Game Theory for Cognitive Radio

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Chapter 7
Game Theory for Cognitive Radio

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ABSTRACT

Demands on high data rate applications are increasing and consequently demands on spectral resources are increasing as well. Although electromagnetic spectrum is recently said to be in a scarcity situation, several studies have shown that this scarcity is mainly due to the legacy command-and-control regulation rather than due to physical scarcity of spectrum. For this reason, researchers have started investigating techniques to better manage the usage of spectrum. Among these techniques there exist the methods allowing the primary/secondary usage of spectrum, or secondary market. Secondary market techniques mainly manage sensing, accessing, and aborting the spectrum usage by the secondary users. Techniques developed for secondary market context are also referred to as algorithms for Cognitive Radio (CR) networks. Regulators worldwide took measures to promote the deployment of primary/secondary context. In this chapter, the authors give an illustrative discussion on CR and on the application of game theory to overcome the spectrum scarcity problem. Game theory is a field of applied mathematics that describes and analyzes scenarios with interactive decisions. In recent years, there has been considerable interest in adopting game theoretic approaches to model many communications and networking problems such as radio resource management and routing. Nowadays, game theory is also used to model interactive situations for CR terminals.

7.1 INTRODUCTION

We start the chapter by giving a brief about the efforts carried out by regulators to introduce the primary/secondary context. We give an overview on game theory and we discuss the motivations for game theory usage in CR networks modeling. We illustrate the concept of "Nash equilibrium" and we discuss both the convergence and the efficiency of the equilibrium. We also present for the reader examples from the literature on game theory application in cognitive radio networks.

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Several studies, initiated recently by the US regulator Federal Communications Commission (FCC), have shown that the frequency spectrum is underutilized and inefficiently exploited: some bands are highly crowded, at some day hours or in dense urban areas, while others remain poorly used. Regulators worldwide are beginning to recognize that the traditional way of managing the electromagnetic spectrum, called Fixed Spectrum Access (FSA), in which the licensing method of assigning fixed portions of spectrum, for very long periods, is inefficient (Liu, 2011).

Among the efforts taken, by regulators worldwide, in order to achieve better usage of spectrum is the introduction (promotion) of secondary markets. In a secondary usage context, the spectrum owned by the license owner (also called primary user) can be shared by a non-licensee referred to as a secondary user. As an example of these efforts, FCC in USA proposes two models of spectrum leasing to promote the secondary markets. In the proposed models the constraints on the *license owner* and on the *duration of the license* are relaxed[1]. The two models are named De-facto transfer and spectrum manager. In the former model the lessee is responsible of reporting back to FCC the rules compliance with the original license terms. In the latter model, the primary owner is responsible of reporting to FCC.

Regulators in Europe have also taken measures to overcome the spectrum scarcity problem. In France, a secondary market has been recently allowed in the band 3.4–3.6 GHz, where two licenses have been awarded to deploy WiMAX based Wireless Local Loop (WLL) services. It is possible for the license owner to resell the whole license or a part of it. Reselling a part of the license may concern the geographical area, the frequency band, or the license duration. It is also possible for the license owner to keep the license while authorizing another entity to use the frequencies. In this case the primary user is responsible to fulfill the license obligations (Coupechux, Godlewski & Kumar, 2007). The British regulator, Ofcom, proposes a similar framework named spectrum trading. The main difference from the French framework is that the spectrum trading can be applied to several bands, such as cellular, Private Mobile Radio (PMR), or WLL, as given in (OFCOM, 2002).

Besides the promotion for secondary markets, we are currently experiencing rapid evolutions of Software Defined Radio (SDR) techniques. Such techniques allow reconfigurable wireless transceivers to change their transmission/reception parameters, such as the operating frequency that can be modified over a very wide band, according to the network or users' demands. The efforts taken by regulators in order to make better usage of spectrum, in particular the promotion for secondary market, together with the rapid evolution of the SDR techniques, have led to the development of opportunistic Cognitive Radio (CR) systems.

The term Cognitive Radio (CR) was first introduced by Mitola in 1999, and it was defined as: "*The point in which wireless personal digital assistants (PDAs) and the related networks are sufficiently computationally intelligent about radio resources and related computer-to-computer communications to detect user communications needs as a function of use context and to provide radio resources and wireless services most appropriate to those needs.*" (Mitola & Maguire, 1999). CR generally refers to a radio device that has the ability to sense its Radio Frequency (RF) environment and modify its spectrum usage based on what it detects (Sherman et. al., 2008).

7.1.1 Game Theory

Game theory is a decision-making mathematical tool that studies and analyzes interactions among decision makers, whether in conflict-of-interests, or in cooperation situations. It is a tool that provides outcome expectations in complex interactive situations. Game theory was first introduced by John Von Neumann and Morgenstern in 1944 upon publishing "*The Theory of Games and Economic*

Behaviour," however modern game theory has started with the papers of John Nash and with the definition of *equilibrium* in 1950. The theory was extensively and exclusively applied to economics before being applied to other fields such as politics, sociology and also biology where competition between species is modeled.

Game theory has demonstrated its ability to model situations in which participants interact and affect each others' outcomes. In contrast to the optimization perspective; the optimization process is about optimizing an objective function, as seen by one of the participants, independently without considering the reactions of the other users. Nevertheless, interactions among the participants have their influence on the outcome of each of them, and after all other participants made their actions (Srivastava et. al., 2005). Mainly due to this property, game theory was found to be appealing when it comes to networks and telecommunications. It has been applied to resource management, for example to admission control, power control, rate adaptation, congestion control. It has also been applied to routing and load balancing problems.

The fundamental unit in game theory is the definition of the interactive situation, referred to as a *game*. A game is defined by three sets of parameters, i.e. set of finite decision makers or *players*, set of actions or *strategies* available for each player and the final set is the expected outcome, said *payoff*, obtained by each player upon taking a certain decision (action). The payoff obtained by a player does not only depend on the action performed by the player herself, but also depends on the actions performed by the other players (usually considered as opponents) in the game. The payoff is defined using an objective function, or *utility function,* that represents the performance metrics, such as throughput, delay, or capacity, by modeling and taking into account the environment of the game. The decision maker (or the player) is not necessary an individual. The player could be a group of individuals who are having a common interest and are making decision together. As an example, we can imagine a file-sharing situation between a pair of nodes who are competing for resources in a large network. In this case the player can be considered to be the pair of nodes, not an individual node.

Games are divided into two main categories, i.e. cooperative and non-cooperative games. *Cooperative* games require a sort of coordination among the participants. In telecommunications filed, this coordination is translated into signaling protocols. Such protocols add complexity when it comes to the implementation. *Non-Cooperative* games make the most used category of game theory. Non-cooperative games model the conflict of interests among the players who are considered to be rational and selfish in the sense that each of them is mainly interested in maximizing her payoff.

7.1.2 Motivation for Cognitive Radio Modeling using Game Theory

CR networks have characteristics that made them particular and made their studies challenging;

- The distributed and dynamic nature of CR nodes
- The nodes' behavior; cooperative, non-cooperative, selfish or rational.

We briefly discuss below these characteristics. In a centralized network approach a central entity manages the network by setting the appropriate parameters of operation to all nodes of the network, with the target of optimizing the network performance, such as capacity, throughput, or delay. In a centralized architecture, the optimization process usually has a global point of view for the social benefit, where the interaction among the different nodes is hardly modeled. On the other hand, in a distributed approach the central entity does not exist and the nodes take their own decision independently. A global optimization is hard to obtain, where each node acts selfishly trying to maximize its own benefits.

CR networks are characterized by their distributed architecture and by the dynamicity of the CR nodes that are capable of taking decisions as well as adapting the operating parameters, such as power level or frequency of transmission, according to the surrounding environment (e.g., perceived interference level, capacity requirement at a certain instant, etc.). This situation involves high level of interaction among the nodes. Talking for example about the dynamic spectrum sharing issue; with the introduction of secondary markets, primary/secondary access context is usually referred to as CR networks. In these networks the secondary users whether perform an opportunistic access to the spectrum or negotiate the access to the spectrum. For both cases game theory provides appropriate analysis tool to tackle the dynamic spectrum sharing issue whether from a negotiation or from an opportunistic approach.

Game theory suits to the most the modeling and studying of the interactions (cooperation or conflict) among cognitive radio terminals, in particular the *non-cooperative* games category, where efficient distributed algorithms can be driven using local information. One of the advantages of game theory is that it can be used to provide incentives for players to cooperate and behave in a constructive manner.

In most of the studies dealing with CR networks, that made use of the game theoretical framework, the CR networks are modeled as games where radio terminals are considered to be the players, while the strategies of the players has varied to take several forms; for example in references (Etkin, Parekh & Tse, 2007) and (Giupponi & Ibars, 2009) the power level of the radio terminals is considered to be the players' strategies. In other studies, the choice of the spectrum band (channel) accessed by each terminal (Nie & Comaniciu, 2005), is considered to be the players' strategies. Though independently of the choice of the strategies' the utility function should represent the metric of interest to the players while taking into consideration the parameters affecting the payoff (interest) of the nodes, e.g., frequency, power, etc.

7.2 NASH EQUILIBRIUM: CONVERGENCE AND EFFICIENCY

7.2.1 Introduction

Formally a game G can be defined as, $G = (P, S, U)$, where P is the set of players, S is the strategy (action) set for each player, and U is the payoff (utility) obtained by each player given the strategy S. Rationally, each player i chooses a strategy $s_i \in S$ in order to maximize her utility u_i. Let $u_i(s_i, s_{-i})$ be the utility of player i given her strategy s_i, and the strategy s_{-i} of the opponent players. The strategy profile $s*$ is a strict Nash Equilibrium (NE) strategy if, for each player i,

$$u_i(s_i^*, s_{-i}^*) > u_i(s_i, s_{-i}^*), \forall s_i \in S_i, s_i \neq s_{-i}^* \qquad (1)$$

In other words, the equilibrium point is the steady-state where none of the selfish players has an incentive to unilaterally deviate from her strategy. In case each player plays his *best-response* strategy against the opponent player. The best-response function $br_i(s_i)$ of player i to the opponents' strategies s_{-i} is denoted by,

$$br_i(s_i) = \max u_i(s_i, s_{-i}), \forall s_i \in S_i \qquad (2)$$

In other words, it is the strategy s_i played by player i that maximizes her own payoff u_i knowing that the opponents play the strategy s_{-i}. We present below the most well-known game, the Prisoners Dilemma (PD).

The PD game tells the story of two arrested persons for a crime. Police put them in separated rooms for investigation. Each of them has two options, whether to "confess" the crime or to

Table 1. Outcomes of the PD game

		Prisoner 1 (P1)	
		Confess (C)	Remain Silent (RS)
Prisoner 2 (P2)	Confess (C)	P1: 3 and P2: 3	P1: 5 and P2: 1
	Remain Silent (RS)	P1: 1 and P2: 5	P1: 2 and P2: 2

Table 2. Normal form of the battle of the sexes (BoS) game

		Boy	
		Theatre (T)	Football game (F)
Girl	Theatre (T)	(10,8)	(0,0)
	Football game (F)	(0,0)	(8,10)

"remain silent." We use in this section the abbreviations (C) for "confess" and (RS) for "remain silent." Police authorities offer them a deal; if one prisoner confesses, while the other remains silent, the cooperating (with the authorities) person will be awarded by serving only one year of prison, while the other person will be sentenced five years of prison. If they both confess, each one will be sentenced 3 years in jail (instead of five). Nevertheless, the prisoners know that if they both remain silent, the police will not be able to prove charges against them, and hence each of them will be sentenced two years in jail. What should be the choices of the prisoners? Obviously, the PD game has four outputs. Table 1 summarizes the outputs (payoffs) of the game, represented by the number of years the prisoners will be served in jail according to their strategies. The way of representing a game in the form of a matrix, such as the case of Table 1, is called *normal form*. The *extensive form* is a second method of representing games, however, in a more graphical appearance.

According to the payoffs in Table 1, the strategy (C, C), where both the prisoners confess the crime to the authorities, is the unique stable strategy. That is because while adopting (C, C) strategy none of the players has the intensive to unilaterally change her strategy in order to obtain better payoff. As an example, considering the strategy (RS, RS), each player has the possibility to obtain better payoff if she changes her strategy from "remain silent" to "confess," while the other player remains silent. This change will allow the prisoner to serve one year in jail instead of two years. It is to be noted that the strategy (C, C) is Nash equilibrium (NE) for the PD game. As we can see from Table 1, the NE strategy is not the best choice for the prisoners. If both prisoners choose "remain silent" they are better off, on the other hand the (RS, RS) strategy is not stable. We highlight here that the strategy (RS, RS) is a Pareto Optimal (PO) for the PD game. We illustrate later in this chapter the definition of Pareto optimality.

Another well-known game is the Battle of the Sexes (BoS). In this game a couple decide to meet, but they are not sure about where to spend the evening. The girl prefers to go to the theatre while the boy prefers to go to the football game. Nevertheless, they both prefer to spend the evening together rather than spending it separately. Table 2 gives the payoff matrix of the BoS game.

We see from Table 2 that two strategies (T, F) and (F, T) are not interesting for the couple. We can also see that the other two options (T, T) and (F, F) are NE. It is to be noted that the BoS game is categorized among a type of games said to be *coordination games*.

The strategies (T, T), and (F, F) of the BoS game, and the strategy (C, C) of the PD game are called *pure* NE strategies. Pure NE is a deterministic NE where the players are choosing to play their strategies with probability 1. On the contrary, in *mixed* strategies, players choose to play a certain strategy (let's say strategy C in the PD game) with a certain probability (say probability q), while playing the other strategies (RS in the PD game) with different probability ($1 - q$). The mixed strategies are characterized by a set of probabilities assigned to the pure strategies. All coordination games have mixed strategies NE.

Before using game theory as a tool to model and analyze CR networks (or model any other interactive situation), the reader needs to pay attention to the following inquiries:

- Does the game have a NE?
- Is the NE unique?
- Is the NE efficient?
- How long the players need to converge to NE?

Nash equilibrium concept is usually associated with convergence as well as efficiency notations. In this section we illustrate both notations, while giving examples from the literature.

7.2.2 Convergence

Few types of games are known to have Nash equilibrium such as supermodular games and potential games. A game is said to be a supermodular game if its utility function satisfies the following condition:

$$\frac{\partial^2 u_i(s)}{\partial^2 s_i \partial^2 s_j} \geq 0 \forall j \neq i \in P \quad (3)$$

Supermodular games with players deploying best-response algorithm do converge to pure NE (Topkis, 1998). This framework has been used to analyze power control issue in wireless networks (Saraydar, Mandayam & Goodman, 2002). The authors in (Saraydar, Mandayam & Goodman, 2002) have modelled the power control problem through the formulation of a non-cooperative game where the wireless terminals are the players. Each player (wireless terminal) aims at maximizing its utility. The utility function takes into account both the power level of the terminal and the perceived Signal to Interference Ratio (SIR) level. This way the payoff obtained by each terminal does not only depend on its chosen power level but also depends on the power level chosen by the other players. The players adopt *best-response* strategies such that the power level chosen by each player forms a best response to the power levels chosen by the opponent players.

A game is said to be an Exact Potential Game (EPG) if there exists a function F such that

$$u_i(s_i, s_{-i}) - u_i(s_i^{'}, s_{-i}) = F(s_i, s_{-i}) - F(s_i^{'}, s_{-i}), \forall s_i, s_i^{'} \in S_i. \quad (4)$$

Giupponi and Ibars have formulated the channel and power allocation problem for secondary users into Bayesian potential game (Giupponi & Ibars, 2009). The adopted strategy of the secondary users, according to (Giupponi & Ibars, 2009), relies in the selection of both the frequency channel and the transmission power level in order to maximize their throughput, while not causing interference for the primary users. As the EPGs are shown to converge to pure Nash when best-response algorithm is deployed, the authors have demonstrated that the formulated Bayesian potential game converges to pure Bayesian equilibrium.

An important issue for the implementation of game-theoretical algorithms in CR terminals is the convergence to NE. The choice of the utility function has its major impact on the convergence issue. While the utility function should give an appropriate physical representation of the players' payoff, it also needs to have the mathematical properties that ensure convergence to NE.

In case the game has more than one NE point (NE is not unique), none of the equilibrium points dominate the others, and if the players are deploying best-response method, the game will not converge to a stable point, making the players' actions oscillate. As an example, we refer to the reference (Kamal, Coupechoux & Godlewski, 2009) where a non-zero sum game is formulated to tackle the Dynamic Spectrum Access (DSA) problem in cellular networks. In (Kamal, Coupechoux & Godlewski, 2009), cellular operators are considered to share a common pool of spectral resources in a specific region. The common pool is divided into spectrum blocks of equal size, and each cellular operator operates one radio network, e.g. one 2G network or one 3G network. The operators do not own the spectrum but rather share the common pool. The operators access the pool in a direct and simultaneous manner, according to the load variations of their radio networks. In the game formulation the operators are the players, and the strategy of each player is the number of spectrum blocks it accesses from the pool. It is shown in (Kamal, Coupechoux & Godlewski, 2009) that for specific arrival rate values (loads) the formulated game has more than one pure NE point where none of them dominates the others. Simulations show that in 62% of the cases the operators converge to NE (they oscillate in 38% of the cases), depending on the initial strategy of both players. The authors in (Kamal, Coupechoux & Godlewski, 2009) consider that the players while playing best-response strategies, and at each play instant, they consider to maximize their reward for the next play, only for the next play, without considering future rewards. The reader needs to note that in order to take into consideration the future rewards, *repeated game* model is to be used.

A *repeated game* (or a multi-stage repeated game) is a game in which the players have the possibility of playing several rounds (or trials). It is the repetition of a game. Each of the trails can be represented by the normal form or a matrix as given in Section 2.1. Repeated-game analysis is not the focus of this chapter; the reader interested in more details can consult the references (Richard & Anantharam, 2002) and (Hongyan, Yang & Dexian, 2010).

Figure 1 gives the simultaneous plays of the operators as given in (Kamal, Coupechoux & Godlewski, 2009) for a game with two NE points. The figure shows two different cases where the players have different initial strategies for each case. In one of the cases (on the left side of Figure 1) the operators converge to one of the NE points, illustrated by the number of spectrum blocks accessed by each player. Though in the other case, they do not converge but they oscillate between a mixes of the two NE strategies.

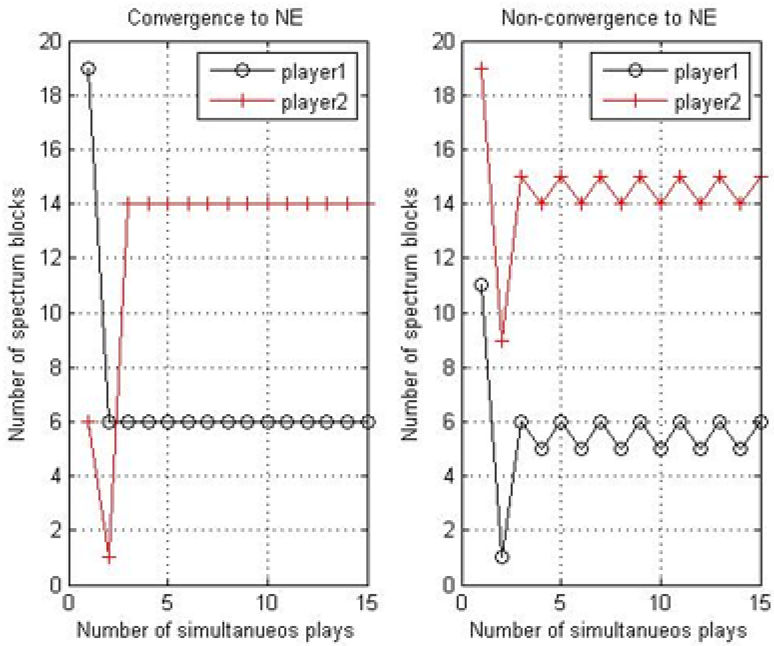
Smoothed best-response technique with mixed strategies can be used to ensure convergence to NE. A smoothed best response will avoid the sudden alternate between pure strategies and ease the convergence to NE. Mixed strategies are characterized by a set of probabilities assigned to the pure strategies.

7.2.3 Efficiency

The existence of Nash equilibrium (or the steady state of a game) does not guarantee its efficiency. We have seen this issue clearly in the PD game. The NE points are not always efficient compared to Pareto optimal points (Ji & Liu, 2007). Traditionally, Pareto concept is used to evaluate the efficiency of Nash equilibrium usually using the Price of Anarchy (PoA) notation. The PoA is the ratio of payoff obtained at the NE point compared to the payoff obtained at the PO point. A strategy is Pareto-optimal when no Pareto improvements can be made. The strategy s'' is Pareto-superior to the strategy profile s if, for at least one player i,

$$u_i(s_i'', s_{-i}'') > u_i(s_i, s_{-i}), \forall s_i \in S_i, \quad (5)$$

Figure 1. Number of simultaneous plays performed by the players



without making another player worse off (Felegyhazi & Hubaux, 2007).

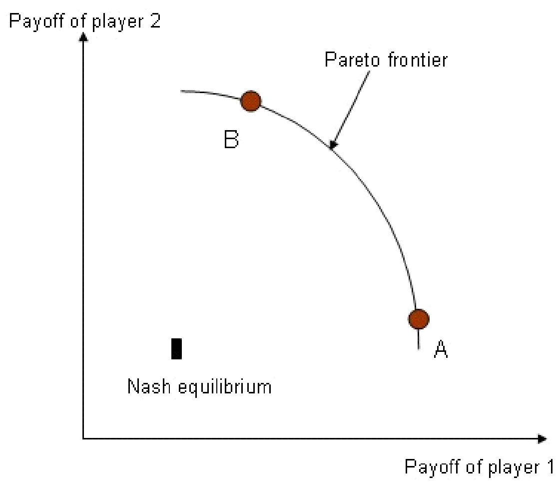
It is likely to have more than one PO point for the same game. In this case, all Pareto optimal points form the Pareto frontier. A Pareto frontier is the set of points that are Pareto efficient. Figure 2 illustrates the idea of Pareto frontier in a game where NE is not efficient. We can see that all points on the Pareto frontier curve have higher payoffs (for both players) than the payoff obtained at NE.

Although points A and B are Pareto efficient, however we can notice that for point A player 1 is better off than player 2. The opposite is correct for point B. In this case a selection criterion (or fairness criterion) is needed in order to choose a unique PO point. As an example, the authors in (Kamal, Coupechoux & Godlewski, 2009) have chosen to maximize the sum of operators' utilities (social welfare maximization) in case the game solution gives more than one PO point. In reference (Kamal, Coupechoux & Godlewski, 2009), a game theoretical framework, based on the Pareto optimality concept, is proposed for the DSA problem among cellular operators.

7.3 EXAMPLES OF GAME THEORY APPLICATION IN COGNITIVE RADIO

Game theory is being used to formulate several problems related to cognitive radio networks. In this section we present to the reader few examples from the literature, trying from our side to provide clear illustration on how game theory can be used as a tool to tackle research challenges in CR networks. We start by illustrating the game formulated by the authors in (Etkin, Parekh & Tse, 2007). The authors made use of game theory to analyze the power allocation problem of peer- to-peer systems, such as Bluetooth or 802.11 networks, in unlicensed bands. The player is considered to be a system formed by a single transmitter-receiver pair. The objective is to determine the power allocations of each system in order to maximize a global utility function, while satisfying the power

Figure 2. Pareto frontier in a two-player game



constraints. Two forms are considered for the global utility function of the system, both related to the achieved bit rate. The first one represents the sum of the achieved players' bit rates, while the second utility function represents the sum of the *log* of the achieved rates. Applying the *log*(.) function to the bit rates promotes the system in disadvantage, as a sort of fairness criterion, according to (Kelly, Maulloo & Tan, 1998). In a first part of the study, the authors have implicitly assumed that the players cooperate to maximize the global utility function by choosing appropriate power allocations. A system model of two players has been studied in (Etkin, Parekh & Tse, 2007), see Figure 3. The antenna size in Figure 3 represents the transmission power while the distance between the antennas is directly related to the propagation conditions (the channel gains).

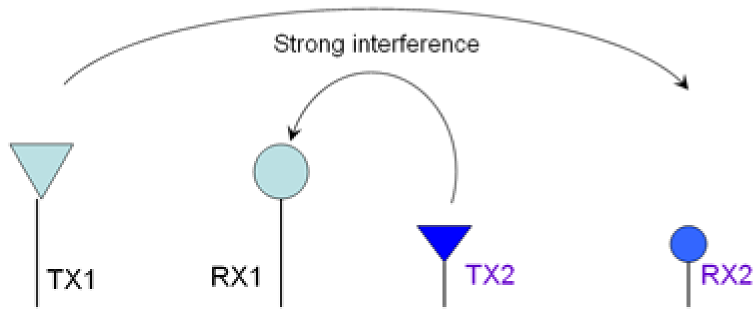
Etkin, Parekh and Tse have represented the bit rate R_i obtained by system i, in a spectrum sharing situation with system j, as a function of: (1) the used bandwidth W, (2) the noise variance N_0, (3) the transmission power level of both systems p_i and p_j, and (4) the cross channel gains $c_{i,j}$ and $c_{j,i}$. The authors studied a game scenario using the following set of parameters: $N_0 = 1$, $W = 1$, $c_{1,2} = 0.5$, $c_{2,1} = 10$ and the power constraints of both systems P_1 and P_2 have been set to *10* and *1* respectively. The authors presented a plot for the obtained Pareto frontier curve for this game (Figure 2 in Etkin, Parekh & Tse, 2007); this curve is similar to the one we plotted in Figure 2 of Section 2.3 where the payoff in this case is the bit rate of the two players. On the curve of the figure presented in (Etkin, Parekh & Tse, 2007), the authors make clear the two Pareto points corresponding to the different considered utility functions, i.e. simple summation of rates, and summation of the rates' logarithms (proportional fair).

In coherence to what we have mentioned in Section 2.3, in case the non-cooperative game results in several achievable rates, hence a selection (fairness) criterion is needed. The authors in (Etkin, Parekh & Tse, 2007) mention that "*the operating point is chosen by the protocol to achieve efficiency and fairness. We can think of this protocol as a widely known standard that the systems can choose to follow or as a set of spectrum sharing rules imposed by the regulation authority*."

The reader needs to keep in mind that in order to perform a cooperative frame, all the information is supposed to be known to all cooperative players. Since that in a spectrum sharing scenario transceivers are competing to gain access to the shared spectrum, assuming selfish behavior is more realistic. For this reason, Etkin, Parekh & Tse have also analyzed non-cooperative behavior of the players, i.e. selfish and rational, and their effect on the achievable rates. For more details about the non-cooperative model and the related issues of efficiency, fairness and compatibility, the reader is invited to consult the mentioned reference.

The second reference example we give in this section is presented by Nie and Comaniciu, where they have used game theory to analyze node-conflicts in CR networks. The transmitting-receiving pairs of nodes are considered to be the players of the game (Nie & Comaniciu, 2005). The objective of the players is to maximize their

Figure 3. Two CR systems sharing the same band in an asymmetric situation, i.e. asymmetric Tx power and asymmetric cross channel gains according to (Etkin, Parekh & Tse, 2007)



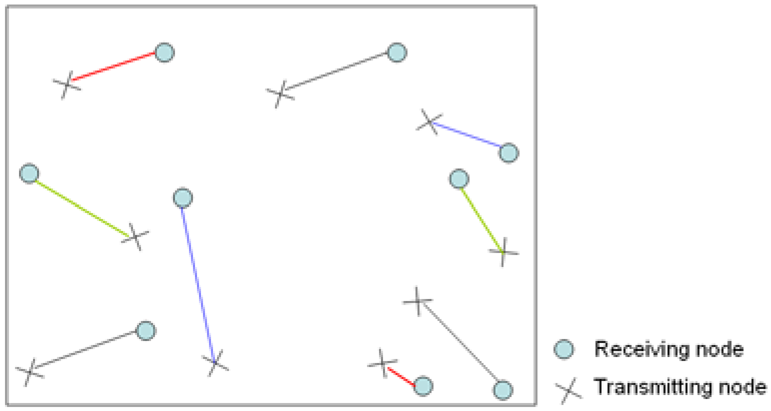
utility (payoff) by determining the appropriate operating channel (frequency) in a spectrum sharing context. In such a system where the number of node-pairs is larger than the number of available frequencies, a frequency reuse situation is inevitable. Figure 4 gives a simple example of a spectrum sharing system as adopted and illustrated by Nie and Comaniciu.

According to the example given in Figure 4, we can note a system that contains a number of $N = 9$ players (node-pairs) sharing a number of $K = 4$ frequencies. Each used frequency is represented by a different line-color in Figure 4. The strategy of the players is represented by the choice of the transmitting frequency. For a given modulation format and channel coding, a target Signal-to-Interference Ratio (SIR) can be determined for a certain application or Bit Error Rate (BER) requirement. The players' utility is directly related to the channel quality. The utility functions considered in (Nie & Comaniciu, 2005) take into consideration the level of interference generated from the frequency reuse performed by the nodes. The authors have proposed two utility functions in order to model different levels of cooperation. The first utility function models the "selfish" users while evaluating the chosen frequency channel based on the received interference level. The second utility function models the "cooperative" users while evaluating the interference seen by the users upon using a particular channel at the same time as considering the interference this particular channel causes on the neighboring nodes. The authors used the second utility function to formulate an exact potential game, which fundamentally converges to pure NE solutions when the players adopt best-response strategies (as we have mentioned in Section 2.2).

In (Nie & Comaniciu, 2005), the authors have simulated a system model with $N = 30$ players, randomly distributed over a 200*m* x 200*m* area, and sharing $K = 4$ frequency channels. The authors have provided plots for the selected pure NE frequency assignments by the nodes 1, 8, 16 and 24 (Figure 4 in the reference). The plots represents the strategies, or the chosen frequencies by the nodes, versus the number of plays (trials) performed by the nodes. According to the result's plots, the players hop among different frequency channels as they play, for a number of play-rounds, until they converge, i.e. their chosen frequency channels remain fixed and do not change versus the number of trails. The plots show that the players converge to pure NE solutions and that the convergence speed is very fast that equals to around 30 trials (or play-rounds).

For more examples on game theory applications, the reader can consult the reference (Wang & Wassell, 2002). A distributed channel allocation algorithm has been proposed by Wang and Wassell in (Wang & Wassell, 2002) for Broadband Fixed Wireless Access (BFWA) networks. The

Figure 4. A simple illustrative example of the studied system of nodes according to (Nie & Comaniciu, 2005)



proposed method is supposed to replace the regular frequency planning method. The algorithm is based on a mixed strategy game.

7.4 CONCLUSION

In this chapter, we have presented the different efforts carried out by regulators worldwide to overcome the spectrum scarcity situation: i.e. mainly promoting the introduction of primary/secondary spectrum usage. We gave an overview on game theory including the definition of a "game" and the presentation of two well known games, i.e. the Prisoner's Dilemma (PD) and the Battle of the Sexes (BoS) games. We discussed the motivations for game theory application in cognitive radio: The distributed and dynamic nature of CR nodes along with the nodes' behavior. We gave the definition of Nash Equilibrium (NE) concept and we discussed the associated notations: the convergence and the efficiency. Concerning the convergence, we presented the definition of games' types who are known to have Nash equilibrium; i.e. supermodular and Exact Potential Games (EPG). Regarding the efficiency we presented the definition of Pareto optimality. We finally gave examples from the literature on game theory application for cognitive radio networks. The examples are treating with spectrum sharing situations for CR networks. In one of the examples, the player's strategy is about choosing the appropriate power level. In the second presented example, the strategy of the players lies behind the choice of the frequency channel. The presented examples in this chapter give the reader an illustrative view on how game theory can be used to tackle research challenges in cognitive radio.

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ENDNOTE

[1] It is to be noted that in the licensing method actually deployed by the regulators and during the license period, the primary user (license owner) has no-right to resell the spectrum nor to change the type of service originally obtained the license for.