Spectrum Access Games for Cognitive Radio Networks

Moshe T. Masonta[1,2], Thomas Olwal[1,2], Mjumo Mzyece[2] and Ntsibane Ntlatlapa[1]
Meraka Institute[1]
Council for Industrial and Scientific Research[1], P. O. Box 395, Pretoria 0001
Tel: +27 12 841 2085, Fax: +27 12 841 4720
and French South African Institute of Technology (F'SATI)
Tshwane University of Technology[2]
email: {mmasonta, tolwal, nntlatlapa}@csir.co.za[1]; mzyecem@tut.ac.za[2]

Abstract—Cognitive Radio (CR) is seen as a key enabling technology for addressing current under-utilization and inefficient use of radio frequency spectrum. The use of CR will see most of the spectrum white spaces being used opportunistically without causing any interference to the licensed or primary users. CRs can collaborate in order to address the channel fading and hidden terminal problems that may be experienced by a single radio. For modeling and analysis of CR networks, the use of game theory has received a wide acceptance in next generation and intelligent wireless communication systems. In this paper we make use of game theory approach to model and analyze cognitive radio networks in order to allow dynamic spectrum access in broadband wireless access networks. We start by motivating the use of cooperative spectrum sensing to address the channel fading and hidden terminal problems. We show that using repeated games and the discount factor, players can fairly access the uplink available channel without causing interference to each other.

Index Terms—Cognitive Radio, Spectrum Sensing, IEEE 802.16, Game Theory

I. INTRODUCTION

The demand for broadband access in the modern information society is seen as a driver for rapid growth and development of wireless communication systems. In wireless communication networks, radio frequency spectrum is the most precious and expensive wireless network resource which need to be regulated properly for an interference free communication. Most countries have regulatory agencies to regulate radio spectrum by means of renewable licenses. While this approach ensured a non-interfering communication between radio terminals, it has resulted into an inefficient utilization of the spectrum [1]. Recent literature on spectrum management techniques focused mainly on Cognitive Radio (CR) [2] as a technological solution to implement dynamic or opportunistic spectrum access approach without causing any interference to the licensed users or Primary Users (PUs). The use of CR as a suitable technology for addressing spectrum scarcity based on opportunistic spectrum access has resulted into more research by the wireless communication research community. Research on spectrum sensing is divided on whether to perform sensing in a cooperative or single radio manner. Work presented in [3]-[10] motivates the use of cooperative spectrum sensing because it ensures little or no interference is caused to PUs by the Secondary Users (SUs) as opposed to single radio spectrum sensing technique. It also allows CR to exploit the diversity gain provided by associated radios. Based on this motivation and advantages, our work assumes cooperative spectrum sensing operation. In this paper, by PU we refer to a radio that is licensed to operate in a given frequency spectrum band, and a SU is CR that accesses the frequency spectrum band opportunistically, thus it has lower priority on a given band.

The use of game theory in wireless communications network is receiving more attention recently due to the intelligence and flexibility offered in Cognitive Radio Networks (CRNs). Mehta and Kwak [11] discussed some modeling of fundamental questions on CRN as interactive games between nodes. Some inter-discipline research issues on game theory and CRN are also discussed in [11]. However, no actual modeling or results are provided in this work.

MacKenzie and Wicker in [12] presented two applications of game theory in wireless networks: random access and power control. It is also shown that game theory tools can lead to strategies in which optimal behavior emerges naturally from the selfish interests of the agents and the rules of the games. Nie and Comaniciu [13] proposed a game theoretic framework to analyze the behavior of CRs for distributed adaptive channel allocation. They found that non-cooperative games offer a very low overhead for information exchange in the network, while cooperative games improves the overall network performance at the expense of an increased overhead.

In this paper we propose a spectrum decision model for uplink access in broadband wireless access CRNs. In some broadband wireless access (BWA) systems, such as IEEE 802.16, resource allocation and management mechanisms are crucial to guarantee quality of service (QoS) requirements. In order to transmit data, users need to first request bandwidth from the centralized Base Station (BS). Contention based and polling mechanisms are used for resource allocation. Instead of using the contention based random access mechanism; we proposed game theoretic approach for CRN users to access the uplink channel for sending bandwidth request (BW-REQ) messages.

The rest of this paper is organized as follows: Section II presents spectrum management approach using CR. Some related work is presented in Section III. Section IV presents our proposed model. The basic concept and brief introduction to game theory is presented in Section V. This section also covers our spectrum decision game model and the results. Section VI concludes the paper with some future work.

II. Cooperative Spectrum Sensing in CRN

Spectrum sensing is the most crucial function of the CR and it should ensure adaptive transmission in wide bandwidths without causing harmful interference to PUs. It involves identification of spectrum holes and the ability to quickly detect the onset of primary transmission on the spectrum hole occupied by the SU. Two approaches are commonly used for spectrum detection [3]: *1)* To employ detection technique with high performance at individual radios, or local detection. *2)* To conduct cooperative spectrum sensing; where the detection results of multiple radios are combined to obtain a more detailed and correct sensitivity.

A. Spectrum Sensing Approaches

Local detection: Sensing of very weak signals requires a CR to have significantly better sensitivity than primary radios. For local spectrum detection (for example: using energy detection technique), the goal is to distinguish between the two hypotheses:

$$x_i(t) = \begin{cases} n_i(t) & H_0, \\ h_i(t)s(t) + n_i(t) & H_1, \end{cases} \qquad (1)$$

where $x_i(t)$ is the signal received by the SU, *s(t)* is the PU's transmitted signal, $n_i(t)$ is the Additive White Gaussian Noise (AWGN), and $h_i(t)$ is the amplitude gain of the channel. H_0 denotes null hypothesis, i.e. no PU signal in a spectrum band. H_1 is an alternative hypothesis, i.e. there is some PU signal. However, local spectrum sensing suffers from deep channel fading and hidden terminal problem.

In channel fading environments, the SU is challenged to distinguish between a white space (i.e. available spectrum band) and the deep fade (where it is hard to detect the primary signal) [7]. The hidden terminal problem may occur when the SU is shadowed within the vicinity of the active PU. As a result, a SU may not notice the presence of the PU and mistakenly try to access the primary channel, which will lead to interference with the primary system [10]. To address the channel fading and hidden terminal problems experienced in local spectrum sensing, cooperative among different SUs is proposed where SUs shares their individual sensing results.

Cooperative Spectrum Sensing: Cooperative spectrum sensing and decision can be used over single radio spectrum sensing in order to reduce the probability of interference to PUs. To ensure reliable and efficient spectrum sensing, it is important to associate the detection of multiple radios through cooperative spectrum sensing [3]–[9]. A typical model for cooperative spectrum sensing in CRN setup is shown in Figure 1. In the model, a CRN is operating opportunistically within the coverage area of a primary/licensed network.

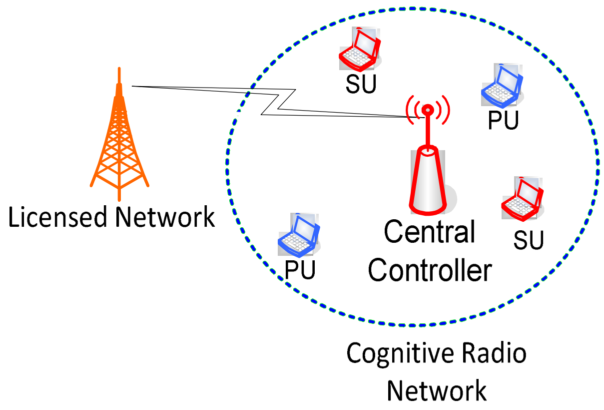

Figure 1: Cooperative Spectrum Sensing in CRN

SUs perform individual spectrum sensing and forward their decisions to their central controller for a global decision making. The central controller will then broadcast the decision to all the SUs attached to it for interference free opportunistic access of licensed spectrum.

Cooperative spectrum sensing involves the following general steps [8]:

1. Every SU performs local spectrum measurement independently and then makes a (binary) decision
2. All of the SUs forward their (binary) decisions to a central controller (or band manager/Fusion Center).
3. The central controller then combines those decisions and makes a final decision to infer the absence or presence of the PU in the observed spectrum band.

Cooperative sensing will allow CR to exploit the diversity gain provided by associated radios. Cooperative spectrum sensing advantages includes: Diversity gain due to associated radios, improved detection probability, and mitigating the sensing requirements (high cost) on individual radios. One of the main challenges faced by cooperative spectrum sensing is the transmission overhead, where each radio transmits its decision to the central controller. The information transmitted by each SU to the central controller may be soft or hard decisions. If soft decision is used, SUs will transmit their decision statistics instead of a one-bit decision. And hard decision occurs when only the final 1-bit decision is transmitted (0 or 1). It is generally argued that soft decision combining of sensing results yields much better gains than hard decision combining [9].

Cooperation allows independently faded radios to collectively achieve robustness to severe fades while keeping individual sensitivity levels close to the nominal path loss [9]. However, [10] argues that when one radio has higher signal-to-noise ratio (SNR) compared to other radios, cooperative spectrum sensing performs worse than the individual spectrum sensing.

III. Game Theory Overview

Game theory is a set of tools originally developed in economics for the purposes of analyzing the complexities on human interactions. It is concerned with strategic interactions where two or more players have to make a decision. The deregulation of the telecommunication industry and the improvements in computation power, which allows network terminals to make independent and selfish operational decisions, motivates the use of game theoretic approaches [15]. Recently game theory has been applied in communication systems as an analyzing and modeling tool [11]–[13] to address wireless communication problems such as spectrum management, power control, congestion control, topology control and routing, among others. Game theory, therefore, offers a suite of tools that, if used effectively, can model the interaction among independent nodes in a CRN.

A. *Basic Elements of Game Theory*

The fundamental component of game theory is the notion of a game, and every game should at least have three elements: a set of players, a set of actions for each player, and a set of preferences. Players are the decision makers, actions are the alternatives available to each player, and preferences are utility functions mapping action profiles into the real numbers. Table 1 relates a typical game with a CRN.

A game can be expressed as $G = \langle S, A, \{u_i\} \rangle$ where G is a particular game, S denote a finite set of players $\{1, 2, 3, ..., s\}$. A_i is the set of possible actions available to player i for each player $i \in S$, and $A = A_1 \times A_2 \times A_3 \times ... \times A_h$ denotes the action space. And finally $\{u_i\} = \{u_1, u_{2,} u_3, ..., u_s\}$ denotes player i 's utility function, which is an objective function the players wish to maximize. For every player i, the utility function u_i is a function of the particular action chosen by the player i, a_i, and the particular actions chosen by all of the other players in the game, a_i. Based on this model, Nash Equilibria are identified wherein no player would rationally choose to deviate from their chosen action as this would diminish their payoff, $u_i(a_i) \geq u_i(b_i, a_{-i})$ for all $b_i \in A_i$. The action tuples (i.e. a unique choice of actions by each player) corresponding to the Nash Equilibria are then predicted as the most probable outcomes. Of most importance in game theory is the celebrated concept of Nash Equilibrium. Nash Equilibrium is an action profile at which no user may gain by unilaterally deviating. It is a stable operating point because no user has any incentive to change strategy.

IV. PROPOSED SYSTEM MODEL

We consider a CRN consisting of one central controller and N SUs operating opportunistically within an IEEE 802.16 [16] point-to-multipoint (PMP) primary network. The SUs are CR users and they periodically perform spectrum sensing in order to find the spectrum holes or unused spectrum bands for uplink access on the primary network. The SUs wish to access the primary network BS opportunistically, following the standardized method [16]. They have to do this with minimum or no interference to the PUs. If a SU has data to send, it must first check which uplink channel is available, and then send a bandwidth request (BW-REQ).

A. *Assumptions*

In our model above, the following assumptions are made:

- Cooperative spectrum sensing is employed by the SUs. Each SU perform spectrum sensing and send the results to a central controller.
- The central controller will make the final decision on the available spectrum band and broadcast to all the SUs.
- We assume non-real time and best effort traffic exchange between the SUs.
- We assume that all SUs are attached to the BS, meaning they already performed initial ranging.

B. *Uplink Channel Access in IEEE 802.16*

The IEEE 802.16 or WiMAX standard [16] is based on connection-oriented Medium Access Control (MAC). The MAC frame in PMP architecture is modelled as a stream of mini-slots, and it is divided into Uplink (UL) sub-frame and Downlink (DL) sub-frame.

Figure 2 shows a single MAC frame in PMP Time Division Access Multiple (TDMA) operation. The DL sub-frame is used by the BS to broadcast to all subscriber stations (SSs). It begins with a frame control section that contains a preamble, a DL-MAP and an UL-MAP.

Resource management and allocation mechanisms are crucial to guarantee QoS requirements in 802.16 networks. The IEEE 802.16 standard suit defines reservation-based bandwidth allocation mechanisms since multiple SSs share a common UL to the BS on a demand basis. If an SS needs some amount of bandwidth for communication, it has to make a reservation with the BS by sending a BW-REQ. Two methods are suggested in order to determine which SS is allowed to transmit its BW-REQ from multiple candidates: *Contention-based random access* and *contention-free centralized polling.*

In contention-based random access, an SS transmits a BW-REQ during a predefined contention period and a random back-off mechanism is used to resolve contention among BW-REQ from multiple SSs.

C. *Spectrum Decision Modeling*

As opposed to the contention-based random access, SUs will use their intelligence to access the UL channel. Since the number of SUs for a given CRN may be large enough (more than one), it might happen that one SU decides to be greedy and use the available spectrum selfishly. This will mean that other users may never have an opportunity to access the spectrum, as a result, they are deprived an opportunity to communicate. In order to address the selfish and greedy behavior by some users, we propose a game theoretic approach, whereby the decision to access the spectrum will have either conflicting consequences.

Table 1. Typical Components for Wireless Network Game [11]

Components of Game	Elements of CRN
A set of players	Nodes in wireless network
A set of actions	A modulation scheme, power control, waveforms, spectrum
A set of preferences	Performance metrics (e.g. SINR, delay)

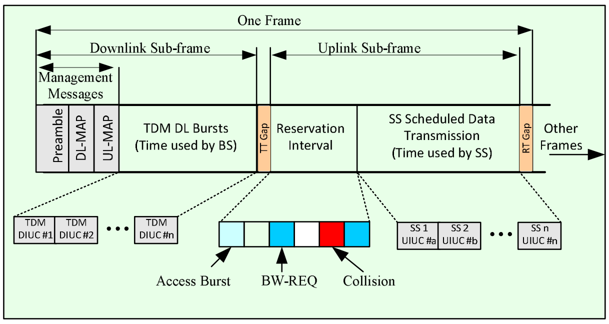

Figure 2: IEEE 802.16 MAC Frame in PMP TDMA [17]

V. SPECTRUM DECISION GAME

A. Spectrum Decision Game Modeling

For a simplified decision model, we assume that players (SUs) know the number of other users wishing to transmit on the same available band, n. Let $G(n)$ be the game in which there are currently n SUs wishing to transmit or send. In each stage of $G(n)$, each of the n players must decide whether to send (S) or wait (W). If one player decides to transmit and the rest decide to wait, the player who transmits will receive a payoff of 1, and each of the other $(n-1)$ players will play $G(n-1)$ in the next period. If no player (SU) transmit or more than one player transmits, all players will play $G(n)$ again in the next period. Players place a lower value on payoffs in later stages than on current payoffs. This is represented by a per period discount factor $q<1$. Let $u_{i,n}$ represent user i 's utility from playing $G(n)$ and let K be a random variable denoting the number of other users within the CRN, but not participating in the game (i.e. not having data to transmit). For $n=1$, the player should transmit and achieve the utility of 1 ($u_{i,1}=1$) and for $n>1$ we express $u_{i,n}$ as a function of player i 's action (S) or wait (W) recursively:

$$u_{i,n}(S) = P[K=0] + q \cdot u_{i,n} P[K>0] \quad (2)$$

$$u_{i,n}(W) = q \cdot u_{i,n-1} P[K=1] + q \cdot u_{i,n} P[K \neq 1] \quad (3)$$

So, for $n>1$, we can simplify (2) as follows:

$$u_{i,n}(S) - q \cdot u_{i,n} P[K \neq 0] = P[K=0]$$

$$u_{i,n}(S)\left[1 - q \cdot P[K \neq 0]\right] = P[K=0]$$

$$u_{i,n}(S) = \frac{P[K=0]}{1 - q \cdot P[K \neq 0]} \quad (4)$$

Similarly, (3) can also be simplified as represented in (5)

$$u_{i,n}(W) = \frac{q \cdot P[K=1]}{1 - q \cdot P[K \neq 1]} u_{i,n-1} \quad (5)$$

B. Results Discussion

We focus our results to the calculation of the utility function achievable by players in a given game. Shown in Figure 3 is the utility by n players in a given game $G(n)$. It is shown that for a game, $G(n)$ with one player, $n=1$, a utility of 1 is achieved. As the number of players n increases, the utility decreases rapidly to the point where the number of players n approaches half the total users, and then increases again. As mentioned earlier, the highest discount factor (q) a transmitting user can receive is 1 if one user transmits and others wait. Therefore each player's goal is to maximize its utility. We varied the q between 0.9 and 0.99.

It can be observed from our first results, in Figure 3, that as the number of users in the games increases, the utility starts by decreasing, and then it increases again. These are sort of strange results that we aim at addressing in our ongoing research.

If we adopt the strategy in [12], and consider mobile SUs, where users are battery powered. Power saving mechanisms are introduced in [16] for mobile WiMAX. Therefore for a battery powered SU, we have to introduce some cost, c. The SU cost will represent the battery usage of a device as it access the UL channel for BW-REQ and also for data transmission. This will change equation (4) to become equation (6), as shown below.

$$u_{i,n}(S) = \frac{P[K=0] - c}{1 - q \cdot P[K>0]} \quad (6)$$

Figure 4 shows a new utility function with varying transmission cost, c, and fixed discount factor. There are some simple asymmetric Nash Equilibrium strategies in our games. For instance, if n SUs are having traffic to transmit, SU 1 can transmit in period 1, SU 2 in period 2, and so on until SU n transmits in period n.

For a strategy in which each player selects a vector of transmit probabilities can be played in order to achieve a symmetric equilibrium, where each player's decision of whether to transmit or not is independent of all other players' decisions.

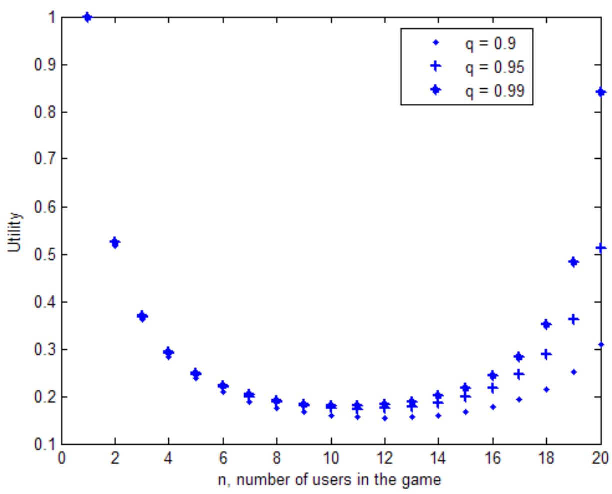

Figure 3: User utilities for playing $G(n)$

VI. CONCLUSION

In this paper we presented the use of game theory in CRNs to analyze and model the spectrum access decision in broadband wireless access networks. Secondary users must first perform spectrum sensing in order to identify unoccupied uplink channels. We used the game theory to compute the utility function, and plotted it versus the number of SUs.

There are still more challenges to be addressed in spectrum access decision games in CRNs. While this work covers our preliminary results, more research work is still underway in our research group to enhance this model so we can be able to use the potential game approach to compute the equilibrium access probability. In future we aim at finding reliable and efficient techniques to perform spectrum characterization and PU activity to allow an enhanced spectrum decision modeling. Our future work will also include building an outdoor CRN testbed to allow real-life simulations and experimentations for the verification of our analytical results.

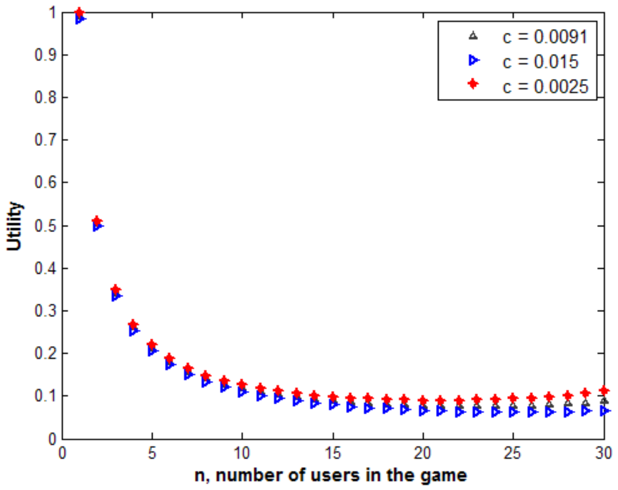

Figure 4: User Utilities with transmission cost, *c*

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Moshe Masonta received his M. Tech degree and MSc degree in 2008 from Tshwane University of Technology (TUT) and Ecole Supérieure d' Ingénieurs en Electrotechnique et Electronique (ESIEE) de Paris, respectively. He is presently studying towards the D. Tech degree at TUT. His research interests include cognitive radios, spectrum management and energy efficiency in broadband wireless networks.