A Novel Bargaining-Based Spectrum Sharing Game in Cognitive Radio Network

Yang Yan, Xiang Chen, Xiaofeng Zhong, Ming Zhao, and Jing Wang

State Key Laboratory on Microwave and Digital Communications
Tsinghua National Laboratory for Information Science and Technology
Department of Electronic Engineering, Tsinghua University, Beijing 100084, China
Email: {yanyang07, chenxiang98}@mails.tsinghua.edu.cn, {zhongxf, zhaoming, wangj}@tsinghua.edu.cn

***Abstract*—Cognitive Radio (CR) can significantly alleviate the network pressure caused by rapid development of wireless communication via allowing secondary users (SUs) to obtain spectrum resources from primary users (PUs). One key issue of CR technology is spectrum sharing, *i.e.,* how spectrum should be allocated between entities of a CR network without interference to PUs. In this paper, we propose a *bilateral bargaining* scheme to achieve efficient and fair spectrum sharing between two secondary users. The SUs have to reach an agreement on the partition of a piece of spectrum resources by making alternating offers to each other in a decentralized way. We model such a process as dynamic finite/infinite horizon multi-stage game with observed actions and fully characterize the corresponding subgame perfect equilibrium (SPE). Moreover, we analyze and compare different equilibria outcome and show that our proposed scheme can effectively and fairly allocate spectrum resources for SUs.**

***Keywords*-cognitive radio technology, spectrum sharing, bargaining, subgame perfect equilibrium, multi-stage game**

I. Introduction

Cognitive radio technology [1] can greatly improve spectrum efficiency by allowing secondary unlicensed users (SUs) to opportunistically obtain spectrum with primary licensed users (PUs), and thus can effectively alleviate the ever-increasing network pressure due to the rapid growth of wireless data service. As a key component of CR technology, efficient *spectrum sharing* requires that CR network access should be coordinated to prevent multiple secondary users colliding in overlapping portions of the spectrum [2]. In this paper, based on the spectrum availability, we consider a bilateral bargaining process with alternating offers between two SUs to achieve this goal.

Spectrum sharing technique typically consists of two types: spectrum sharing within one CR network (*i.e.,* intra-network spectrum sharing) and among multiple coexisting CR networks (*i.e.,* inter-network spectrum sharing) [2]. This paper mainly deals with the intra-network spectrum sharing, where SUs of a CR network try to access the available spectrum resource without causing interference to PUs. Some literatures focus on *cooperative* intra-network spectrum sharing. Reference [3] considered a cooperative local bargaining to provide both spectrum utilization and fairness. Local bargaining is performed by constructing local groups according to a poverty line that ensures a minimum spectrum allocation to each user. Reference [4] proposed an reinforcement-learning-based spectrum sharing scheme. CR users are learning from the interaction among themselves and the environment to assess the success level of a particular action and they always choose the spectrum with the highest weight. Reference [5] considered *noncooperative* intra-network spectrum sharing, where an opportunistic spectrum management scheme was proposed. Users allocate channels based on their observations of interference patterns and neighbors.

In this paper, we use *noncooperative* bargaining theory to realize decentralized intra-network spectrum sharing between SUs. Based on the network characteristic of equal sharing right, we propose an *alternating offers* spectrum bargaining scheme where bargainers can be the offer proposer and offer responder, *i.e.,* they have equal bargaining positions. However, our previous work [6]–[8] considered a cooperative spectrum sharing between PUs and SUs under different system scenarios via a *one-side* noncooperative bargaining mechanism. Different from our proposed scheme in this paper, since PUs own spectrum resource, the bargaining position for PUs and SUs are not equal: PUs have priority over SUs during bargaining process.

The main contributions of this paper are as follows:

- *New intra-network spectrum sharing bargaining model:* To the best of our knowledge, this is the first paper that studies intra-network spectrum sharing using *non-cooperative bargaining theory*. Moreover, we propose a *bilateral alternating offers* bargaining model, which better captures the reality where SUs have equal bargaining powers in spectrum sharing process and has never been discussed in previous literatures concerning this issue.
- *Finite/infinite horizon dynamics and subgame perfect*

This work is supported by National Basic Research Program of China (2012CB316002), National S&T Major Project (2010ZX03003-002), National NSF of China (60832008), China's 863 Project (2009AA011501), Tsinghua National Laboratory for Information Science and Technology (TNList) Cross-discipline Foundation, and International Science Technology Cooperation Program (2010DFB10410).

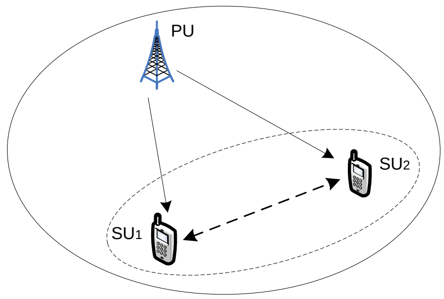

Figure 1. Spectrum sharing bargaining model

equilibrium: We model the bargaining process into two subcases: (i) finite horizon game where two SUs bargain over the partition of spectrum during a fixed period of time; (ii) infinite horizon game where two SUs do not know the exact time for the bargaining to end. We employ subgame perfect equilibrium (SPE) for the study of the interaction between SUs in two subcases. We fully characterize and analyze the corresponding SPEs.

The rest of this paper is organized as follows. We introduce the system model and methodology in Section II. In Section III, we analyze the finite horizon bargaining game. In Section IV, we extend our analysis to the infinite horizon bargaining game. We discuss and compare the bargaining equilibria in Section V. Finally, we conclude in Section VI.

II. System Model and Methodology

A. Spectrum Sharing Bargaining Model

We consider a simplified model shown in Figure 1.[1] The dashed ellipse denotes the secondary system where two SUs coexist, *i.e.,* SU_1 and SU_2.[2] Their bargaining interaction over spectrum division is indicated by the dashed line between them, which will be analyzed in details in Section III and IV. We further assume that the channel model considered in this paper is AWGN channel and the channel gain between SUs remains fixed during bargaining process. One primary user (PU) exists in the network and the solid lines between SUs and PU indicate that SUs can obtain feasible spectrum resources via proper spectrum sensing and decision mechanism.[3] We allow SUs to bargain via *common control channel* (CCC) [11] so as to reach an agreement on the spectrum division. Once any agreement is reached, SUs work in *FDMA* fashion for their own transmissions.

[1]For ease of illustration, we simplify this figure by not marking the transmitters and receivers of PU and SUs.

[2]The two-user secondary system assumption can greatly simplify the analysis of spectrum bargaining scheme, however, enlightened by Antoni's work [9]- [10], our framework can be easily extended to the general case with multiple SUs by using certain *bargaining-opponent selection* schemes.

[3]We focus on driving the equilibrium and engineering insights for the bargaining-based intra-network spectrum sharing. For simplicity, we do not jointly consider the spectrum sensing and decision issues in this paper, and will leave them as future work. All later discussions are based on the assumption that spectrum has been available for SUs.

The bargaining protocol is as follows. In the first period (stage), SU_1 proposes a division of spectrum; after *observing* SU_1's offer, SU_2 decides whether to accept or reject this offer; if SU_2 accepts, then the proposed division is implemented, and the game ends; otherwise, the bargaining moves into the second stage. In the second stage, SU_2 makes a counteroffer; after *observing* SU_2's offer, SU_1 decides whether to accept or reject this offer; if SU_1 accepts, then the proposed division is implemented, and the game ends; otherwise, the game moves into the third stage, and so on. Both SUs can perfectly observe all proposed offers in previous stages.

The bargaining process can last for a fixed period of time (*i.e.,* finite horizon where the number of stages is fixed), or an unlimited period of time (*i.e.,* infinite horizon where SUs do not know when the game will end). Generally, in any stage $t = 1, 2, ..., N(\text{or } \infty)$ if no division is accepted in prior to t, and if t is odd (even), then:

- SU_1 (SU_2) proposes a division
- After observing SU_1's (SU_2's) offer, SU_2 (SU_1) decides whether to accept or reject this offer
- If SU_2 (SU_1) accepts, then the spectrum resource is divided according to the proposal and the game ends; otherwise, the game moves into stage $t + 1$

The corresponding bargaining game trees are depicted in Figure 2 and Figure 3, respectively.

B. Utility Functions

We assume that both SUs are rational players, who make optimal strategies in order to maximize their own utilities in the bargaining game. **The SU's utility** is defined as *its achievable data rate*:

$$U_i(W_i) = W_i \log(1 + \mathrm{SNR}_i), \ \forall i \in N, \tag{1}$$

where $N = \{1, 2\}$ and W_i is spectrum resource SU_i gets in the bargaining agreement. SNR_i is SU_i's signal-to-noise ratio for a given time and location in the network. Given spectrum resource $\mathcal{W}$ which is available from PU in a certain period, we have $W_1 + W_2 \leq \mathcal{W}$.

For simplicity of presentation, we modify this utility function in Eq.(1) from two aspects. Firstly, we normalize the spectrum resource as $\mathcal{W} = 1$. Moreover, let $\mathbf{x} = (x_1, x_2)$ with $x_1 + x_2 = 1$ denote spectrum allocation in one stage if an agreement is reached. Secondly, with the fact that $W \log(1 + \mathrm{SNR})$ is an increasing function of parameter W, we can equivalently replace the original utility function in Eq.(1) with a simpler form as follows,

$$U_i(x_i) = x_i, \ \forall i \in N. \tag{2}$$

Eq.(2) means that the more spectrum SU obtains, the higher data rate it can achieve. In Section II-A, we elaborate the bargaining process where SU_1 and SU_2 are indifferent about *timing* of an agreement. However, in reality the bargaining process takes time. In this paper, we assume that SU is an *energy-constrained* device (*e.g.,* wireless sensor or mobile device with limited battery life) and thus player's bargaining preference should also reflect the factor of time t. So, the revised utility function should be $U_i(x_i, t)$. Moreover, as the bargaining proceeds, the battery life decreases. Thus, SUs value time and have preferences towards *earlier* agreements by *discounting* the future utility at a rate. We can express the utility function with the consideration of timing preference as follows [12],

$$U_i(x_i, t) = \delta_i^t x_i, \ \forall i \in N, \tag{3}$$

where $N = \{1, 2\}$ and $\delta_i \in (0, 1)$ is SU_i's *discount factor*, which is related to SU_i's battery status and can also be viewed as SU_i's *bargaining patience*. Intuitively, SU with a larger δ tends to be more patient during the bargaining process.

C. Subgame Perfect Equilibrium

The bargaining process elaborated in Section II-A is a dynamic multi-stage game with observed actions, which involves SUs' dynamic decision-making in multiple periods (finite or infinite horizon) and thus is challenging to analyze. In this paper, we employ a refined Nash equilibrium (NE) concept, *i.e.,* subgame perfect equilibrium (SPE) for bargaining result analysis, which we define briefly by the following:[4]

Definition 1: A strategy profile s^* is a Subgame Perfect Equilibrium (SPE) in game Γ if for any subgame Γ' of Γ, $s^*_{|\Gamma'}$ is a Nash equilibrium of Γ'.
where $s^*_{|\Gamma'}$ is the restriction of strategy profile s^* to subgame Γ'.

Backward Induction (BI)[5] is a commonly used method for characterize equilibrium of *finite* horizon dynamic game with observed actions, which we will employ in Section III. For the infinite horizon game, however, BI method cannot be applied, instead we will introduce "*one-stage deviation principle*" to characterize SPE in Section IV.

III. Finite Horizon Bargaining Game

In this section, we consider the finite horizon bargaining game for spectrum sharing between SUs. For ease of illustration, we focus on the two-period bargaining case. The more general finite multi-period bargaining can be similarly analyzed.

[4]The detailed definitions and discussions about NE, subgame, and other related concepts are beyond the scope of this paper. See [13] for more details.

[5]Loosely speaking, it refers to starting from the last subgame of a *finite* game, then finding the best response strategy profiles or the Nash equilibria in the subgames, then assigning these strategy profiles and the related utilities to be subgames, and moving successively towards the beginning of the game.

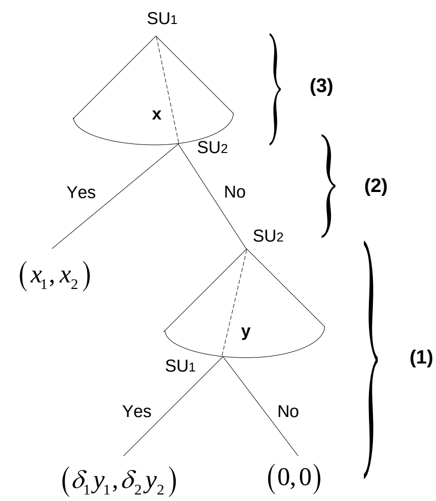

Figure 2. Two-period bargaining game with alternating offers

Figure 2 illustrates a two-period bargaining with alternating offers, where the bargaining procedure is the same as depicted in Section II-A. SU_i's future utility is discounted using the constant discount factor $\delta_i \in (0, 1)$ in each period. The available spectrum resource is normalized as $\mathcal{W} = 1$. $\mathbf{x} = (x_1, x_2)$ with $x_1 + x_2 = 1$ denotes spectrum allocation in the first period, and $\mathbf{y} = (y_1, y_2)$ with $y_1 + y_2 = 1$ denotes the allocation proposed by SU_2 in the second period. The sector in each proposal means that proposed offer can be any scalar, not necessarily integral. If there is no any agreement reached after two periods, the two players cannot divide spectrum and thus the utility is $(0, 0)$, *i.e.,* no one will get spectrum.

We will find the SPE by using BI method. We first consider the last subgame denoted by (1) in Fig. 2, where BI method can also be applied. There is a different possible subgame for each value of $\mathbf{y}$, so we should find the optimal strategy of SU_1: if $y_2 > 0$, then SU_1 should accept this offer; if $y_2 = 0$, then SU_1 will be indifferent between accepting and rejecting this offer. We further divide the case where $y_2 = 0$ into two contingencies:

- Accept offer for all $y_2 \geq 0$
- Accept offer if $y_2 > 0$ and reject if $y_2 = 0$

For the first possible strategy of SU_1, it is obvious that SU_2's optimal offer will maximize $y_1 = 1 - y_2$ when $y_2 \geq 0$. Therefore, the optimal offer should be $\mathbf{y} = (y_1, y_2) = (1, 0)$. Then, SU_1 accepts all offers. For the second possible strategy of SU_1, SU_2 should offer $y_2 > 0$ so as to get positive utility $1 - y_2$. Thus, its optimal offer will be

$$y_2^* = \arg\max_{y_2 > 0} (1 - y_2). \tag{4}$$

However, there is no optimal solution for Eq.(4) and hence there is no SPE in this contingency. Therefore, the *unique* SPE of subgame (1) in Fig. 2 is

- SU_2 offers 0 to SU_1
- SU_1 accepts all $y_2 \geq 0$
- Bargaining outcome: (0, 1)

Next, we track back to phases (2) and (3) in Fig. 2. Considering the discount factor, the outcome of subgame (1) is $(0, \delta_2)$. That is, SU_2 will get δ_2 if it reject SU_1's offer in phase (2). Similarly, there are two cases for SU_2's strategies:

- Accept offer if $x_2 \geq \delta_2$ and reject if $x_2 < \delta_2$
- Accept offer if $x_2 > \delta_2$ and reject if $x_2 \leq \delta_2$

Combining phase (3), we can get SU_1's optimal offer in (3) as $(1 - \delta_2, \delta_2)$. Then, the *unique* SPE of this game is:

- SU_1's initial proposal is $(1 - \delta_2, \delta_2)$
- SU_2 accepts all offers when $x_2 \geq \delta_2$ and rejects all $x_2 < \delta_2$
- SU_2 propose (0, 1) after any case where it rejects SU_1's offer in the first period
- SU_1 accepts all proposals of SU_2 (after SU_2 rejects SU_1's opening proposal)

And the *outcome* of this game is:

- SU_1 proposes $(1 - \delta_2, \delta_2)$
- SU_2 accepts this offer
- Utility: $(1 - \delta_2, \delta_2)$

From the unique SPE, the bargaining ends in the first period. For the more general case with finite multiple periods, we can similarly analyze by utilizing the backward induction method.[6]

In this section, we have investigated how SUs bargain with each other in a finite number of periods. In next section, we extend our analysis to the infinite horizon bargaining, where two SUs do not know exactly when the bargaining will end.

IV. Infinite Horizon Bargaining Game

We extend the bargaining game to infinite horizon where both bargainers are unknown about the exact ending time of bargaining.[7] Figure 3 illustrates the structure of this bargaining game. We assume that SUs get zero utility if no agreement is reached ever.

For the infinite horizon game, BI method cannot be applied for SPE analysis as in Section III. Therefore, we will instead *conjecture* a strategy profile and then verify that this strategy profile can form an SPE by using the *one-stage deviation principle*.

A. One-stage Deviation Principle

The one-stage deviation principle is a shortcut method to verify whether a strategy profile of a finite or infinite horizon game is an SPE or not. In this paper, we use this principle for analyzing the infinite horizon bargaining game. First,

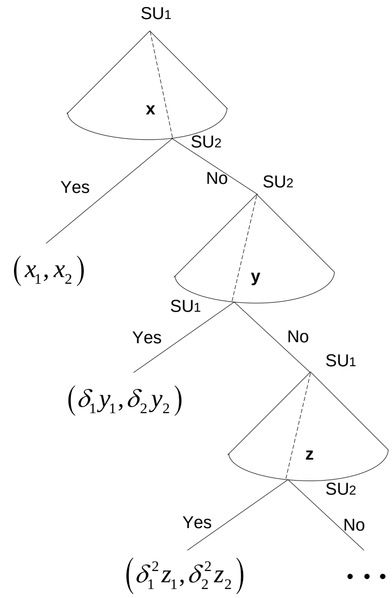

Figure 3. Infinite horizon bargaining game with alternating offers

we introduce the concept of "*history*" of dynamic multi-stage game, which helps to better understand the one-stage deviation principle.

For period $t = 1, 2, ..., \infty$, a *t-period history* h^t is a record of chosen actions from the beginning of the game up to period (stage) t, defined as follows,

$$h^t = \left(a^1, ..., a^t\right) = \left((a_1^1, ..., a_n^1), ..., (a_1^t, ..., a_n^t)\right), \quad (5)$$

where a_i^t is player i's action in period t. $a^t = (a_1^t, ..., a_n^t)$ is the profile of actions in period t.

Before formally introducing the one-stage deviation principle, we definite *continuity at infinity* by the following:

Definition 2: Consider a infinite horizon multi-stage game with observed actions, denoted by Γ^∞. Let h^∞ denote an ∞-horizon history, i.e., $h^\infty = \left(a^1, a^2, ...\right)$, is an infinite sequence of actions. Let $h^t = \left(a^1, ..., a^t\right)$ be the restriction to first t periods. The game Γ^∞ is continuous at infinity if for all players i, the utility function u_i satisfies

$$\lim_{t \to \infty} \sup_{h^\infty, \tilde{h}^\infty \in H^\infty(h^t) \text{ for some } h^t} \left| u_i(h^\infty) - u_i(\tilde{h}^\infty) \right| = 0,$$

where $H^\infty(h^t)$ is the set of infinite histories that follow h^t.

With the definition of continuity at infinity, we have the following lemma.

Lemma 1: The continuity at infinity condition is satisfied when the overall utilities are a discounted sum of utility in each stage, and the stage utility is uniformly bounded.

Lemma 1 shows that our infinite horizon bargaining game with discounted utility in each stage satisfies the continuity at infinity condition. With Lemma 1, we have the following

[6] In fact, the more general case is similar to the classic *Stahl's Bargaining Model*. See [14] for more details.

[7] This extended model complies with the classic *Rubinstein's Alternating Offers Model* [12].

theorem about one-stage deviation principle for infinite horizon game.

Theorem 1: Consider an infinite horizon game with observed actions Γ^{∞}, that is continuous at infinity. Then, the one-stage deviation principle holds, i.e., the strategy profile s^* is an SPE if and only if for all i, h^t, and t, we have

$$u_i\left(s_i^*, s_{-i}^*|h^t\right) \leq u_i\left(s_i, s_{-i}^*|h^t\right),$$

for all s_i that satisfies $s_i(h^t) \neq s_i^*(h^t)$ and $s_{i|h^t}(h^{t+k}) = s^*_{i|h^t}(h^{t+k})$ for all $h^{t+k} \in \Gamma^{\infty}(h^t)$ and for all $k > 0$.

The proofs of Lemma 1 and Theorem 1 can be found in [13]. If one game satisfies the one-stage deviation principle, then it is relatively easy to verify if one strategy profile is an SPE or not by checking if there is any history h where some player i can increase its utility by deviating from $s_i(h)$ *only once* at h and conforming to s_i thereafter. Theorem 1 shows that the bargaining game considered in this section satisfies the one-stage deviation principle. Next, we will use this result to characterize SPE of the bargaining game.

B. SPE Analysis

The strategy of an SU in this game includes:

- Offer in period n
- Optimal response to its opponent's offer in period $n+1$
- Counteroffer to its opponent in period $n+2$

Note that for each SU i, all subgames that begin with SU_i's making an offer and SU_i's response to its opponent's offer are *structurally equivalent*. Therefore, we consider a *stationary* strategy profile where each SU always makes the same proposal and its response to the other SU's offer depends only on the current proposal.

Define the following parameters,

$$x_1^* = \frac{1-\delta_2}{1-\delta_1\delta_2},\ x_2^* = 1 - x_1^* = \frac{\delta_2(1-\delta_1)}{1-\delta_1\delta_2},$$

and

$$y_1^* = \frac{\delta_1(1-\delta_2)}{1-\delta_1\delta_2},\ y_2^* = 1 - y_1^* = \frac{1-\delta_1}{1-\delta_1\delta_2}.$$

And we consider such a strategy profile $s^* = (s_1^*, s_2^*)$:

- SU_1 proposes $x^* = (x_1^*, x_2^*)$ and accepts y_1 if and only if $y_1 \geq y_1^*$
- SU_2 proposes $y^* = (y_1^*, y_2^*)$ and accepts x_2 if and only if $x_2 \geq x_2^*$

The following theorem asserts that this strategy profile we conjecture is an SPE of this bargaining game.

Theorem 2: The strategy profile s^* mentioned above constitutes an SPE for the infinite horizon alternating offers bargaining game with observed actions.

Proof Sketch: We use the one-stage deviation principle to verify this theorem. Note that there are two types of subgame structures. The first subgame is the one where first action is an offer provided by SU_i. The second is the one where first action is a response from SU_i to an offer provided by its opponent.

For the first type subgame, suppose that this offer is made by SU_1. Fix SU_2's strategy as s_2^*. If SU_1 makes actions based on s_1^*, then SU_2 will accept offer and thus SU_1 get utility $x_1^* = \frac{1-\delta_2}{1-\delta_1\delta_2}$. If SU_1 deviates from s_1^* and offers $x_2 > x_2^*$, then SU_2 will accept and thus SU_1 gets lower utility than x_1^*. If SU_1 offers $x_2 < x_2^*$, then SU_2 will reject and proposes y^*. SU_1 will accept (due to one-stage deviation) and get a discounted utility $\delta_1 y_1^*$. Since $\delta_1 y_1^* < x_1^*$, SU_1 will not be better off if deviating from s_1^*.

Similarly, for the second type subgame, suppose that SU_1 responses SU_2's offer. Fix SU_2's strategy as s_2^*, *i.e.,* SU_2 offers y_1^*. SU_1 will accept and get utility y_1^* if adopting s_1^*. If not, SU_1 will reject offer $y_1 \geq y_1^*$ and propose counteroffer x_1^* (due to one-stage deviation) and SU_2 will accept offer. SU_1 will get a discounted utility $\delta_1 x_1^* = y_1^*$, which means it cannot gain more by such a one-stage deviation.

Thus, the strategy profile s^* is an SPE. ■

From the SPE, we get the *outcome* of this infinite horizon game as

- SU_1 proposes $\left(\frac{1-\delta_2}{1-\delta_1\delta_2}, \frac{\delta_2(1-\delta_1)}{1-\delta_1\delta_2}\right)$
- SU_2 accepts this offer
- Utility: $\left(\frac{1-\delta_2}{1-\delta_1\delta_2}, \frac{\delta_2(1-\delta_1)}{1-\delta_1\delta_2}\right)$

V. Bargaining Equilibrium Analysis

In this section, we briefly evaluate the bargaining outcomes (SPE) derived in Section III and IV from two points of view, *i.e.,* fairness and efficiency.

A. Fairness

We consider the *intra-network* spectrum sharing in cognitive radio network, where multiple secondary users want to equally share spectrum resource obtained from PU. The SUs have identical spectrum sharing powers, *i.e.,* no *priority* exists during spectrum bargaining process. Although there is a conflict of interest from the two SUs, no agreement would be imposed on any SU without its approval. Taking this fact into account, we propose an explicit bargaining process with alternating offers, which is consistent with the bargaining process in reality. Any bargaining participant has fair rights to provide a proposal as well as to response to any offer proposed by its opponent. Both SUs in this bargaining game must make decisions to maximize its own utility.

B. Efficiency

For both bargaining game scenarios: finite and infinite horizon game in Section III and IV, we fully characterize the corresponding SPE outcomes. Each bargaining ends in the first period if SUs adopt the equilibrium strategies, *i.e.,* there is no *delay* and thus *no inefficiency* due to delay in SPE outcomes. Although we model a multi-stage bargaining game to divide spectrum resources, the agreement can be reached at the very beginning of the game. Under the situation where all actions can be perfectly observed and all information about player's time preference (discount factor) is complete, each SU knows its opponent's value of rejecting an offer, and thus enables to find an offer which is acceptable for its opponent and optimal for itself. Furthermore, bargaining *impatience* plays an important role: *desirability of an earlier agreement yields a time-efficient bargaining result*, which can save time (and thus energy) in spectrum sharing process and enable SUs to utilize and vacate spectrum when PU returns back.

VI. Conclusion

This paper investigates an intra-network spectrum sharing scheme achieved by a bilateral bargaining between two SUs. The more general case with multiple SUs can be decomposed into several pairwise one-to-one bilateral bargaining games studied in this paper. We discuss such a bargaining process under two different system models, *i.e.,* finite and infinite horizon scenario. By modeling such a mechanism as a multi-stage game with observed actions, we are able to characterize the subgame perfect equilibria. Furthermore, we analyze the properties of equilibria and verify that such a bargaining scheme can effectively and fairly realize spectrum sharing among SUs in cognitive radio network.

References

[1] S. Haykin, "Cognitive radio: Brain-empowered wireless communications," *IEEE Journal on Selected Areas in Communications*, vol. 23, no. 2, pp. 201-220, Feb 2005.

[2] I. F. Akyildiz, Won-Yeol Lee, M. C. Vuran, and S. Mohanty, "A Survey on Spectrum Management in Cognitive Radio Networks," *IEEE Communications Magazine*, vol. 46, no. 4, pp. 40-48, April 2008.

[3] L. Cao and H. Zheng, "Distributed Spectrum Allocation via Local Bargaining,"*IEEE SECON*, pp. 475-486, Sep 2005.

[4] T. Jiang, David Grace, and Y. Liu, "Performance of Cognitive Radio Reinforcement Spectrum Sharing Using Different Weighting Factors,",*IEEE DySPAN*, pp. 1195-1199, Aug. 2008.

[5] H. Zheng and L. Cao, "Device-centric Spectrum Management,", *IEEE DySPAN*, pp. 56C65, Nov 2005.

[6] Y. Yan, J. Huang, X. Zhong and J. Wang, "Dynamic Spectrum Negotiation with Asymmetric Information," *GameNets*, April 2011.

[7] Y. Yan, J. Huang, X. Zhong, and J. Wang, "Dynamic Bayesian Spectrum Bargaining with Non-Myopic Users," *International ICST Conference on Wireless Internet*, Xi'An, China, Oct 2011.

[8] Y. Yan, J. Huang, X. Zhong, M. Zhao and J. Wang, "Sequential Bargaining in Cooperative Spectrum Sharing: Incomplete Information with Reputation Effect," *IEEE Globecom*, Dec 2011.

[9] C. Antoni, "Bargaining power in communication networks," *Mathematical Social Sciences*, vol. 41, pp. 69-87, 2001.

[10] C. Antoni, "On bargaining partner selection when communication is restricted," *International Journal of Game Theory*, vol. 30, no. 4, pp. 503-515, 2001.

[11] IEEE 802.22 Working Group on Wireless Regional Area Networks, "IEEE P802.22/D0.1 Draft Standard for Wireless Regional Area Networks Part 22: Cognitive Wireless RAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: Policies and procedures for operation in the TV Bands," *IEEE doc*: $22-06-0067-00-0000-P80222-D0.1$, May 2006.

[12] A. Rubinstein and M.Osborne, *Bargaining and Markets*, Academic Press, 1990.

[13] D. Fudenberg and J. Tirole, *Game Theory*, The MIT Press, Cambridge, Massachusetts, 1991.

[14] I. Stahl, *Bargaining Theory*, Economics Research Institute, Stockholm School of Economics, 1972.