CPE can in addition be utilized to increase the frequency usage factor and improve the data throughput locally.

Channel Allocation Negotiation: Because CPEs at different locations would have different perspectives of their own “available” channels, a channel allocation negotiation procedure should be needed before a data link can be set up between two adjacent CPEs. Such a negotiation procedure can be categorized as one of functions in the control plane of a CRN. A dedicated control channel can be set up by utilizing a common frequency band that is not occupied by any TV channel throughout a CRN. The control packets can be exchanged in an ad hoc manner, or a base station controls the channel allocation among CPEs while CPEs should send some feedback about their “available” channels to the base station. For example, the channel allocation negotiation procedure for unidirectional transmission could be performed between the communicating pair as follows: If one CPE has data to transmit, it should at first send the “Allocation Request” control packet that contains a list of its available transmission channels to the intended receiver. After having received this “Allocation Request”, the receiver should check its own available reception channels to decide which channels can be allowed for receiving data. Then the receiver sends back “Allocation Confirm” that indicates allowed transmission channels to the transmitter. If this negotiation is completed successfully, both transmitting CPE and receiving CPE will tune on the same frequency bands and start data transmission. Similarly, the bi-directional link can be set up by exchanging available transmission channel sets and reception channel sets between two communicating CPEs.

Routing Method: The location information can facilitate the routing selection in the CR network. Since, CPEs at different places would have different available channels and thus different throughput; a routing method can be developed to find a shortest

path, or a path with maximum throughput from a source CPE to a destination. If energy-related factors, such as the path loss model, the transmit power, the interference level, the transmission distance, the circuit power consumption and so on, are considered, a kind of energy-efficient routing method can be derived especially for a CRN. After all, the cross-layer design strategy can gather information from almost all aspects, so we can reach optimal solutions for various requirements.

Network Layer Games: Issues such as the presence of selfish nodes in a network, convergence of different routing techniques as the network changes, and the effects of different node behavior on routing, can be analyzed using game theory. Routing is modeled as a zero sum game between two players – the set of routers and the network itself. In a zero-sum game the utility function of one player (minimizing player) is the negative of the other's (maximizing player). The game has an equilibrium when the minmax value of any player's payoff is equal to its maxmin value. In a zero sum game, the maxmin value is defined as the maximum value that the maximizing player can get under the assumption that the minimizing player's objective is to minimize the payoff to the maximizing player. In other words, the maxmin value represents the maximum among the lowest possible payoffs that the maximizing player can get; this is also called the safe or secure payoff.

In the routing game the payoff to each player consists of two cost components, one being the amount of network overhead and the other varying with the performance metric under consideration. For example, for evaluating soundness the cost to the routers is 0 if all routers have a correct view of the topology when the game ends and 1 if any one router does not. The objective of the routers is to minimize the cost function. The action for the routers involved is to send routing control messages as dictated by the routing technique and update their routing information, and for the network to change the state of existing links from up to down and vice versa.

Table 2. Current related works

Subject	The Proposed work/solution	References
Ad-hoc Networks	- cooperation without incentives - incentives for cooperation: currency - incentives for cooperation: reputation system	[5,7,15] [3,6] [13,17,18]
Hybrid ad hoc Networks	-incentives for cooperation	[4,16]
Sensor Networks	-cooperative packet forwarding	[11]
Cognitive radio	- multi-radio channel allocation -IEEE 802.22 Working Group	[21] [23]
Cellular and Wi-Fi Networks (WWANs and WLANs)	-spectrum sharing in cellular Networks - selfish behavior in CSMA/CA -reputation-based Wi-Fi development	[19,22] [9,12] [8,10]
General Networks	- reputation in social Networks	[14]

The game is solved to determine the minmax value of the cost function. It serves to compare the different routing techniques in terms of the amount of routing control traffic required to achieve convergence and the soundness of the routing protocol to network changes. Another issue related to routing involves studying the effect of selfish nodes on the forwarding operation. We summarize the current related works/trends to above mentioned challenges as shown in the table 2.

As describe in the above mentioned games selfish behavior by nodes in a CRN may lead to a suboptimal equilibrium where nodes, through their actions, reach an undesirable steady state from a network point of view. Hence, incentive mechanisms are needed to steer nodes towards constructive behavior (i.e., towards a desirable equilibrium). Even though the bulk of work done in the past few years to answer above mentioned games still they are at a nascent stage.

4 Conclusions

Game theory allows us to model wireless networks in which there is no centralized entity with full information of network conditions. Game theoretic models, like other mathematical models, can abstract away some important assumptions and un-mask critical unanswered questions. We hope this paper will motivate students and researchers to peep at this fascinating analytical tool, and encourage them in modeling problems of a CRN.

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