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Sequential Bargaining in Cooperative Spectrum Sharing: Incomplete Information with Reputation Effect

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***Abstract*—Cooperative spectrum sharing can effectively improve spectrum usage by allowing secondary users (SUs) to dynamically share the licensed bands with primary users (PUs). Meanwhile, an SU can relay a PU's traffic to improve the PU's effective data rate. In this paper, we consider a sequential spectrum bargaining process to achieve cooperative spectrum sharing between one PU and one SU over multiple time slots. The SU may be a Low type or a High type, depending on its energy cost. Such information is private to the SU and is unknown to the PU. We model such a dynamic bargaining with incomplete information as a dynamic Bayesian game, and characterize several types of equilibria under different system parameters. In particular, we show that a Low type SU may maximize its total utility by utilizing the reputation effect, *i.e.,* rejects profitable offers initially in order to create the reputation of a High type SU.**

I. Introduction

Cooperative spectrum sharing (CSS) can effectively improve spectrum efficiency, and thus alleviate the network pressure due to rapid increase of wireless data traffic. The key technology behind CSS is the *cooperative communication*, where a primary licensed user (PU) with a poor channel condition (between its transmitter and receiver) can achieve a higher data rate by using a secondary unlicensed user (SU) as a relay. Such relay-based cooperative communication has already been widely supported in industry and is part of the next generation communication standards (*e.g.,* IEEE 802.16J standard [1]).

Different from the traditional cooperative communications, CSS further requires the PU to *compensate* the SU by allocating some network resources for the SU's own communications. The central question of a CSS mechanism is how the PU and SU agree on the cooperative transmissions and resource splitting. In this paper, we study a CSS mechanism where one PU and one SU sequentially bargain with each other over N time slots. A brief illustration of the two users is shown in Fig. 1, where PU has a transmitter TP and a receiver RP, and the SU has a transmitter TS and a receiver RS. Detailed discussions will be introduced in Section II-A.

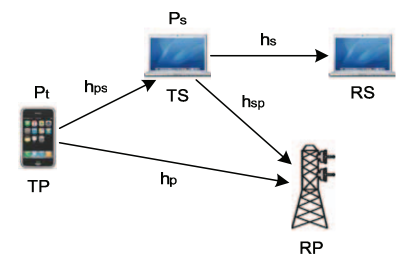

Fig. 1. The Cooperation between One PU (TP-RP) and One SU (TS-RS)

The concept of CSS has only been proposed in recent literatures (*e.g.,* [2]–[6]). References [2]–[4] considered CSS mechanisms based on *complete* network information, which is often difficult to achieve in real networks. Duan *et al.* [5] proposed a contract-based CSS mechanism for a *static* network with incomplete network information. Our prior work [6] is the first work that considered a CSS in a *dynamic* environment with *incomplete* information. The focus of [6] is to consider the multi-stage bargaining between one PU and one SU in a *single* time slot.

In this paper, we propose a sequential spectrum bargaining scheme between one PU and one SU over a finite number of time slots. In each time slot, the PU decides whether and how to share its licensed spectrum to SU, and the SU decides whether to accept PU's offer by considering its potential energy cost. Compared with [6], the model in this paper is more practical, since the PU and SU typically interact over many time slots in practice (*e.g.,* transmitting many packets over time). The analysis is much more complicated and the results are very different from [6]. In particular, we will focus on discussing the *reputation effect* emerging during the multi-

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slot sequential bargaining, which did not exist in a single slot model in [6].

The main contributions of this paper are as follows:

- *New dynamic multi-slot bargaining model:* We model the CSS interaction between the PU and the SU over N consecutive time slots as a dynamic bargaining game. This model better captures the reality of wireless communications and has never been studied in the previous CSS literatures.
- *Incomplete information and sequential equilibrium:* We model the SU's energy cost as private information, which determines the SU's type (*i.e.,* High or Low). We further characterize the sequential equilibrium, where the PU updates its belief on the SU's type, and both users choose actions to maximize their utilities based on the interaction history.
- *Reputation effect:* We show that an SU may choose to sacrifice some immediate benefit in order to build a strong *reputation*, which will help to improve the SU's long-term utility.

The rest of the paper is organized as follows. We introduce the system model and the problem formulation in Section II. In Section III, we analyze the equilibria of the multi-slot bargaining under different system parameters. In Section IV, we focus on discussing when and how the reputation effect will affect the equilibrium. In Section V, we discuss various insights obtained from the equilibrium analysis with some numerical results. Finally, we conclude in Section VI. **Due to the page limit, all proofs are included in the online technical report [11]**.

II. PU-SU Cooperation and Bargaining Model

A. Cooperative Communication

We consider a time-slotted system with the two-user cooperation model as in Fig. 1. Here, TP and RP represent PU's transmitter and receiver, and TS and RS represent SU's transmitter and receiver. Let h_p, h_s, h_{ps}, and h_{sp} denote the channel gains of links TP-RP, TS-RS, TP-TS, and TS-RP, respectively. For simplicity, we assume that channel gains do not change across time slots. We further assume that both PU and SU know the channel gains of all links through a proper feedback mechanism. The PU and SU transmit with fixed power levels P_t and P_s, respectively.

B. Sequential Bargaining

The bargaining happens over N consecutive time slots as in Fig. 2. To make the discussions easier to follow later on, *we index time backwards, i.e., the bargaining starts with time slot N and ends in time slot 1.* Without loss of generality, we normalize the length of each time slot to 1. Finally, we assume that the overhead due to bargaining is negligible. During each time slot, the PU can choose either *direct transmission only* or *bargaining with the SU*. There are three possible bargaining results for each time slot as illustrated in Fig. 2.

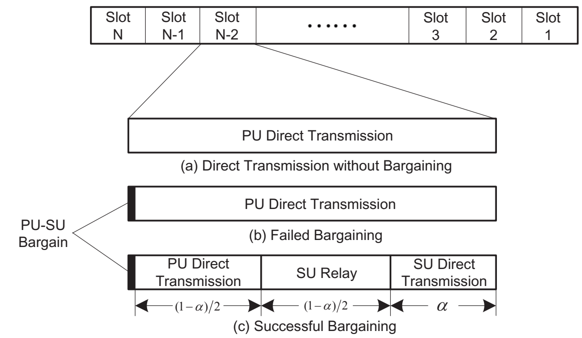

Fig. 2. The Slotted System Model with Three Possible Bargaining Results in a Single Time Slot

- Figure 2(a): If PU's direct channel condition h_p is good enough, it will choose direct transmission during the whole time slot and achieve a data rate $R_{dir} = \log(1 + P_t h_p)$. In this case, the SU cannot transmit and thus achieves a zero utility.
- Figure 2(b): If PU believes that cooperation may be beneficial, it can offer α fraction of the time slot for SU's own transmission. If SU rejects the offer, PU proceeds with direct transmission for the remaining time, and achieve the same payoff as in Figure 2(a).
- Figure 2(c): If SU accepts PU's offer α, then PU and SU transmit in the amplified and forward (AF) relay mode. The PU achieves a data rate (per unit time) [7]

$$R_r = \frac{1}{2}\log\left(1 + P_t h_p + \frac{P_t P_s h_{ps} h_{sp}}{P_t h_{ps} + P_s h_{sp} + 1}\right), \quad (1)$$

and the SU achieves a data rate (per unit time)

$$R_s = \log(1 + P_s h_s). \quad (2)$$

The effective transmission rate for PU is $\frac{1-\alpha}{2}R_r$ and αR_s for SU. PU and SU will bargain over the value of α by taking into consideration the bargaining results in previous time slots.

C. Incomplete Information of Energy Cost

The dynamic bargaining is further complicated by the incomplete information. We assume that SU is an *energy-constrained* device with an energy cost C. A larger C means that the SU's transmission is more costly. For simplicity, we consider two types of SU ($C_h > C_l$) based on the value of C:

- **High type SU**: $C = C_h$,
- **Low type SU**: $C = C_l$.

The SU knows its own type, but the PU does not (and hence incomplete information). However, the PU has a *belief* on C's distribution in each time slot $n = N, ..., 1$, *i.e.,* Pr$(C = C_h) = q_n$ and Pr$(C = C_l) = 1 - q_n$. How PU's belief is updated over time depending on the bargaining results in previous time slots will be one of the key analysis focuses of this paper.

III. Multi-Slot Bargaining Game

In this section, we will discuss how the PU and SU make decisions to maximize their utilities in the *multi-slot* bargaining game. As a baseline, we will first consider the one-slot bargaining game (*i.e.,* $N = 1$).

A. Utility Functions in the Single-Slot Game

The SU's single-slot utility $U_s(\alpha)$ after accepting an offer α is

$$U_s(\alpha) = \alpha R_s - \frac{1+\alpha}{2} P_s C, \tag{3}$$

which is the difference between the SU's achievable data rate R_s and energy cost for relay $P_s C$ (both weighted by the time). Note that the SU can always achieve a zero utility by not participating in the cooperative communication. Given PU's offer α, it is *optimal* for SU to accept the offer if and only if $U_s(\alpha) > 0$.

The PU's single-slot utility $U_p(\alpha)$ is its *achievable data rate*. Without SU's relay, the PU can achieve a data rate of R_{dir}. If PU's offer α is accepted by SU, then the PU's effective data rate is $\frac{1-\alpha}{2} R_r$, where R_r is given in (1). Knowing the SU's potential strategy, PU makes the optimal decision by maximizing its utility

$$U_p(\alpha) = \max\left\{R_{dir}, \frac{1-\alpha}{2} R_r\right\}. \tag{4}$$

B. Sequential Equilibrium

Now we return to the multi-slot bargaining. We assume that the SU is a *non-myopic* player, whose utility is its total utilities in all N time slots. For simplicity of presentation, we assume that the PU is a *myopic* player, who only maximizes its utility in the current single time slot.[1]

The sequential bargaining process is a dynamic Bayesian game [9], which involves the PU's and SU's dynamic decision-making and belief updates. The *sequential equilibrium* (SE) is a commonly used solution concept for the dynamic Bayesian game, and is defined as a strategy profile and belief system which satisfy the following three requirements [10]:

Requirement 1: The player taking the action must have a belief (probability distribution) about the incomplete information, reflecting what that player believes has happened so far.

Requirement 2: The action taken by a player must be optimal given the player's belief and the other players' subsequent strategies.

Requirement 3: A player's belief is determined by the Bayes' rule whenever it applies and the players' hypothesized equilibrium strategies.

The belief in Requirement 1 is the PU's probability assessment q_n about the High type SU in time slot n, with an initial value $q_N = \eta$ in the first time slot indexed N. As the game progresses, both users observe all prior moves. These moves enable the PU to *update* its belief about the SU's type. The SU's belief in all time slots is deterministic since it knows its own type.

C. Equilibrium Characterization

Intuitively, an SU will only choose to cooperate and serve as a relay if it can get a positive total utility in N time slots. This not only depends on its energy cost (either C_h or C_l), but also on its average data rate per unit power, R_s/P_s. Next we will discuss three different cases based on the relationship between the energy cost and R_s/P_s.

[1]In a companion paper [8], we have shown that the results in this paper are also true for the case of non-myopic PU.

*1) **Case 1**: $R_s/P_s \in (0, C_l]$:* In this case, we have the single-slot SU utility $U_s(\alpha) \le 0$ for any $\alpha \in$ [0,1]. This means that even the low energy cost C_l is too costly for the SU to achieve a positive data rate increase under any resource splitting arrangement. Therefore, SU will reject any offer from PU in any time slot. By considering SU's response, PU will choose the direct transmission without cooperation in each time slot (Fig. 2(a)). PU's belief about the SU's type becomes irrelevant here.

*2) **Case 2**: $R_s/P_s \in (C_l, C_h]$:* In this case, a High type SU will reject any offer, as $U_s(\alpha)$ is negative for any α. However, a Low type SU may accept a large enough α. To attract the help from a Low type SU, PU needs to provide an offer α that makes the SU's single-slot utility $U_s(\alpha)$ *slightly* larger than zero [11]. For ease of discussion, we first define

- $\alpha_l = \frac{1}{\frac{2R_s}{C_l P_s}-1} + \varepsilon$, where ε is an arbitrarily small positive number. This represents PU's minimum offer that can attract a Low type SU to help as the relay,
- $R_l = \frac{1-\alpha_l}{2} R_r$: the PU's single-slot utility if SU accepts α_l.

Theorem 1 summarizes the SE for this case.

Theorem 1: Consider a multi-slot bargaining game where $R_s/P_s \in (C_l, C_h]$. If $R_{dir} \ge R_l$, PU always chooses direct transmission only regardless of SU's type. If $R_{dir} < R_l$, PU always offers α_l to SU. A High type SU rejects the offer α_l, and a Low type SU accepts the offer α_l.

Under the conditions in Theorem 1, we can decompose the multi-slot bargaining into N independent single-slot bargaining. For the proof of Theorem 1, see [11].

*3) **Case 3**: $R_s/P_s \in (C_h, \infty)$:* This is the most interesting case, as both the High and Low type SU may accept a large enough offer α. Different from the discussion in Case 2, we have a total of three subcases. Similarly, we define

- $\alpha_h = \frac{1}{\frac{2R_s}{C_h P_s}-1} + \varepsilon$, where ε is an arbitrarily small positive number. This is PU's minimum offer that can attract a High type SU to help as the relay,
- $R_h = \frac{1-\alpha_h}{2} R_r$: the PU's single-slot utility if SU accepts α_h.

Theorem 2 summarizes the SE for two easy subcases.

Theorem 2: Consider a multi-slot bargaining game with $R_s/P_s \in (C_h, \infty)$. If $R_{dir} \in [R_l, \infty)$, PU always chooses direct transmission only regardless of the SU's type. If $R_{dir} \in [R_h, R_l)$, PU always offers α_l to SU. A High type SU rejects the offer, and a Low type SU accepts the offer.

In the two subcases in Theorem 2, PU's decision does not depend on its belief on the SU's type. The analysis of the multi-slot game can again be decomposed into N independent single-slot game. The proof of Theorem 2 is given in [11].

The only remaining subcase is $R_{dir} \in (0, R_h)$, where the multi-slot game cannot be decomposed. The PU and SU need to make decisions by considering both the history and the future decisions of each other. We will discuss this subcase in details in Section IV.

IV. Sequential Bargaining with Reputation Effect

In this section, we focus on investigating the sequential equilibrium when $R_s/P_s \in (C_h, \infty)$ and $R_{dir} \in (0, R_h)$.

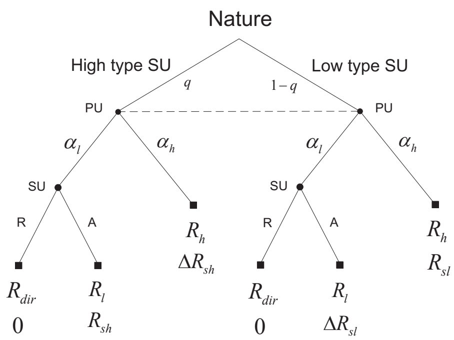

Fig. 3. Game Tree of the Single-Slot Bargaining with $R_l > R_h > R_{dir}$ and $C_l < C_h < R_s/P_s$

In this case, PU has *three* options: no offer(and thus direct transmission only), offer α_h, or offer α_l. Since R_{dir} is small in this case, PU will never choose "no offer" option. Thus we will discuss whether the PU will provide α_h or α_l in each time slot $n = N, \cdots, 1$.

A. Basic Analysis of the Single-Slot Bargaining Game

Before discussing the sequential equilibrium of the multi-slot game, let us first consider the game tree of the *single-slot* game as shown in Fig. 3. *Nature* moves first and determines the SU's type. PU and SU make decisions alternatively at the *non-leaf* nodes. The dotted line connecting two nodes means that the PU does not know the SU's type. Each possible game result is denoted by a *leaf* node (a black solid square) together with the corresponding PU utility (upper value) and SU utility (lower value). PU's belief (about SU's type) is $\Pr(C = C_h) = q$. Notations α_l, α_h, R_{dir}, R_l, R_h are defined in Section III. Here we further define

- $\Delta R_{sl} = \left(R_s - \frac{1}{2}P_sC_l\right)\varepsilon > 0$: the Low type SU's single-slot utility if accepting α_l,
- $\Delta R_{sh} = \left(R_s - \frac{1}{2}P_sC_h\right)\varepsilon > 0$: the High type SU's single-slot utility if accepting α_h,
- $R_{sh} = \alpha_l R_s - \frac{1+\alpha_l}{2}P_sC_h$: the High type SU's single-slot utility if it accepts the low offer α_l,
- $R_{sl} = \alpha_h R_s - \frac{1+\alpha_h}{2}P_sC_l$: the Low type SU's single-slot utility if it accepts the high offer α_h.

When ε approaches zero in the definitions of α_l and α_h, we have $R_{sh} < 0$ and $R_{sl} > 0$. Intuitively, a High type SU will not accept a low offer, while a Low type SU has the incentive to accept a high offer (and hence the discussion of reputation effect in the multi-slot game as in Section IV-B).

In Fig. 3, PU first decides to offer α_h or α_l. Then SU makes the acceptance (**A**) or rejection (**R**). If PU offers α_h, a SU will always accept it regardless of its type as $\Delta R_{sh} > 0$ and $R_{sl} > 0$. Hence there is only one leaf node following an offer α_h. If PU offers α_l, a High type SU will reject as $R_{sh} < 0$, and a Low type SU will accept since $\Delta R_{sl} > 0$.

By considering the SU's potential response, PU's *expected* utility if offering α_l is

$$U_p^{\alpha_l} = qR_{dir} + (1-q)R_l, \quad (5)$$

where q is the probability that the SU is the High type. PU's utility if offering α_h is R_h. Thus PU will offer α_l if $U_p^{\alpha_l} > R_h$, or equivalently $q < (R_l - R_h)/(R_l - R_{dir})$ (*i.e.,* the probability of having a High type SU is low).

B. Sequential Equilibrium (SE) of the Multi-Slot Bargaining

Now let us consider the multi-slot game, where the PU's belief might change over time (*i.e.,* q_n for time slot n instead of a fixed value q) based on the game history. The SU's behavior may also change depending on the game history and its anticipation of the future. In particular, a Low type SU may choose to reject α_l in a particular time slot even if the offer brings a positive single-slot utility. The purpose of such strategy is for a Low type SU to create a *reputation* of a High type SU and induce the PU to offer α_h in the future.

An SE of the multi-slot bargaining includes the following components: (i) The update of PU's belief q_n (*i.e.,* the probability of a High type SU) in time slot $n (= N, ..., 1)$, (ii) PU's strategy (offer α_l or α_h) in time slot n, (iii) SU's strategy (accept or reject) in time slot n. We summarize the sequential equilibrium in the following theorem. Here, we define the parameter

$$d = \frac{R_l - R_h}{R_l - R_{dir}} \in (0, 1). \quad (6)$$

Theorem 3: The sequential equilibrium of the multi-slot bargaining game is given in (a) to (l).

- **PU's Belief Updates:**[2]
  - (a) If $q_{n+1} = 0$, then $q_n = 0$.
  - (b) If $q_{n+1} > 0$ and SU accepts the high offer α_h in time slot $n+1$, then $q_n = q_{n+1}$.
  - (c) If $q_{n+1} > 0$ and SU accepts the low offer α_l in time slot $n+1$, then $q_n = 0$.
  - (d) If $q_{n+1} > 0$ and SU rejects the low offer α_l in time slot $n+1$, then $q_n = \max\left(d^n, q_{n+1}\right)$.
- **PU's Strategy:**
  - (e) If $q_n < d^n$ in time slot n, offers α_l.
  - (f) If $q_n > d^n$ in time slot n, offers α_h.
  - (g) If $q_n = d^n$ in time slot n, offers α_h with probability $\frac{\Delta R_{sl}}{R_{sl} - \Delta R_{sl}}$ and offers α_l with probability 1-$\frac{\Delta R_{sl}}{R_{sl} - \Delta R_{sl}}$.[3]
- **The High type SU's Strategy:**
  - (h) Always accepts α_h and rejects α_l.
- **The Low type SU's Strategy:**
  - (i) Always accepts α_h.
  - (j) If $n = 1$ (the last time slot), accepts α_l.
  - (k) If $n > 1$ and $q_n \geq d^{n-1}$, rejects α_l.
  - (l) If $n > 1$ and $q_n < d^{n-1}$, rejects α_l with probability $y_n = \frac{(1-d^{n-1})q_n}{d^{n-1}(1-q_n)}$ and accepts α_l with $1 - y_n$.

For proof of Theorem 3, see [11]. Next we will discuss the reputation effect emerging from Theorem 3.

[2]Recall that we index time backwards, and thus we will compute q_n based on q_{n+1} since time slot n is after time slot $n+1$. See Fig. 2.

[3]Since ε is an arbitrary small positive, thus ΔR_{sl} is arbitrarily small. Therefore, it is valid that $R_{sl} > 2\Delta R_{sl}$.

V. Reputation Effect Analysis

Theorem 3 provides a rich set of engineering insights and intuitions about the cooperative spectrum sharing as follows.

Remark 1: In game theory, a player's "reputation" is its opponents' current beliefs about its type [9]. In the multi-slot bargaining, the Low type SU's reputation can be understood as the PU's belief Pr(High type SU)=q_n in time slot n. The "reputation effect" refers to the fact that a Low type SU has incentive to reject α_l to create a reputation of a High type SU and get a higher total utility (see (k) and (l)). The incentive of doing so becomes higher when the bargaining lasts longer, *i.e.,* reputation effect is more likely to happen in long relationships than in short ones [9]. Therefore, we discuss such an effect when N is sufficiently large in this paper.

Since $d \in (0,1)$, then d^N can be arbitrarily small for a large enough N, and thus it is easy to satisfy the condition of $q_N = \eta > d^{N-1}$ even if the initial belief η (in the first time slot N) is small. From (k), the Low type SU will reject α_l during the initial time slot $n = N$. Anticipating this, the PU will offer α_h as in (f). As a result, a Low type SU receives a high offer α_h and gets the high utility R_{sl} in the first time slot.

Remark 2: We can define the probability $q_n^* = d^n$ as *the limiting belief*, which is the threshold for PU to decide whether to offer α_l or α_h as in (e), (f), and (g).[4] It can also be viewed as the SU's *limiting threshold reputation* as a High type in order to *deter* PU from offering α_l.

When the SU does not have a strong reputation yet (*i.e.,* $q_n < q_n^*$), it will choose to reject the low offer α_l with a certain probability to increase its reputation as in (l). By substituting $q_n = q_n^* = d^n$ into $y_n = \frac{q_n(1-d^{n-1})}{(1-q_n)d^{n-1}}$,[5] we have the *the balancing strategy* $y_n^* = \frac{d-d^n}{1-d^n}$, which denotes the probability that the Low type SU rejects α_l in time slot n to make the PU update its belief to $q_n = q_n^*$ and becomes indifferent between offering α_l and α_h. It indicates the Low type SU's willingness to sustain a reputation of a High type SU. Note that y_n^* is only relevant when the SU has a low reputation (lower than the limiting value q_n^*). In this case, the Low type SU needs to decide whether to improve its reputation or just accept the current offer α_l.

Figure 4 shows how the balancing strategy y_n^* evolves as the game proceeds. We choose three different values of $d = 0.4, 0.6, 0.7$. Note that the balancing strategies begin from $n = 5, 8, 11$, respectively. *Prior to these time slots, the Low type SU always rejects α_l as in (k) and does not need to randomize its action.* As the game approaches the end (i.e., the time slot index decrease from 20 to 1), y_n^* monotonically decreases and becomes zero in the last time slot ($n = 1$). This is consistent with the intuition that the SU puts a higher priority on getting a positive utility in the current time slot (by accepting α_l) over the potential higher future utility (by rejecting α_l and sustaining the reputation) when the game is closer to the end.

[4] In time slot n, the limiting belief q_n^* makes the PU's *expected* utility when offering α_l equal to the one when offering α_h. See [11] for details.

[5] Note that y_n in (l) includes the PU's belief q_n. As the SU has complete information, it can compute the PU's belief q_n in each time slot.

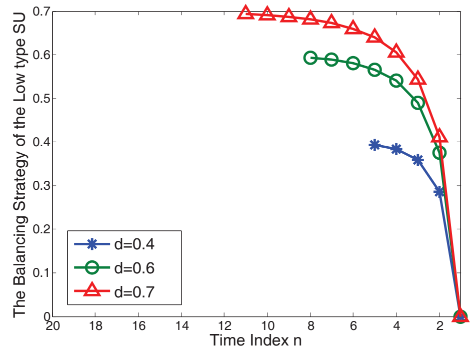

Fig. 4. The Balancing Strategy of the Low type SU for Different Values of d

VI. Conclusion

This paper studies a cooperative spectrum sharing mechanism achieved by a multi-slot spectrum bargaining between one PU and one SU. We model the bargaining as a dynamic Bayesian game, and characterize different types of equilibria under various system parameters. In particular, we discuss in details the reputation effect which is unique in a multi-slot dynamic game with incomplete information. The analysis shows that a Low type SU may obtain a higher total utility by establishing a strong reputation of a High type SU from the beginning of the game.

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