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# Application of Game Theory to Cognitive Radio Networks for Power Allocation: An Overview

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***Abstract***

*Due to continuously increasing demand of wireless communication technology, the problem of spectrum shortage arises. Cognitive radio technology enables efficient utilization of the existing wireless spectrum resources. CRN utilizes spectrum band by allowing secondary users to use the spectrum opportunistically, by changing their transmission parameters. We need to analyze the performance of a wireless network. To analyze the performance of a wireless network, game theory is used due to its ability to model individual, independent decision makers. In this paper we model how game theory can be used to allocate power levels to different CR nodes in a CRN at physical layer to ensure a certain QoS.*

***Keywords**: Cognitive Radio, Wireless Networks, Game Theory, Physical Layer, Power Allocation, Cooperative and Non-Cooperative Game Theory*

## 1. Introduction

### Cognitive Radio Network

The entire radio spectrum can be divided in two types of spectrum bands, which are licensed spectrum band and unlicensed spectrum bands. Licensed spectrum bands such as spectrum reserved for the industrial, scientific and medical (ISM) radio bands. Unlicensed band is used by Bluetooth, 3G, digital cordless phone, Wi-Fi, NFS, etc. In recent years, there is a shortage of unlicensed spectrum as a consequence of increased demand and strict allocation policies. There are a number of applications and devices that exclusively depends on the availability of the unlicensed bands, makes the unlicensed bands over crowded, on the other hand, major portion of the licensed bands are underutilized. Licensed band is used 15-85% only and hence is underutilized.

Cognitive radio (CR) is a radical technology that aims for improvements in efficiency of spectrum usage. Cognitive radios are radio systems that continuously perform spectrum sensing, dynamically identify unused (“white”) spectrum, and then operate in this spectrum when it is not used by any licensed user. It requires new techniques such as spectrum sensing, dynamic spectrum assignment, and cross layer design [1]. Basic steps of cognitive cycle are: spectrum sensing, spectrum analyze, and spectrum decision. The main characteristics of a CRN are cognitive capability and reconfigurability. Cognitive capability is the capability of a CRN to

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sense spectrum and capture temporal and spatial variations. Reconfigurability is the ability of a CR node to change its transmission parameters while transmission i.e. radio channel can be dynamically programmed.

CR technology senses spectrum, selects best available channel, access channel and then also vacates channel if any PU activity is detected. CR changes its transmitter parameters based on the spectrum sensing results. These reconfigurable parameters are operating frequency, transmission power, modulation, communication technology. Transmission parameters can even be changed during transmission. A CR has a cognitive process that can perceive current network and environmental conditions, and then plan, decide and act on those conditions. The CR learns from these versions and then uses them to make future decisions and then changes transmission parameters dynamically.

Cognitive radio techniques can substantially improve the efficiency of the spectrum usage [2]. Before cognitive radio transceivers start communicating with each other, they sense the environment for the presence of the primary users [3]. In the absence of a primary user in a particular spectrum [4] or without affecting the interference limits of the primary users [5], the secondary or cognitive radios can establish communication with other users.

The main components of Cognitive Radio Network (CRN) are classified into two groups: the licensed (primary) network and the CR (secondary or unlicensed) network. The licensed network is referred to a network, where the primary/licensed users have licenses issued by the government licensing authorities to operate in certain spectrum bands. Due to their priority in spectrum access, the operations of primary users must not be affected by unlicensed users. On the other hand, the CRN does not have a license to operate in a desired band and may sheath with the licensed networks. In multi-hop mobile cognitive radio ad hoc networks, the CR nodes sense spectrum and identify available frequency bands, which are not currently being used by licensed/primary users, named as Spectrum Opportunities' (SOP) or white holes [6], then select one candidate from SOP via any predetermined policy, such that it should not cause harmful interference to the licensed nodes. Based on this sensed information, CR users access these white holes opportunistically and vacate the channel immediately upon any primary user activity detection. Since PUs have the authority to use the licensed spectrum band, SUs must not interrupt the transmissions of PUs by performing reconfiguration of transmission parameters or moving to other vacant spectrum bands [1]. This creates dynamic use of spectrum bands, where the SUs are able to switch among different spectrums. Thus, CR provides a more effective way to increase the overall network capacity.

CR approach introduces a different concept of physical layer operations and ultimately affects the whole upper layers. Cognitive radios provide the ability for secondary users (SUs)/CR users/unlicensed users to use and share the licensed spectrum bands opportunistically and support prioritization for the transmissions of licensed/primary users (PUs), simultaneously. Various benefits that CRNs provide are high bandwidth, efficient usage of spectrum, and they operate in best available channel.

## Game Theory

Game theory, first introduced by J.V. Neumann and O. Morgenstern in 1944 [9], is a mathematical tool that analyzes the strategic interactions among multiple decision makers. It provides a mathematical basis for the analysis of interactive decision making process between a numbers of rational players. It also provides tools for predicting what might happen when players with conflicting interests interact. Game theory is basically a collection of modeling tools that aid in the understanding of interactive decision problems.

Game theory can be divided in two main categories: (i) cooperative game theory, and (ii) non-cooperative game theory. Cooperative games are defined as games in which CR players cooperate with each other to maximize overall network utility. Non-cooperative games are games in which players are selfish users and take actions independently aiming to maximize their own utility functions.

Three main components of a game are: players, a set of actions and objective function (a set of preferences). The players are the decision makers and actions are the alternatives available to each player. A game can be mathematically represented as G= {N, A, {$u_i$}}, where:

- N= {1, 2… N} is the set of finite number of players.
- A= $A_1$ x $A_2$ x…..x $A_n$ is the set of actions, $A_i$ – action set of player i.
- $u_i$ : A→ R is the payoff/utility function of the player i.

The purpose of game theory analysis is to reach Nash equilibrium *i.e.*, an optimal decision with an appropriate combination from all the available players. Nash equilibrium is a set of strategies, one for each player, such that no player has incentive to change his/her strategy given what the other players are doing. Informally, a set of strategies is Nash equilibrium if no player can do better by unilaterally changing his or her strategy. To see what this means, imagine that each player is told the strategies of the others. Suppose then that each player asks himself or herself: "Knowing the strategies of the other players, and treating the strategies of the other players as set in stone, can I benefit by changing my strategy?" If any player would answer "Yes", then that set of strategies is not Nash equilibrium. But if every player prefers not to switch (or is indifferent between switching and not) then the set of strategies is a Nash equilibrium. Thus, each strategy in Nash equilibrium is a best response to all other strategies in that equilibrium [10]. Nash equilibrium is equilibrium where everyone plays the best strategy when taking decision-making of others in to account.

## 2. CRN and Game Theory

In CRNs, network users need to make intelligent decisions on their spectrum usage and operating parameters based on the sensed spectrum dynamics and actions adopted by other users. Furthermore, users who compete for spectrum resources may have no incentive to cooperate with each other and as a result users behave selfishly. Therefore, it is natural to study CRN user's behavior and interactions from a game theoretic view. The optimization of spectrum usage is generally a multi-objective optimization problem, which is generally very difficult to analyze and solve. To solve this, game theory provides us with well defined equilibrium criteria to measure game optimality under various game settings. Non-cooperative game theory enables us to derive efficient distributed approaches for dynamic spectrum sharing using only local information.

Game theory models have been developed to better understand congestion control, routing, power control, topology control, trust management, and many other issues in wired and wireless communication systems. In a wireless system, actions may be 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. Non-cooperative game theory can be used to investigate the resource allocation problem in CRNs. Utility function of SUs depends on some factors, which are: satisfaction of its own transmission, revenue from selling spectrum to the secondary user, profit, the corresponding payment to the base station, and the performance loss due to the shared spectrum with the secondary users.

 

**Table 1. Mapping of CR Elements to a Game**

| **Game Component** | **Comments** | **Modeled element of CRN** |
|---|---|---|
| Players | Players should aim to maximize their utility function by considering the activity of primary users. | Nodes in wireless network. |
| Strategy/Set of actions | Actions that are related to functionality being observed. | Modulation scheme, coding rate, channel allocation, transmission power level, route selection etc. |
| Utility Function/ Set of preferences | The player's objective which measures the result for a CR player. | Performance metrics *e.g.* throughput, delay, SINR, QoS etc. |

## 3. Power Allocation

Game theory can be applied to model and analyze CRNs at different layers listed in OSI model, which are physical layer, link layer, network layer and all other upper layers of network. Game theory can be applied to the problem of resource allocation in CRNs *e.g.* distributed power control, rate and channel allocation. The key challenge of the physical layer in CRNs is to avoid interference with the users of primary network and to provide good QoS to the users of CRN. Power control is an essential part in CRNs to protect PUs and to provide good QoS to CRs. Effective use of transmission power helps to conserve energy to maximize battery life and to minimize the interference to others. Power control could be implemented in CRNs because of potentially significant performance gains achieved when nodes limit their power level. The major goal of power regulation is to achieve a certain signal to interference noise ratio (SINR) and minimizing the interference due to terminal transmitter power level. There are two major reasons to perform power control: i) to limit the energy available to the mobile node, ii) increase in QoS by minimizing the interference. Non-cooperative game theory has been used to study the problem of power control in CRNs (see, for example, [11]-[13]). In [11] non-cooperative power control game has been proposed for MC-CDMA cognitive radio system to meet the communication needs for both PUs and CRs.

 

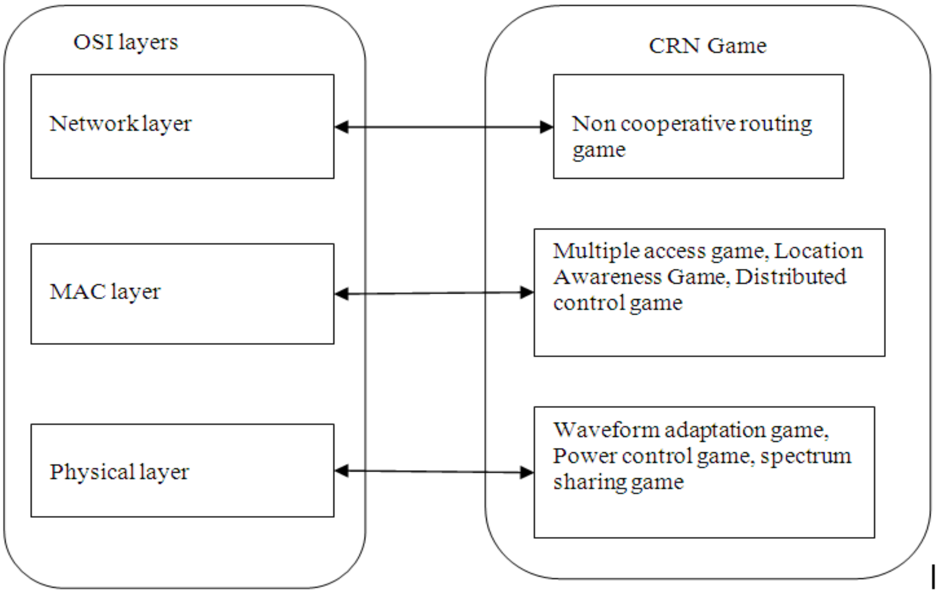


**Figure 1. Classification of CRN Games According to Different OSI Layers**

Similarly, in [12] the uplink power control has been modeled using non-cooperative game. Pricing based power control has been proposed to minimize the interference generated to the PUs in order to provide efficient spectrum sharing. In [13] proposed a non-cooperative power control algorithm. CDMA-pricing cognitive radio system has been proposed to provide dynamic spectrum sharing among CR users.

In [14] to meet the communications needs between PUs and SUs in CRNs and to ensure that the unimpaired operation of the PUs and SUs' communications be not intermitted, a MC-CDMA cognitive radios system and a hand-off technique were proposed for secondary users. In order to efficiently use the limited cognitive radio resources, a novel power control game algorithm in CR systems was adopted. The novel algorithm can regulate their transmitter powers to meet the different SINR requirements and enhance the total throughput effectively. The computer simulations show that the performance of CR system is thereby improved. In this paper, we study the power control of transmitter in cognitive radio system and employ game theory for modeling. Also non-cooperative power control game created by D. Goodman is applied for decentralized users; also a new sigmoid efficiency function with non-liner pricing only related with user's SINR was proposed. It is very suitable for cognitive radio system because of its regardless of the modulation of users' RAT.

In [15] presents a game theoretic solution for joint channel allocation and power control in cognitive radio networks. The problem is analyzed under the physical interference model. The objective is to find a distributed solution that maximizes the network utility with limited information. A different criterion to define this network utility: capacity in bps and number of links fulfilling the *SINR* requirements is considered. A game theoretic framework to perform distributed joint channel and power allocation in cognitive radio networks has been proposed and evaluated. The problem has been analyzed under the physical interference model, including the *SINR* constraint to establish a link. The users' utility has been defined with different criteria, according to the application requirements. Simulation results show that the proposed local game provides a performance similar to a less scalable potential game. In addition it ensures a global performance close to that obtained with a centralized genetic algorithm. This opens an interesting perspective to develop realistic protocols capable of performing efficient opportunistic spectrum access based on the modeled interactions.

In really case, the cooperator only have partial or no information concerning in advance to making decision. However, the current game theory models in cognitive radio networks always regard they have enough information. In [16] an Incomplete Information is taken into account and proposes an algorithm based on game theory to resource allocation. As far as it concerned the MQAMI method, the iterative allocation algorithm has been presented. The results have shown that the method achieves higher rates, although it cannot be implemented in a distributed way like MQAMI based allocation. Algorithm of allocation is the optimal one, even if the practice is not usable due to the complexity rising exponentially with the number of users.

[17] Investigates how the adoption of a cognitive radio strategy can help in the coexistence problem of two wireless networks operating on the same spectrum of frequencies. A DVB-SH based satellite network was considered as primary system, while an infrastructure wireless terrestrial network constituted the cognitive radio based secondary system. The proposed approach is suitable for distributed implementation; furthermore it provides performances comparable to an heuristic allocation method representing the optimum allocation. The game concerning power allocation is a Potential Game. The potential function has been found and it has been discussed how it can be implemented in a distributed way. Performances of the game theoretic approach have been given in terms of rate, actual BER and signal-to-noise ratio. Finally the method has been compared with the results achieved by a heuristic approach to the power allocation, representing the optimum. In the comparison the heuristic method outperformed game theory based one; however this result has not to be interpreted as a failure for the Game Theory allocation since, respect to heuristic method, it can be implemented in a distributed way. A final issue emerged, and it lets assume the proposed method is intrinsically more oriented to fairness than the heuristic one.

## 4. Conclusion

In this survey we first studies about the cognitive radio networks. Then we provided a detailed concept of game theory and its application to research on CRNs. Non-cooperative game theory is then applied to physical layer to perform efficient power allocation in CRNs. Implementing game theory in CRNs helps in improving network performance. Further game theory can also be used to improve other network characteristics. Power allocation is yet another direction of future work.

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