Cognitive Radio: An intelligent Device for Dynamic Spectrum Access (DSA) and Radio Resource Management (RRM)

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ABSTRACT

Radio spectrum is a scarce and non-reproducible natural resource hence spectrum management policies play a vital role in ensuring the efficient use of spectrum. Optimum usage of radio resources will be done by sharing these resources among various radio services. Last two decade has seen a tremendous growth in Indian telecommunications because of effective policies launched by governing body and effort of entrepreneurs. As the growth is fast the spectrum access demands are increased enormously. The increasing demand of spectrum imposes spectrum management policies as well as various issues in management of telecommunication domain.

As radio resource is limited; the resource needs must be efficiently shared and reused by a number of users who may be simultaneously accessing a variety of mobile services. This paper investigates the cognitive radio resource management using game theory. Cooperative game theory provides the shared radio resources fairly among multiple non cooperative cognitive radio networks to optimize overall performance.

General Terms
Cognitive Radio, Dynamic Spectrum Access

Keywords
Cognitive Radio, Spectrum management, Dynamic Spectrum Access, Radio Resource Management, Game Theory

1. INTRODUCTION

The electromagnetic radio spectrum is a natural resource and its use by transmitters and receivers is licensed by government. Regulatory bodies in the world found that most radio frequency spectrum was inefficiently utilized [1]. Studies performed in some countries confirmed that Cellular network bands are overloaded in most parts of the world, but military, amateur radio and paging frequency bands are insufficiently utilized [2,3,4]. Radio resource survey concluded that spectrum utilization depends on time and place. Unlicensed user can not access the rarely used frequencies from the fixed frequency allocated spectrum, though it does not cause interference to assigned service. Therefore, regulatory bodies in the world have been considering allowingunlicensed users in licensed bands if they would not cause any interference to licensed users. These initiatives have focused cognitive-radio research on dynamic spectrum access [5].

This paper provides an initial investigation into cooperative resource management for multiple cognitive radio networks. Interference from co-located, co-band, and non-cooperative wireless technologies is anticipated and is a part of the study [6].

The allocation of the unlicensed frequency bands has resulted in overcrowding of these bands. The usable spectrum is already allotted to licensed users for the various services and this leads to shortfall in of spectrum for upcoming requirements. To solve this problem government has come up with new spectrum allocation policies. The spectrum sharing and leasing was introduced by policy makers and regulators. As per new policy the spectrum allotment to the licensee for the services for various purposes can be given. Licensee can use the entire spectrum flexibly for various services and even lease their spectrum to third parties.

The FCC is considering a new spectrum sharing paradigm which not only beneficial for the licensed band but also to the unlicensed bands. Without interference, allocation of licensed band to unlicensed operations is the main objective of the new technique. The licensed band users are called primary users and secondary otherwise. When primary users don't use the band for operations, the band can be assigned to the secondary user. Most of the licensed bands are underutilized and hence this policy provides efficiency in allotment of limited resources to multiple requesters [7].

A tight coupling between the spectrum management functionality and the software-defined radios attributes is required in Cognitive radio resource management.

2. COGNITIVE RADIO

In November 2002, the Federal Communications Commission (FCC) published a report prepared by the Spectrum-Policy Task Force, aimed at improving the way in which this precious resource is managed in the United States [8].

The allocation of the unlicensed frequency bands has resulted in the overcrowding of these bands. Shortage of spectrum for new and emerging wireless applications was an important issue in radio resource management because the most of the usable electromagnetic spectrum already has been allocated for licensed use. To resolve this, policy regulators and policy makers are working on new spectrum management policy.

In the 1999 paper that first coined the term "cognitive radio", Joseph Mitola III defines a cognitive radio as [Mitola_99]: "A radio that employs model based reasoning to achieve a specified level of competence in radio-related domains."

Depending on transmission and reception parameters, there are two main types of cognitive radio:

Full Cognitive Radio, where every possible parameter observable by a wireless node (or network) is considered.

Spectrum-Sensing Cognitive Radio, in which only the radio-frequency spectrum is considered.
The term cognitive radio is derived from "cognition".
According to Wikipedia cognition is referred to as

- Mental processes of an individual, with particular relation
- Mental states such as beliefs, desires and intentions
- Information processing involving learning and knowledge
- Description of the emergent development of knowledge and concepts within a group

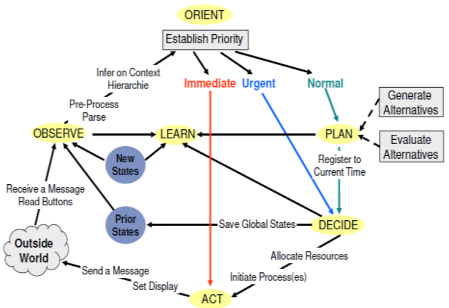

Figure: Cognitive Radio - An Integrated Agent Architecture for Software Defined Radio [9]

"Cognitive radio is an intelligent wireless communication system that is aware of its surrounding environment (i.e. its outside world), and uses methodology of understanding-by-building to learn from environment and adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters (e.g. transmit power, carrier frequency and modulation strategy) in real time, with two primary objectives in mind: highly reliable communication whenever and wherever needed; efficient utilization of radio spectrum." [10].

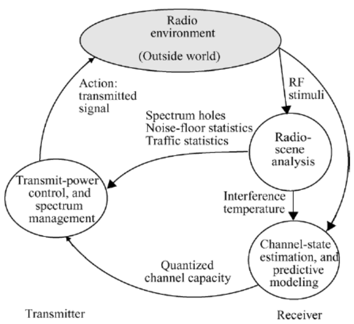

Figure 1: Basic cognitive cycle [10]

3. DYNAMIC SPECTRUM ACCESS (DSA)

Spectrum access means, to enhance the efficiency in the usage of spectrum in a specific geographic region, CRs access spectrum holes left by the licensed user's system (primary users) as secondary users. In other words Spectrum access happens in time, frequency and space domain. Dynamic spectrum access is a promising approach to alleviate the spectrum scarcity that wireless communications face today. In short, it aims at reusing sparsely occupied frequency bands while causing no (or insignificant) interference to the actual licensees.

Most of the radio spectrum relevant to wireless communications is densely allocated by regulators. The bandwidth requirements of emerging technologies can be fulfilled up to certain extent by such allocation. The scarcity is not a result of heavy usage of the spectrum; in contrast, it is merely due to the inefficiency of the static frequency allocation pursued by regulators. A typical spectrum utilization of around five percent or even less is reported [11, 12].

The majority of research, so far, has focused on DSA in the spatial domain. Spatial domain means, "If the primary user's absence in a certain area can be detected reliably, and if we carefully confine our transmissions to this area, interference is limited by this sufficient spatial separation. Reusing TV bands that are allocated, but not broadcast, across the entire country are a prominent example of this paradigm" [12]

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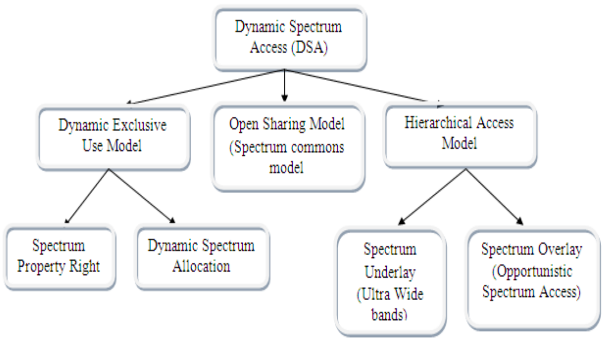

Figure 2: Dynamic Spectrum Access (DSA) [13]

4. RADIO RESOURCE MANAGEMENT (RRM)

Radio Resource Management (RRM) can be best understood as a constrained probabilistic optimization problem that can be formulated as follows:

"Given a particular infrastructure deployment (constraints), allocate resources (variables) in a manner that (ideally) maximize or minimize some operational parameter(s) (objective functions)."[14]

RRM problem is different from mathematical optimization problems because of probabilistic aspect of it. When evaluating RRM objective functions various statistical measures are frequently used. RRM has following inversely related objectives

- Maximize user resources ⇔ Maximize coverage/capacity
- Maximize mobility support ⇔ Maximize Capacity
- Maximize Coverage ⇔ Minimize Cost

However, efficient spectrum use and optimal resource allocation are critical to the network performance [14].

RRM is categorized at fixed RRM and dynamic RRM. In a fixed RRM, resource management decisions are made just once, typically before deployment. Once this decision is made then reallocation cannot be done. The system wide network parameters are based on anticipated operational parameters and performance & economic criteria. Some of the parameters are total system bandwidth, frequency reuse factor, number of base stations, Antenna heights etc.

Mobility is a central to wireless networks and expected load distributions, mobile locations, fading profiles, and virtually every other assumption considered during fixed resource design and allocation change during operation. Thus nearly every allocation decision is subject to change in wireless network.

5. GAME THEORY

A set of mathematical tools used to analyze interactive decision makers is called Game theory. The fundamental component of game theory is the notion of a game, expressed in normal form:

"$G = \langle N, A, \{u_i\}\rangle$ where G is a particular game, $N = \{1,2,\ldots,n\}$ is a finite set of players (decision makers), Ai is the set of actions available to player i, $A= A_1 \times A_2 \times A_3 \times \ldots \times A_n$ is the action space, and $\{u_i\} = \{u_1, u_2, u_3, \ldots, u_n\}$ is the set of utility(objective) functions that the players wish to maximize. Each player's objective function, u_i, is a function of the particular action chosen by player i, a_i, and the particular actions chosen by all of the other players in the game, a_{-i} and yields a real number. Other games may include additional components, such as the information available to each player and communication mechanisms. In a repeated game, players are allowed to observe the actions of the other players,remember past actions, and attempt to predict future actions of players" [15].

Nash equilibrium is a solution concept of a game involving two or more players, in which each player is assumed to know the equilibrium strategies of the other players, and no player has anything to gain by changing only his own strategy unilaterally. If each player has chosen a strategy and no player can benefit by changing his or her strategy while the other players keep their unchanged, then the current set of strategy choices and the corresponding payoffs constitute Nash equilibrium [16].

5.1 Game Theory terms

Fundamental terms used in Game theoryare as follows [15]:

Players

Players are the decision making entities in the modeled system.

Actions

An action set represents the choices available to a player. Note that these choices may be quite complex and, for instance, may represent a sequence of real world actions. Each player in the game has its own action set and makes itsdecision by choosing an action from its action set. A choice of actions by all players in the game produces an actionvector or action tuple. All possible action vectors in the game are contained within the game's action space. The action space is formed the Cartesian product of every player's action set.

Outcomes

Each action vector produces a well defined and expected outcome. Note as an outcome is jointly defined by every player's action choice, there is an interactive relationship. Thus in every game there exists a mapping from the action space to some outcome space. As this mapping is presumed subjective, most game analyses ignore outcomes and focus solely on the actions that produce the outcomes.

Utility Functions

While games can be analyzed based on the ordinal relations implied by preference relations, cardinal relations have a richer tool set and are generally preferred for analysis. Utility functions (objective functions) transform the ordinal relationships of players' preference relationships to cardinal relationships. Generally a utility function is constructed over the action (outcome) space so that if 'a' is preferable to 'b', then the cardinal value assigned to 'a' will be greater than the cardinal value assigned to 'b'. Thus in light of utility functions, it may be fair to treat the reference operator, $\succsim$, as the greater than or equal to operator, $\geq$.

5.2 Basic game models

5.2.1 Non cooperative and cooperative game:

A player may be interpreted as individual or a group of individuals making a decision. Once a set of players is defined there are two types of models: those in which a set of possible actions of individual players are primitive and those in which the sets of possible joint actions of groups of players are primitives. Sometimes the model of the first type is referred as "non cooperative" and second type is referred as "cooperative"

5.2.2 Strategic and Extensive game

Strategic game is a model of situation in which each player chooses his/her plan of action once and for all, and all players' decisions are made simultaneously. The model of extensive game specifies the possible orders of events; each player can consider his/her plan of action not only at beginning of the game but also whenever he/she has to make a decision.

5.2.3 Games with and without perfect information

An extensive game is a detailed description of a sequential structure of a decision problems encountered by the players in a strategic situations. There is perfect information in such a game if each player, when making any decision, is perfectly informed of all the events that has previously occurred. In a strategic game, a player, when taking an action, does not know the actions that the other player takes. Such a game is referred as game without perfect information.

5.3 Components of games for Cognitive Radio Network

Study of cognitive radio networks in a game theoretic frame work is multifold. First, by modeling dynamic spectrum sharing among network users as games, network users behaviors and actions can be analyzed in a formalized game structure, by using this theoretical achievements in game theory can be fully utilized.Second, game theory provides us various optimality criteria for the spectrum sharing problem.Optimization of spectrum usage is a multi objective optimization problem. Third, non cooperative game theory, one of the most important branches of game theory enables us to derive efficient distributed approaches for dynamic spectrum sharing using local information.

The basic game models for cognitive radio network can be summarized as follows [17]

	Open spectrum sharing	Licensed spectrum sharing (auction)
Players	Secondary users that compete for an unlicensed spectrum	Both primary and secondary users
Actions	Transmission parameters, such as transmission power level, access rates, etc.	Secondary users: which licensed band they want to rent and how much they would pay for leasing the licensed band Primary users: which secondary users they will lease each unused band and the charge
Payoffs	Non decreasing functions of quality of service by utilizing the spectrum	Monetary gains e.g. revenue minus cost, by leasing the licensed spectrum

6. APPLICAONS OF GAME THEORY IN RRM

Game theory was at first a mathematical tool used for economics, political and business studies. It helps understand situations in which decision-makers interact in a complex environment according to a set of rule. Many different types of game exists which are used to reflect to analyzed situation for example potential games, repeated game, cooperative or non-cooperative games. In the cognitive radio network (CRN), the formal game model for the power control can be defined as follows:

Players: are the cognitive users (secondary users (SUs)).

Actions: called also as the decisions, and are defined by the transmission power allocation strategy.

Utility function: represents the value of the observed quality of-service (QoS) for a player, and is defined later in this section.

The central idea in game theory is how the decision from one player will affects the decision-making process from all other players and how to reach a state of equilibrium that would satisfy most of the players [18].

We formulate the problem of resource allocation in the context of a Cognitive Radio Networks (CRN) to reflect the needs of Primary Users (PUs) and Secondary Users (SUs). We consider the primary uplink of a single CRN, where cognitive transmitters transmit signals to a number of SUs, while the primary Base Station (BS) receives its desired signal from a primary transmitter and interference from all the cognitive transmitters.

To resolve the problem of resource allocation, we propose a utility function that meets the objective to maximize the SUs capacity, and the protection for PUs. Specifically, we define a payoff function that represents the Signal to noise and interference ratio (SNIR) constraint, and a price function specifies the outage probability constraint. The utility function is defined as:

Utility function = payoff function - price function

We introduce a payoff to express the capacity need of SU m, and a price function to represent the protection for PUs by means of the outage probability. And each SU adjusts its transmitted power to maximize its utility function. This defines a power allocation algorithm that maximizes the defined utility function to compute the transmitted power of each SU [19].

7. CONCLUSION

Next-generation wireless networks are expected to use flexible spectrum sharing techniques for achieving more efficient and fair spectrum usage. Game theoretical dynamic spectrum sharing is important for developing efficient spectrum sharing scheme. Game theoretic research on cognitive radio networking is categorized into four parts, non-cooperative spectrum sharing, spectrum trading and mechanism design, cooperative spectrum sharing, and stochastic spectrum sharing games. However, to ensure efficient and fair spectrum sharing in next-generation networks, more research is needed on modeling cooperation overhead and primary user cooperation.

We can implement open spectrum game model as a one shot game and can study of behavior of throughput function and parameter dependency [Bit Error Rate (BER)]. One shot game can be played multiple times to enforce cooperation and comparing the results may give most effective scheme for maximizing throughput. The open spectrum repeated games can be evaluated for different punishment strategies like ‘tit for tat’ and fictitious play to discourage the player deviation.

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