A Survey on Dynamic Spectrum Sharing Using Game Theory In Cognitive Radio Networks

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***Abstract*— Due to the tremendous increase in wireless data traffic, a usable radio spectrum is quickly being depleted. Current Fixed Spectrum Allocation (FSA) strategy give rise to the problem of spectrum scarcity and underutilization. Cognitive Radio (CR) is proposed as a new wireless paradigm to overcome the spectrum underutilization problem. CR is a promising technology which for future wireless communications. CRs can change its operating parameters intelligently in real time to account for dynamic changes in a wireless environment. CR enables a technique called Dynamic Spectrum Allocation (DSA) where the users are able to access unlicensed bands opportunistically. Since idle spectrum from PU is a valuable commodity, many cognitive users will be competing for it simultaneously. Therefore, there arises competition among the users. Users may be only concerned about maximizing their own benefits by behaving rationally and selfishly. Thus spectrum allocation problem falls under NP-hard complex based on its complexity to solve. Out of several solution approaches, Game theory is found to be an efficient mathematical tool since it deals with solving the conflicts among the users. This survey is aimed at providing a comprehensive overview on dynamic spectrum allocation using game theory.**
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Keywords—Cognitive Radio; Dynamic Spectrum Sharing; Game Theory; NeXt Generation networks

Introduction

With the development of wireless communication technology, the use of mobile radio systems is growing in a rapid rate. The radio spectrum is a natural resource regulated by governmental or international agencies and is assigned to license holders on a long term basis using a fixed spectrum assignment policy. Current fixed spectrum allocation policy(FSA) is static, that is, spectrum is allocated for a particular application (e.g., TV broadcasting), and such allocations do not change over space and time. Due to the non-renewable nature of spectrum resource, the available spectrum becomes scarcer. To improve the utilization of the available spectrum cognitive radios (CR) has been proposed by J. Mitola in 1999 in his Ph.D thesis "Cognitive Radio: integrated agent architecture for software defined radio" as a new wireless paradigm for exploiting the spectrum opportunities. [1][2].

Cognitive radio systems (CRS) may offer functional and operational versatility and flexibility in mobile radio systems. According to the study conducted by International Telecommunication Union–Radio (ITU-R) group, cognitive radio system can be defined as

> "a radio system employing technology that allows the system to obtain knowledge of its operational and geographical environment, established policies and its internal state; to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives; and to learn from the results obtained."

Basically, at a given time and location, CR aims to avoid the existence of portions of the spectrum going underutilized while others are crowded with many devices competing for the same channels[3].

This paper is organized as follows. Section II gives an overview of Cognitive Radio network, its functions and applications in the area of wireless communication. Section III describes about different techniques of spectrum sharing. It also deals with a few of the existing solutions to spectrum allocation problem. Section IV introduces game theory as an efficient technique to solve SA problem. It provides basic concepts of game theory, its types and its applications in different spectrum sharing scenarios. Finally, the paper concludes with an overall summary.

Cognitive Radio Network

CR devices perform a kind of operation that is often designated as Dynamic Spectrum Access (DSA) and hence such networks are called Dynamic Spectrum Access Networks or cognitive radio networks or NeXt Generation (xG) communication network. The concept of DSA was first implemented by Defense Advanced Research Project Agency (DARPA) in their project in year of 2003[4]. In DSA, it is assumed that there is a primary user or licensed user (incumbent radio system) that owns the spectrum rights and several Secondary Users (SUs). These SUs do not have direct rights for accessing spectrum bands but could use the primary spectrum in an opportunistic manner. Secondary transmissions are in such a way that it should not harm legacy users (primary users)[5].

Licensed spectrum includes UHF/VHF, GSM, UMTS, TV frequency bands. On the other hand unlicensed spectrum includes, for instance ISM (Industrial, Scientific and Medical), U-NII(Unlicensed National Information Infrastructure) frequency bands. Several standards for cognitive radio networks have been proposed by various organizations. IEEE 802.22 [6] was the first proposed standard for wireless networks based on CR techniques. This standard aims to use the TV bands in an opportunistic manner, avoiding causing interference to licensed users. The basic features of a CR includes; location awareness, intelligent learning, adaptability, negotiated use, adaptive modulation, Transmit Power Control.

A. Cognitive Radio Cycle

Simon Haykin proposed a basic cognitive cycle in 2005. He considered CR as a feedback system and the functionalities that are required to carry out by a cognitive radio to access a white space spectrum in DSA forms a CR cycle [7]. The cognitive cycle starts with the passive sensing of RF stimuli and executes a series of tasks sequentially. The tasks performed by a CR include spectrum sensing, spectrum management, spectrum sharing and spectrum mobility.

Spectrum sensing enables CR users to detect the primary user's signal in licensed bands. CR users periodically monitor spectrum bands to find spectrum holes. CR users must avoid conflict with primary users by determining their transmission activity in a band. In *spectrum decision/ management* process the best available channel is selected which meets the user communication requirements. CRs analyses the channel characteristics of the sensed idle channel in order to determine if it satisfies the desired quality of service (QoS).Also, they must be aware of the activity of licensed users to get a calculation on how long SUs can use that channel without interrupting PU activity.

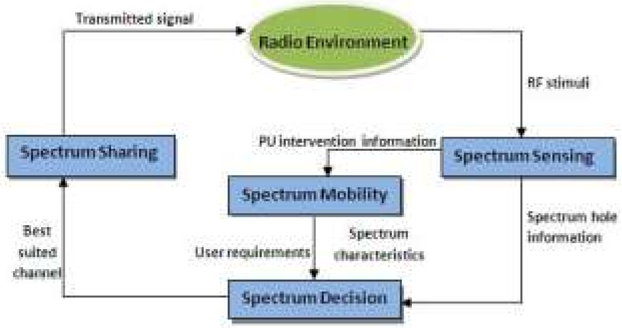

Fig. 11. *Cognitive Radio Cycle*

Spectrum sharing is the core of dynamic spectrum access since it determines how fairly the white space is being shared different SUs. The objective is to assign spectrum bands to cognitive users in order to avoid interfering with licensed users and maximize their performance. *Spectrum mobility* refers to CR users' ability to quickly adapt and leave a channel in a changing environment. Even after initiating transmission in the best suited channel, CRs must continue to monitor the same channel since PU may appear at any time. When the presence of PU is detected, CR must ceases its transmission in that channel and make it available for the PU. In the meantime it should find another white space to continue its transmission.

B. CRN Applications

1) Leased Networks

The primary user can provide a leased network by allowing opportunistic access to its licensed spectrum with an agreement. a primary network (PN) allows unlicensed or secondary networks (SNs) to temporarily use part of its spectrum in exchange for monetary payments and/or some type of service provided by the SNs to the spectrum owner, assuring the absence of harmful interference at the primary users (PUs). The PN improves its revenue, its performance, or both, while the SNs gain access to spectrum resources, achieving a *win-win* situation [9]. Besides that, SU should reduce their interference level within a specified limit so that PU doesn't have to sacrifice the required QoS. Leased network is more preferable for the PU since its utility is increasing. Eg:- A Primary network can provide its spectrum access rights to a regional community for the purpose of broadband access.

2) SMART *grid networks*

When intelligence is added to the conventional power grid, it becomes a smart grid. A smart grid transforms the way power is generated, delivered, consumed and billed. One of the high level layer of smart grid called as Advanced Metering infrastructure (AMI) or field area network (FAN) that carry information between premises via smart meters often require a bandwidth in a range of 10-100Kb/s per device. Therefore legacy cellular network cannot be assisted for AMI/FAN as cellular data traffic grows dramatically year by year. Also, it has coverage issues in rural areas. Cognitive-radio-based AMI/FANs may offer many advantages such as bandwidth, distance and cost, as compared with other wireline/wireless technologies in certain markets.CR-enabled AMI/FAN devices are not immune from interference or congestion [8].

3) Public safety networks

Public safety and emergency networks are another area in which CRN can be implemented. In the case of natural disasters, which may temporarily disable or destroy existing communication infrastructure, emergency personnel working in the disaster areas need to establish emergency networks. As emergency networks deal with the critical information, reliable communication should be guaranteed.[16] Also, emergency communication requires a significant amount of radio spectrum for handling huge volume of traffic including voice, video and data. CRN can enable the usage of the existing spectrum without the need for an infrastructure and by
maintaining communication priority and response time.

4) Cellular network

Rural areas with low population density are known to have poor cellular coverage. It is because of the fact that the installation cost for infrastructure cannot be recovered back due insufficient number of subscribers. If white space spectrum such as TVWS is being made available for unlicensed use, cellular operators can use them for backhaul, to connect their cell towers to their backbone networks. Thus reducing labor intensive backhaul cables installation and thereby providing coverage to more customers in underserved areas. Another access network application is in femtocell networks. Usually, femtocell consumers buy a mini-cell tower from their cellular operator and install them in their homes since they are getting bad coverage in certain parts of the home. Major issue with these femtocells is, since these operate in same frequency of cellular network, QoS is sacrificed due to interference. In addition, coverage of these cells is limited.[8] When TVWS is used for femtocells, above mentioned issues can be avoided to a greater extend since there is no interference between femtocell and main cell.

DYNAMIC SPECTRUM SHARING

Spectrum Sharing Techniques

xG networks provide high bandwidth to mobile users via heterogeneous wireless architectures and dynamic spectrum access techniques. Spectrum sharing in a CRN can be classified based on three different aspects.

1) *Centralized and distributed* :

According to the network architecture spectrum sharing is classified into centralized and distributed sharing. In centralized method, there will be a central entity usually called spectrum broker to control the spectrum allocation and access procedures [11][28]. A distributed sensing approach is suggested such that each SU forward their sensing measurements to the spectrum broker. It is the spectrum broker which constructs spectrum allocation map and coordinate allocation among the SUs. In distributed approach, each user is responsible for the spectrum allocation and access is based on its own local policies. Such a sharing technique is adopted in cases where an infrastructure is not preferable [12][13].

2) *Cooperative and Non Cooperative*:

This classification is based on the access behavior. In cooperative spectrum sharing, each node is aware of the existence of neighboring nodes. They exchange their interference information with each other. This allows a reduced interference transmission in the network which results in the improvement of sum utility of the network. On the other hand, users in non-cooperative sharing mode is selfish and don't bother the existence of other nodes [14]. Non-Cooperative solutions may result in reduced spectrum utilization.

3) *Overlay and Underlay*:

This classification is based on access technology. Overlay Cognitive Radios identifies the white spaces and opportunistically use the radio spectrum in the absence of PU. Spectrum sensing technique relies mainly on PU detection. Any type of modulation can be used in this type of sharing. One of the major limitations is that interference will be created to PU when SU takes to vacate the hole.In underlay CR, SU co-exist with PU in the same spectrum so that continuous transmission is possible for SU. The transmission power of SUs is so adjusted to avoid interference to PU. PU uses spread spectrum communication and thereby considers SU transmission as noise. SU transmits using Ultra wideband modulation in order to get high data rate with low transmission power. Since UWB modulation is used, only short range communication is possible.[15] The difference in the two techniques can be easily depicted from figure.

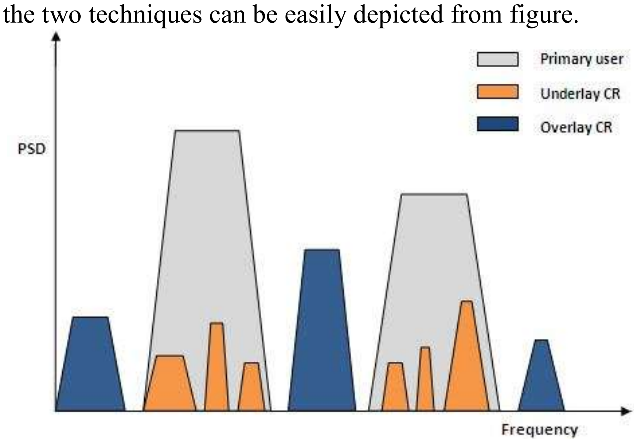

Fig. 12. Overlay and Underlay Spectrum Sharing

Spectrum Allocation Problem

SA is responsible for assigning the most appropriate frequency band at the interface of a cognitive radio device according to some criteria (i.e., maximize throughput, spectral efficiency, etc.), while, at the same time, avoid causing interference to primary networks operating in the same geographical area. The SA function for each SU should determine not only the central frequency, but also the spectrum bandwidth to be used by that SU. Moreover, the available frequencies and spectrum holes dynamically change with time and location. SA problem lies under NP-complete based on its complexity.

The procedure for solving SA problem in CRN is through following three steps [18]:

- The criteria which define the target objective is selected. E.g.: criteria like maximize throughput, maximize datarate, minimize the interference, spectral efficiency, energy efficiency, etc.
- The selection of an appropriate technique to model the SA problem that best fit to the target objective. E.g.: approaches such as Heuristic method, Linear problem programming, Graph theory, Game theory etc
- Final step is to select a procedure or algorithm that will simplify and help solving SA problem to achieve the target objective.

Methods for solving SA problem

In this section a few of the existing methods that are used for solving SA problem will be discussed.

1) Linear Programming

The Coordinated spectrum access problem in a multi-user single-transceiver CR network is formulated as a mixed integer non linear programming problem (MNLP).The problem in MLNP can be converted to binary linear programming (BLP). Due to its integrality in nature it can be solved using linear programming in the programming time [19].

2) Heuristics

One of the simplest techniques that are used for solving the spectrum allocation is the heuristic approach. In cases where exhaustive search is impractical, Heuristic methods can be adopted as a good candidate to find out a quick solution. They permit the use of models that are more representative of the real-world problems. In [20] channel assignment is done based on Heuristic model in which node cooperation is incorporated to improve spectrum sensing performance.

3) Fuzzy Logics

A Fuzzy Logic System (FLS) is unique in that it is able to simultaneously handle numerical data and linguistic knowledge. Fuzzy can be used in cases where a specific conclusion is needed based on vague, ambiguous, imprecise input information. In [21] a novel approach using FLS is proposed which is used to control the spectrum assignment and access procedures in order to prevent multiple users from colliding in overlapping spectrum portions. One of the demerits using Fuzzy logic method is that it is really hard to determine accurate rules when many numbers of parameters are taken into account.

4) Graph Theory

In [22] Network conflict graph coloring technique is used as the technology to solve spectrum allocation problem. Network graphs have been extensively used in cognitive spectrum assignment, mostly for cases where the structure of the network is considered known a priori. Allocation problem is solved by mapping the cognitive network to a graph. The main drawback of graph modeling is that it is difficult to incorporate all parameters of CRN such as QoS requirements, ACI etc simultaneously.

5) Game Theory

Game theory is found to be the most suitable mathematical tool to deal with conflicts among the users. It tries to find an optimal solution which maximizes every ones need without harming one another. Although first applied in economics, it has been applied in many fields of study and recently used to study coexistence and self-coexistence in cognitive radio networks.

GAME THEORY

A Game is a model of interactive decision process. The fundamental component of game theory is the notion of a game. A game in basic form composed of three elements; No. of players, Action strategy, Utility function. Mathematically, games can be written as,

$$G = \{N, S_1, S_{2,\ldots,} S_{N,} u_1, u_2, \ldots . u_N\} \quad (1)$$

The expression (1) indicates that there are N game players. $\{S_1, S_{2,\ldots,} S_{N,}\}$ is the strategy space or strategy set of all participants. For any one of the game participants i, S_i is its strategy space (e.g.: - set of transmit powers, frequency bands etc) and u_i indicates the utility function (e.g.:- maximize spectrum utilization, maximize datarate etc.) of the game participant i.

A player is assumed to be able to evaluate exactly or probabilistically the outcome or payoff (usually measured by the utility) of the game which depends not only on his action but also on other players' actions[23].

The objective is to maximize each player's utility function, by taking into account the impact of its decisions on the other players. Steady state solution of the game is termed as Nash Equilibrium. NE point defines the strategy for each player such that each player is receiving optimal payoff in the context of other player's choices.

A. Types of Games

1) *Cooperative games and Non cooperative games*

Based on the cooperation among users, games can be classified into cooperative and non cooperative. In cooperative game, there is binding agreement among users. Every user has an idea about other ones action space and its corresponding utilities. There is a common control channel to exchange this information. Therefore users cooperate in taking decisions in such a way to obtain a Nash Equilibrium which is favorable for everyone [26][28]. On the other hand, in Non cooperative games, users behave in a selfish manner. Each one bothers about his own benefit only. Therefore such games need a faster convergence algorithm to reach Nash equilibrium [9][30].

2) *Static games and Dynamic games*

Based on the time of decision taken, games can be classified into Static and dynamic. In static games players make their moves in isolation without knowing what other players have made. But this doesn't necessarily mean that all decisions are made at the same time, but rather only as if the decisions were made at the same time. In dynamic game, there is a sequence to the order of play [23].The amount of information available to players may vary with time. Therefore, players may observe another ones move and take decisions accordingly as the game progresses.

3) *Strategic game and Extensive game*

Strategic games are also called as normal games. In this type of game, players make their decisions simultaneously at the beginning of the game. Normal games are always represented using three elements; No. of players, action space and utility function. In extensive games, players make decisions by reacting to other players' actions as the game progresses[18]. Here a game is played several times and players can observe the outcome of the previous game before attending the next repetition. Extensive games are represented as a game tree consisting of four elements viz. nodes, branches, vectors and information set. Therefore, games in extensive form gives additional information necessary to describe a game such as timing of the decisions to be made and the amount of information available to each player when each decision has to be made.

B. Application of Games in DSA

In Dynamic spectrum sharing, PU allows spectrum leasing in exchange for different types of compensation such as money or resource. In the money –compensation spectrum sharing model, PU collects revenue in return to the spectrum leased. The strategy of money-compensation spectrum sharing is commonly effective, when PUs have some temporarily idle resources.

Most of the related works focuses on non-cooperative nature of the users. Here, the competing users are selfish and dynamic in nature. Every user takes their decisions/actions simultaneously without notifying each other. Such situations can be modeled using non-cooperative Stackelberg game, auction theory [9][23].The utility is the sum of capacity required and revenue collected/payment given. In the competition for idle, PU selects only a few number of SUs with whom it gets the maximum benefit. These users are entitled to access the idle spectrum in the order of hours, days or even months by paying appropriate money to the PU.

The money-compensation model requires a trustworthy billing system by which both the PUs and the SUs can trade the spectrum based on their real individual needs, which is difficult to design in practice. In such cases the resource compensation model is a better choice, in which the PUs can obtain performance amelioration aided by SUs in exchange of spectrum bands. In [25] a cooperative spectrum sharing method is discussed where SU would like to relay PU's traffic for rewards of transmission opportunities. A matching game is used to model the PU-SU interaction, where both PUs and SUs are competing for their own benefits. Matching theory is used in situations to describe the mutually beneficial relationships between two disjoint sets, such as PUs and SUs.

Cooperative Bargaining game can be used for Interference-aware resource allocation scheme in cognitive small cell networks. Utility of the cognitive small cell is maximized while protecting primary microcells' QoS [26].

Stackelberg game can be used for modeling multiuser cooperative communication. Stackelberg game is a leader follower strategy game in which leader chooses his decision firstly and then followers adjust their actions according to the leader decision. In a distributive cooperative communication the source is modeled as a buyer and the relay nodes as "sellers"[27]. Game proceeds in such a way that the source finds relays at relatively better locations and "buys" an optimal amount of power from the relays, but also helps the competing relays maximize their own utilities by asking the optimal prices. Thus a Buyer-Seller strategy is played under Stackelberg game where buyer or source node acts as leader and relays or sellers as followers.

In a distributed sensing environment where multiple SUs exchange their sensing results with each other, there needs a dedicated common control channel. A common control channel may have a limited coverage area due to spectrum heterogeneity. The task is to assign as few as possible frequency channels as common control channels in the secondary user network. Each secondary user prefers the frequency channels with no or minimum primary user activity perceived by itself. The problem can be easily modeled using non-cooperative game named potential game. A potential function is designed such that utilities of all the SUs can be mapped. Nash equilibrium point is found out using the best response dynamics to sequential and asynchronous strategy updates [30].

CONCLUSION

Cognitive radio is a promising technology for future wireless network to alleviate scarcity and underutilization of the spectrum. CR users have the ability to detect spatial and temporal spectrum holes so that it can be used for communication. An overview of cognitive radio technology, different functions performed by them and its applications are given. Dynamic Spectrum Sharing is found to be a key mechanism that ensures efficient operation of both cognitive and primary networks. Its main idea is to assign spectrum bands to secondary users in order to avoid interfering with licensed users and maximize their performance. Some of the existing methods to solve Spectrum Allocation problem have also been briefed.

Game theory, which was adopted from Economics, has been evolved as an efficient mathematical tool to tackle conflicts among cognitive users. We have provided the basic concepts of Game theory and different types of games. Finally, discussed some of the works in literature where game theory concepts have been used for dynamic allocation of the spectrum.

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