Evolutionary Theoretical Game for Cooperative Spectrum Sensing in Cognitive Radio Networks: A Survey

Mr Djamel TEGUIG
Royal Military Academy – CISS department
Dr Bart SCHEERS
Royal Military Academy – CISS department
Dr Vincent LE NIR
Royal Military Academy – CISS department
Belgium
djamel.teguig@rma.ac.be
bart.scheers@rma.ac.be
Vincent.lenir@rma.ac.be

ABSTRACT

Cooperative Spectrum Sensing (CSS) has shown to be a powerful solution to improve the sensing performance in cognitive radio (CR) networks. In this paper, we explore the CSS model based on the evolutionary theoretical game to address the interactions between CR users. This paper also provides a detailed overview and analysis on the state of the art of spectrum sensing based on evolutionary game. We first introduce the formulation of theoretical game in cooperative spectrum sensing. Then, the evolutionary theoretical game model for CSS is described and analyzed. The open research challenges related to evolutionary theoretical game in CSS are also discussed.

Keywords- *Cognitive Radio, Cooperative spectrum Sensing, Evolutionary game theory*

1. INTRODUCTION

Due to the rapid development of wireless communications services, the requirement of spectrum is growing dramatically. The federation Communications Commission (FCC) has stated that some allocated frequency bands are largely unoccupied (under-utilized) most of the time [1]. Cognitive Radio has emerged as a novel approach to enable dynamic spectrum access by allowing unlicensed users to access the under-utilized licensed spectra when/where licensed primary users (PU) are absent and to vacate the spectrum immediately once a PU becomes active without causing harmful interference [2] [3].
Spectrum sensing (SS) is the key technology to achieve such a dynamic spectrum access system. The high accuracy requirement of SS in CR is extremely challenging due to shadowing as well as multipath fading. Cooperative spectrum sensing has been proposed to alleviate these impacts by taking advantage of cooperation among CR users [4] [5]. Cooperative spectrum sensing has attracted a lot of attention in the research community. An extensive overview on CSS in CR networks can be found in [6] [7]. In [7], the author shows that the CSS process can be presented and analyzed by seven key elements: cooperation models, sensing techniques, control channel and reporting, data fusion, hypothesis testing, user selection, and knowledge base as depicted in figure 1. Our main focuses through these elements are the cooperation models. The models in cooperative sensing consider how CR users cooperate to perform spectrum sensing and achieve the optimal detection performance. The authors in [7] discuss two different approaches for modeling CSS in CR networks. The parallel fusion (PF) model is widely used in literature. The detection performance is achieved by using distributed signal processing techniques which determine how the observations are combined and tested and how the decisions are made. A large number of proposed schemes [8], [9], and [5] have adopted the PF model for CSS. The second approach is to use game

theoretical models which have been recently developed, focusing on improving the sensing-parametric utility function by analyzing the interactions and the cooperative or non-cooperative behaviors of CR users.

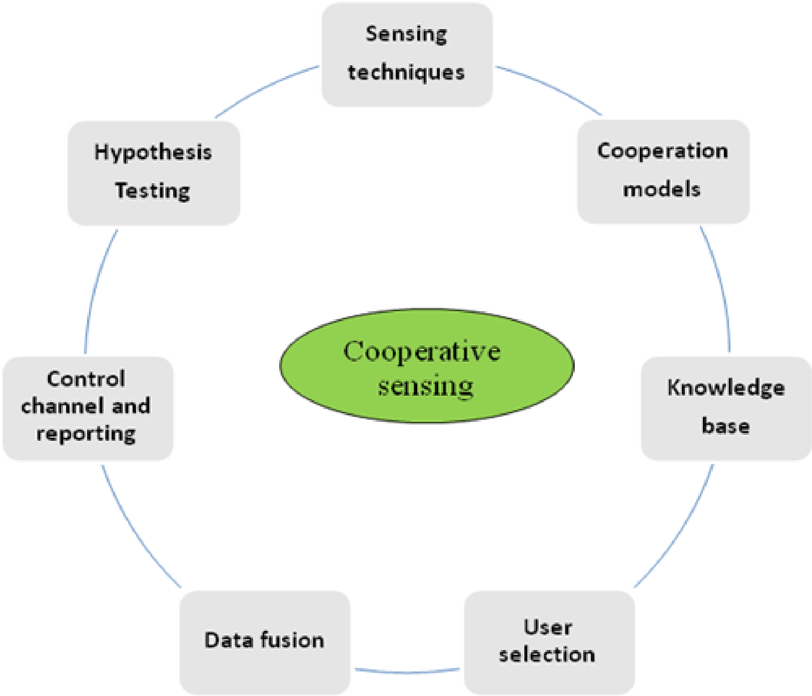

Figure 1 Elements of cooperative spectrum sensing

Game theory provides a mathematical tool to analyze strategic interactions among multiple decision makers (players). Game Theory, which has been applied at the beginning in economics and related domains, is gaining much interest today as a powerful tool to analyze and design communication networks [13]. It is particularly suited to the context of cognitive radio, where CR users could generate an overall messy behavior of the whole network without the appropriate analysis that can be brought by Game Theory (GT).

Basically, game theory can be classified into two families: non-cooperative [10] and cooperative game theory [11], [12]. Non-cooperative game theory studies strategies based on interactions among competing players. In this game, each player is selfish but rational and chooses its strategy independently to maximize its utility or reducing its costs. The most common solution used for non-cooperative game is the Nash equilibrium [10]. Unlike non-cooperative game theory that studies competitive scenarios; cooperative game theory considers the behavior of rational players when they have mutual benefit to cooperate.

In [14], an overview in game theory for cognitive radio is discussed. The tutorial survey in [14] provides a comprehensive treatment of game theory with important applications in CR networks. In [15] the authors summarize the recent developments and findings of game theory, its applications in wireless sensor networks (WSN) and survey the existing approaches to address WSN design problems.

In this paper, we provide a better understanding of the current research issues in cooperative spectrum sensing based on evolutionary theoretical game.

The rest of this paper is organized as follows. The basic concepts of game theory are presented in section 2 and the most significant applications of game theory in spectrum sensing are summarized. The evolutionary theoretical model for cooperative spectrum sensing is formulated and analyzed in section 3.

In addition, a discussion about research challenges in this area is provided in section 4. Finally, the paper is concluded in section 5.

2. Basics of Game Theory

In this section, the basic concepts and elements of game theory are discussed and explained.
A game is defined as a method of interaction between users (or players), where each user adjusts its strategy to optimize its own utility (benefit) while competing with the others. Generally, the major components in a game consist of a finite set of players N={1, 2, ..., n}, a set of strategies s_i for each player i and a set of corresponding utility functions u_i. Often, we denote a strategic game by $< N, \{s_i\}, \{u_i\}>$ [16].

Definition1. The utility function (payoff) assigns for a given player a value (describing preferences) for every possible outcome of the game. We denote by u_i the corresponding payoff function of player i.

Definition2. Nash equilibrium is a solution concept that indicates that no player can improve his payoff by changing only its own strategy unilaterally. In other terms, s^*_i is a Nash equilibrium of a strategic game $< N, (s_i), (u_i)>$ if for every player $i \in N$ we have

$$u_i(s^*_i, s^*_{-i}) \geq u_i(s_i, s^*_{-i}) \quad (1)$$

for all $s_i \in S_i$ where s_i denotes the strategy of player i and s_{-i} denotes the strategies of all players other than player i.

Definition3. Pure Strategy defines a specific move or action that a player will follow in every possible attainable situation in a game. Such moves may not be random, or drawn from a distribution, as in the case of mixed strategies.

Definition4. Mixed Strategy is when a player randomizes over some or all of his or her available pure strategies. That is, the player places a probability distribution over their alternative strategies. Mixed-strategy equilibrium is where at least one player plays a mixed strategy and no one has the incentive to deviate unilaterally from that position. Every matrix game has Nash equilibrium in mixed strategies.

2.1. Game Theory Models For Spectrum Sensing In Cognitive Radio

Game theory has many applications in Cognitive Radio. Most of the work on game theory for CRs has focused on interference management, frequency allocation, power allocation and spectrum sensing. The interactions between CR users in cooperative spectrum sensing can be modeled as a game theoretical model. The most significant game theoretical models which are appropriate for cooperative spectrum sensing in cognitive radio are summarized in table 1.

TABLE I. THE MOST SIGNIFICANT MODELS OF GAME THEORY IN CSS

Models of GT in CSS	References
• Coalition Game for CSS	[17] [18] [19] [20] [21] [22] [23]
• Evolutionary Game for CSS	[25] [27][28] [29][30] [31]

Models of GT in CSS	References
• Bargaining Game for CSS	[32] [33]
• Stackelberg Game for CSS	[34] [35]
• Others Game for CSS	[36] [37] [38] [39] [40] [41]

The design of CR network and optimization of its performance is a complicated process. GT thus offers a supportive tool in designing and operating a CR network. By the following, we will focus on the modeling of cooperative spectrum sensing by evolutionary game theoretical approach. Besides, several works on this topic are reviewed and analyzed.

3. Game Theoretical Model for Cooperative Spectrum Sensing

The Cooperative Spectrum Sensing Game is the Game

$$G=<N, \{s_i\}, \{u_i\}>$$

- N= {1, 2, …., n} is the set of the player (CR users).
- s_i is the strategy of the user i. Let s_i =1 denote CR user i decides to collaborate, and s_i=0 denote the opposite (as an example).
- u_i is the payoff (utility) of the CR users i, and is often defined as the throughput of the CR users.

3.1. *System model for cooperative spectrum sensing*

In a CR networks, N CR users perform spectrum sensing to find the idle spectrum periodically. We denote by $x_n(t)$ the received signal at each CR user, then, which can be written as:

$$\begin{aligned} H_0 &: x_n(t) = w_n(t) \\ H_1 &: x_n(t) = h_n s(t) + w_n(t) \end{aligned} , \qquad (2)$$

where h_k denotes the complex gain of the channel between the PU and the nth CR user; $s(t)$ is the signal of the PU, which is assumed to be an i.i.d random process with mean zero and variance σ_s^2; and $w_n(t)$ is an additive white Gaussian noise with mean zero and variance σ_w^2.

Assume t_s is the spectrum sensing time and f_s denotes the sampling frequency. The number of samples is K ($K= t_s f_s$). In this paper, we suppose that CR users use energy detection method to sense the spectrum state. Then the test statistics E_n for the n^{th} CR user is defined as

$$E_n = \frac{1}{K} \sum_{t=1}^{K} x_n^2(t) \ . \qquad (3)$$

Spectrum sensing performance is denoted by the probability of false alarm and the probability of detection which are defined as follows

$$P_{f,n} = \Pr(E_n > \lambda_n / H_0) \ . \qquad (4)$$

$$P_{d,n} = \Pr(E_n > \lambda_n / H_1) \ . \tag{5}$$

where λ_k is the corresponding test threshold. Assuming the same threshold for all CR users; according to the central limit theorem, E_n is asymptotically normally distributed if K is large enough. In this case, we can model the statistics of E_n as a Gaussian distribution with mean (σ_w^2) and variance ($\sigma_w^4/4$) under hypothesis H_0. Then, $P_{f,n}$ can be written as [24]

$$P_{f,n}(\lambda, K) = \frac{1}{2} erfc((\frac{\lambda}{\sigma_w^2} - 1)\sqrt{\frac{K}{2}}) \ . \tag{6}$$

Similarly, assume the primary signal is a complex PSK signal; E_n under H_1 can be approximated by a Gaussian distribution with mean ($\sigma_w^2(1+\gamma)$) and variance ($1/K\sigma_w^2(1+2\gamma)$), where $\gamma = |h|^2\sigma_s^2/\sigma_w^2$ denotes the received signal to noise ratio of the PU. Then, $P_{d,n}$ can be expressed as [24]

$$P_{d,n}(\lambda, K) = \frac{1}{2} erfc((\frac{\lambda}{\sigma_w^2} - \gamma - 1)\sqrt{\frac{K}{2(2\gamma+1)}}) \ . \tag{7}$$

Cooperative spectrum sensing aims to improve the credibility of sensing results. In the sensing process, CR users perform spectrum sensing individually, and send their sensing results to the fusion center (FC). The FC handles the received sensing results by data fusion rules, and publishes the final sensing results to the CR users about the presence or the absence of the PU. Data fusion rules include soft combining rules, hard combining rules, and quantized combining rule [42].

3.2. Throughput of CR users

The CR users' network might operate at the PU's licensed band if the sensing device decides that the channel is idle, this occurs in two cases:

1- When the PU is inactive and the channel is correctly declared idle, the probability of that state can be written as: $P(H_0|H_0)=P(H_0)(1-P_f)$ where $P(H_0)$ denotes the probability that the PU is absent.

2- When the PU is active and the channel is falsely declared idle, the probability of that state can be written as: $P(H_0|H_1)=P(H_1)(1-P_d)$ where $P(H_1)$ represents the probability that the PU is present.

The average throughput of the CR users can be expressed as [43]:

$$R = (1 - \frac{t_s}{T})\left[(1 - P_f)P(H_0)C_{H_0} + (1 - P_d)P(H_1)C_{H_1}\right] , \tag{8}$$

where C_{H_0} and C_{H_1} is the data rate of the CR user under H_0 and H_1 respectively, t_s is the sensing time slot and T is the total frame duration .

We assume that $C_{H_0} << C_{H_1}$ and since the probability of detection is required by the PU to be closer to 1. So, the achievable throughput can be approximated as

$$R \approx (1 - \frac{t_s}{T})\left[(1 - P_f)P(H_0)C_{H_0}\right] . \tag{9}$$

In figure 2, we show the average throughput per CR user when the number of CR users varies. The throughput values for CSS are higher than of the single CR user sensing case. We can also observe that there is an optimal sensing time at which the throughput is maximized.

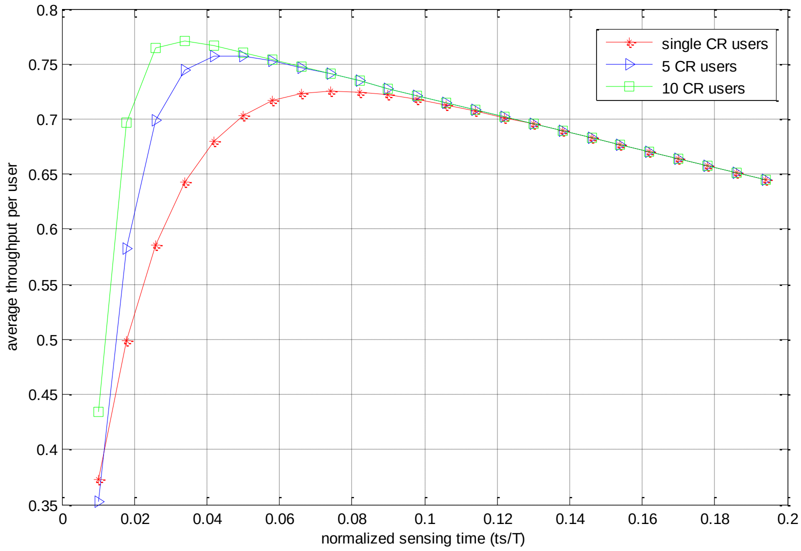

Figure 2 Average throughput

3.3. Evolutionary game for cooperative spectrum sensing

The idea of an evolutionary game was inspired from the biological model for predicting population dynamics; it studies the behavior of large populations of players who repeatedly engage in strategic interactions.

In an evolutionary game, players learn during the evolving of the strategic interactions. By learning, the players approach a stable equilibrium called evolutionarily stable strategy. Evolutionarily Stable Strategy (ESS) is a strategy such that; if all members of the population adopt it, then no alternative strategy could invade the population under the influence of natural selection [26]. ESS is a Nash equilibrium that is "evolutionarily" stable. Players can adapt their strategy and converge to the ESS by using a natural selection process known as replicator dynamics (RD) that determines how populations playing specific strategies evolve [26] [14]. We denote by p_{s_i} the number of members that are playing pure strategies $s_i \in S$. At time t the population size is $p(t)=\sum_{s_i\in S} p_{s_i}(t)$. RD can be written in continuous time as [14]

$$\dot{x}_{s_i} = [u(s_i, x_{-s_i}) - \bar{u}(x)]x_{s_i}, \qquad (10)$$

where $x_{s_i}(t) = p_{s_i}(t)/p(t)$, $u(s_i, x_{-s_i})$ denotes the average payoff of players using s_i and $\bar{u}(x)$ denotes the average payoff of the entire population.

Developing cooperative spectrum sensing using evolutionary game to obtain the optimal strategy for cooperation among CR users was it a main focus of many works such as [25] [27] [28] [29] [31].

The selfish behaviour of CR users in the sensing game was first modelled in [25]. The authors in [25] [27] have proposed an evolutionary game to achieve cooperation between selfish CR users where these latter tend to overhear the others's sensing results and contribute less to the common task. For example, the CR users like to spend less time in sensing and more time for data transmission. The authors have modelled the dynamic behaviour of CR users with the goal of throughput maximization (payoff). However, they have not considered the cost associated with energy for sensing and for transmitting data in the utility

functions.
The authors in [29] have analyzed the behaviour of selfish CR users with heterogeneous requirements (considering a CR network with light traffic users and heavy traffic users) towards cooperative sensing and have made an approach to allocate the spectrum that suits the heterogeneity. In addition, the costs in terms of energy spent on sensing and on data transmission is considered as well in the design of the evolutionary theoretical game. In [28], the evolutionary game theory is used to model the behaviour of the emergency Cognitive Radio Adhoc Networks (CRAHNs), providing an efficient model for cooperative spectrum sensing taken in account the changes in its environment such as signal to noise ratio and number of CR users in the network. Compared to [25] [27], the authors in [28] discussed a proactive spectrum sensing mechanism using LLRT based data fusion. Moreover, fairness with respect to energy consumption among CR users is maintained.
Comparing to [25] [27], in [30], the authors model spectrum sensing as an evolutionary game, in which the strategy for each CR user is able to decide whether to share its sensing result, as well as, when to share, by taking in account the time spent both on sensing and sharing in the payoff function (throughput).

The works cited before separated the analysis of spectrum sensing and access algorithm, in [31], the authors considered a joint spectrum sensing and access game by integrating the design of spectrum sensing and access algorithms together by taking in account the mutual influence between them. An evolutionary game is used to model these complicated interactions among the CR users and to derive the ESS.

In [25], they have assumed that there was only one PU and its licensed band was divided into M sub-bands. Each CR user operates in one of M sub-bands when the PU was idle. The players of the game (CR users) have the same strategy space s_i={C, D} in which C means that the CR user choose to contribute in the sensing part (Contributer) and D means that the CR user refuse to contribute in the sensing part, in the hope that other will do it for them (Denier). The payoff is defined as the throughput of the CR user. Assuming that $S_c=\{cr_1, \ldots, cr_J\}$ is a set of CR users choosing to contribute in cooperative sensing. Then, the payoff of a contributor $cr_j \in S_c$ can be written as

$$U_{C,cr_j} = P_{H_0}(1-\frac{t_s}{|S_c|T})(1-Q_{f,S_c})C_{cr_j},\ if\ |S_c| \in [1,N]. \tag{11}$$

The payoff for a denier $cr_i \notin S_c$ is given as

$$U_{D,cr_i} = \begin{cases} P_{H_0}(1-Q_{f,S_c})C_{cr_i},\ if\ |S_c| \in [1,N-1] \\ 0\ if\ |S_c| = 0 \end{cases}. \tag{12}$$

Equations (11) and (12) show that the payoff of players, who do not contribute in the sensing part is greater than the payoff of contributer players except when no one performs the spectrum sensing.
The sensing game is played repeatedly and evolves over time. Therefore, the replicator dynamics is proposed to describe the evolution of strategies in time. Then we generalize (10) to the spectrum sensing game giving the time evolution of x_{h,cr_j} which denotes the probability that user cr_j adopts strategy h∈ s_i{C, D}at time t.

$$\dot{x}_{h,cr_j} = \frac{1}{\overline{U}_{cr_j}(x)}[\overline{U}_{cr_j}(h, x_{-s_j}) - \overline{U}_{cr_j}(x)]x_{h,cr_j}, \tag{13}$$

where $\overline{U}_{cr_j}(h, x_{-s_j})$ is the average payoff for player cr_j using pure strategy h, and $\overline{U}_{cr_j}(x)$ is cr_j's average payoff using mixed strategy x_{s_j}.
In equilibrium x^*, any player has not incentive to deviate from the optimal strategy. The evolutionary

stable strategy is given by $\dot{x}$ =0.

4. Discussion and Challenges

Although evolutionary game theory has been employed as efficient approaches for CSS, there are still unaddressed issues in this area. The open challenges regarding this area include the following:

- Most existing evolutionary game theoretical models for CSS focus more on detection performance (cooperation gain). However, a proper modeling might include cooperation overhead in forming utility function. Hence, this issue is still an open challenge in the modeling for CSS.
- In CSS, we always need strategies that sustain and recover cooperation from deviation with desired performance. To this end, an open challenge can be devoted to search strategies that can achieve good network performance as well as recover cooperation from failure.
- The rate of changes in the environment can affect the performance of the evolutionary theoretical model. A research challenge is how to tune the period and how to learn it based on the changes of environment.
- A distributed learning algorithm that aids the CR users converge the ESSs based on their own payoff history is still unaddressed issue in this area.

5. Conclusion

In this paper, we have provided a comprehensive tutorial survey of evolutionary game applied to cooperative spectrum sensing in CR networks. For this purpose, we have presented a detailed discussion about the modelling of CSS under evolutionary theoretical game including an overview of the most recent works and existing literature related to this topic.

6. References

[1] Federal Communications Commission, 'Spectrum task force report', 3rd~ed, FCC document ET Docket No. 02-155 , Nov. 2002.

[2] J. Mitola III, GQ. Maguire Jr, 'Cognitive radio: making software radios more personal', Personal communication, IEEE: 13-18, 1999.

[3] S. Haykin, 'Cognitive radio: brain-empowered wireless communications', IEEE J. Select. Areas Commun, pp. 201-220, vol. 23, (2005) February.

[4] S. Chunhua, Z. Wei, and K. Ben, 'Cluster-based cooperative spectrum sensing in cognitive radio systems', IEEE international conference on communications, 2511-2515, UK, 2007.

[5] W. Zhang, R.K. Malik and K. Ben, 'Cooperative spectrum sensing optimization in cognitive radio networks', IEEE international conference on communicatios,3411-3415, china, 2008.

[6] T. Yucek, and H. Arslan, 'A survey of spectrum sensing algorithms for cognitive radio applications', IEEE Communication Survey and Tutorials, vol. 11, no. 1, First Quarter 2009.

[7] I. F. Akyildiz, B. F. Lo, and R. Balakrishnan, 'Cooperative Spectrum Sensing in Cognitive Radio Networks: A Survey', Physical Communication (Elsevier) Journal, vol. 4, no. 1, pp. 40-62, March 2011.

[8] A. Ghasemi, E. Sousa, 'Collaborative spectrum sensing for opportunistic access in fading environments', in: Proc. of IEEE DySPAN 2005, 2005, pp. 131–136.

[9] J. Unnikrishnan, V.V. Veeravalli, ‘Cooperative sensing for primary detection in cognitive radio’, IEEE Journal of Selected Topics in Signal Processing 2 (1) (2008) 18–27.
[10] T. Basar and G. J. Olsder ’Dynamic Non-cooperative Game Theory’. Philadelphia, PA, USA: SIAM Series in Classics in Applied Mathematics, Jan. 1999.
[11] R. B. Myerson, ‘Game Theory, Analysis of Conflict’. Cambridge, MA, USA: Harvard University Press, Sep. 1991.
[12] G. Owen, ‘Game Theory, 3rd edition. London, UK: Academic Press, Oct. 1995.
[13] J. Antoniou and A. Pitsillides ‘Game theory in communication networks cooperative resolution of interactive networking Scenarios’, ISBN: 978-1-4398-4810-4,CRC press 2012.
[14] B. Wang, Y. Wu, and K.J. R Liu, ‘Game theory for cognitive radio networks: An overview’, Computer Networks 54 (2010) 2537-2561.
[15] H.Y. Shi, W.L. Wang, N.M. Kwok and S.Y. Chen, ‘Game theory for wireless sensor network: A survey’, Sensors 2012, 12(7), 9055-9097.
[16] J. Neel, R. Menon, J.H. Reed, and A. MacKenzie, ‘Using game theory to analyze physical layer cognitive radio algorithms’, Economics, Technology, and Policy of Unlicensed Spectrum," Quello Center, Michigan State University, 2005.
[17] W. Saad, Z. Han, M. Debbah, A. Hjørungnes and T. Basar, ‘Coalitional Game Theory for Communication Networks: A Tutorial’. IEEE Signal Processing Magazine: Special issue on Game theory in Signal Processing and Communications 26:77-97, 2009.
[18] W. Saad, Z. Han, M. Debbah, A. Hjørungnes, and T. Basar, ‘Coalitional games for distributed collaborative spectrum sensing in cognitive radio networks’, in Proceedings of the 28th IEEE Conference on Computer Communications (INFOCOM’09), pp. 2114–2122, April 2009.
[19] X. Hao, M. Cheung, V. Wong, and V. Leung, ‘A coalition formation game for energy-efficient cooperative spectrum sensing in cognitive radio networks with multiple channels}, in IEEE Global Telecommunications Conference (GLOBECOM 2011), 2011, pp. 1-6.
[20] W. Saad, Z. Han, T. Basar, M. Debbah, and A. Hjorungnes, ‘Coalition formation games for collaborative spectrum sensing’. IEEE Trans. On Vehicular Technology, vol. 60, no. 1, pp. 276–297, Jan. 2011.
[21] Z. Heli, J. Hong, L. Xi, ‘Collaborative Spectrum Sensing in Multi-Channel Cognitive Networks: A Coalition Game Approach’, Wireless Communications and Networking Conference (WCNC), 2012 IEEE, 1354-1359
[22] L. Yan Y. Zhen, ‘Collaborative Spectrum Sensing Using Coalitional Games in Cognitive Radio Networks’, 3rd IEEE International Conference on Computer Science and Information Technology (ICCSIT), 4839- 11 July 2010.
[23] W. Saad, Z. Han, R. Zheng, A. Hjørungnes, T. Basar and H. Vincent Poor, ‘Coalitional Games in Partition Form for Joint Spectrum Sensing and Access in Cognitive Radio Networks’, IEEE Journal of Selected Topics in Signal Processing, vol. 6, no. 2, p.p. 195-209, April 2012.
[24] Y.C. Liang, Y. Zeng, E. Peh, and A.T. Hoang, ‘Sensing-throuput tradeoff for cognitive radio networks’, in Proc. IEEE ICC 2007, pp. 5330-5335, Glasgow, S cotland, June 2007.
[25] B. Wang,K.J.R. Liu,andT.C. Clancy, ‘Evolutionary game framework for behavior dynamics in cooperative spectrum sensing’, in Proceedings of the IEEE Global Telecommunications Conference (GLOBECOM ’08), pp. 1–5, December 2008.
[26] T. Rees, ‘An Introduction To Evolutionary Game Theory’, 1996.
[27] B. Wang, K.J.R. Liu, and T.C. Clancy, ‘Evolutionary cooperative spectrum sensing game: how to collaborate?’, IEEE Transactions on Communications, vol. 58, no. 3, pp. 890–900, 2010.
[28] S.~GVK and J.~Bapat, ‘Evolutionary Game Theory-Based Collaborative Sensing Model

in Emergency CRAHNs', Journal of Electrical and Computer Engineering , ID 696571, 2012
[29] S. Maharjan, C. Yuen3, Y.H. Chew, Y. Zhang and S. Gjessing, 'Distributed Spectrum Sensing for Cognitive Radio Networks with Heterogeneous Traffic', 3rd International Workshop on Cognitive Radio and Advanced Spectrum Management, ed. by IEEE, IEEE (ISBN: 978-1-4244-8132-3)
[30] Y. Dai, Y. Chen and J. Wu, 'Whether and When to Share: Spectrum Sensing as An Evolutionary Game', CROWNCOM 2013.
[31] C. Jiang, Y. Chen, Y. Gao and K.J. Ray Liu, 'Joint Spectrum Sensing and Acess Evolutionary Game in CRN', IEEE Transactions on Wireless Communications, Vol.~12, NO.~5, May 2013.
[32] M. Pan and Y. Fang 'Bargaining Based Pairwise Cooperative Spectrum Sensing for Cognitive Radio Networks', Military Communications Conference, MILCOM, 2008.
[33] C. Kaitian and Y. Zhen, 'A Novel Cooperative Spectrum Sensing Method Based on Cooperative Game Theory', 2010,V27(2): 183-189.
[34] A. Baharlouei and B. Jabbari, 'A Stackelberg Game Spectrum Sensing Scheme in Cooperative Cognitive Radio Networks', IEEE Wireless Communications and Networking Conference: Mobile and Wireless Networks, 2012.
[35] O. Habachi, R. El-azouzi and Y. Hayel, 'A Stackelberg Model for Opportunistic Sensingin Cognitive Radio Networks'. WirelessDays .April 2012.
[36] J. Lai, E. Dutkiewicz and R.P. Liu, 'Comparison of Cooperative Spectrum Sensing Strategies in Distributed Cognitive Radio Networks', Cognitive Radio and Networks Symposium-Globcom2012.
[37] Z. Wang, H. Wang, G. Feng and H. Lv, 'Distributed Spectrum Sensing Method Based on Non-Cooperative Game Theory in Cognitive Radio Networks', Journal of Information and Computational Science 10: 1 (2013) 313–322.
[38] C. Song and Q. Zhang, 'Achieving cooperative spectrum sensing in wireless cognitive radio networks', ACM SIGMOBILE Mobile Computing and Communications Review, Volume 13 Issue 2, April 2009.
[39] Y. Sun, Z.~Gao, S. Du, S. Li and H. Zhu, 'Towards addressing group selfishness of cluster-based collaborative spectrum sensing in cognitive radio networks', Globecom 2012 – Wireless Communications Symposium.
[40] W. Yuan, H. Leung, S. Chen and W. Cheng, 'A distributed sensor selection mechanism for cooperative spectrum sensing', IEEE Transactions on Signal Processing, Vol. 59, NO. 12, December 2011.
[41] S. Li, H. Zhu, B. Yang, C. Chen, X. Guan and X. Lin, 'Towards a game theoretical modeling of rational collaborative spectrum sensing in cognotive radio networks', 2012 IEEE International Conference on Communications (ICC) (June 2012), pg. 88-92.
[42] D. Teguig, B. Scheers, and V. Le Nir. 'Data Fusion Schemes for Cooperative Spectrum Sensing in Cognitive Radio Networks', In Military Communications and Information Systems Conference (MCC'2012), Gdańsk, poland, October 2012.
[43] E. C. Y. Peh, Y.-C. Liang, and Y.L. Guan, 'Optimization of Cooperative Sensing in Cognitive Radio Networks: A Sensing-Throughput Tradeoff view', ICC 2009, Dresden, Germany, June 14-18.