Chinese Journal of Aeronautics 25 (2012) 605-614

Contents lists available at ScienceDirect

Chinese Journal of Aeronautics

journal homepage: www.elsevier.com/locate/cja

Unlicensed Spectrum Sharing Game Between LEO Satellites and Terrestrial Cognitive Radio Networks

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Received 7 May 2011; revised 18 June 2011; accepted 29 August 2011

Abstract

By cognitive radio, the low Earth orbit (LEO) satellites may prefer to operate in the unlicensed spectrum which is open to all the users, and compete for the limited resources with terrestrial cognitive radio networks (CRNs). The competition can be regarded as a game and analyzed with game theory. This particular unlicensed spectrum sharing problem is modeled here, and the special properties of "spatially-distinguished-interference" and the short period of the interactions between satellites and terrestrial CRNs are explored. Then, the problem is formulated as a "partially-blind" finitely repeated prisoner's dilemma by game theory. Finally, we begin with two promising spectrum sharing schemes, which can be used to enforce the frequency reuse among the remotely located terrestrial CRN players as well as to overcome the observation noise. By analysis and comparison, it is proposed that the novel refreshing-contrite-tit-for-tat (R-CTFT) is the optimal spectrum sharing scheme. Simulation results verify that it can be used to utilize the spectrum most efficiently.

Keywords: satellite communication systems; cognitive radio; unlicensed spectrum sharing; spatially-distinguished-interference; finitely repeated prisoner's dilemma; partially-blind; refreshing-contrite-tit-for-tat

1. Introduction

The large communication satellite constellations such as Iridium and Globalstar have been providing communication services for years. They are constructed of tens of low Earth orbit (LEO) satellites and assigned with an exclusive communication spectrum band all over the world. However, it is hard to assign such a worldwide exclusive band to a small satellite constellation since spectrum is a scarce resource. Moreover, as suggested in the tactical satellite program, the small constellation or the single LEO satellite designed for small-scale and short-lived events should be available over the places of interest with responsive launch. Therefore, it is very important for us to adopt a more flexible spectrum assignment scheme.

Cognitive radio (CR) [1] is an emerging technology that can utilize the existing spectrum more efficiently with dynamic spectrum access (DSA). By cognitive radio, each LEO satellite can observe the available spectrum bands, learn how to use them, and eventually occupy some of them. However, terrestrial cognitive radio networks (CRNs) are developing very fast for commercial applications [2], so the satellites have to share the available spectrum with them. Therefore, the LEO satellites with CR technology and the users in CRNs belong to different authorities, have different goals, and thus will compete for the limited spectrum resources. Furthermore, the small LEO satellite constellation may prefer to operate and compete with the terrestrial CRN users in the unlicensed spectrum, such as the industrial, scientific and medical (ISM) band,

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Foundation item: Ministry Level Project

doi: 10.1016/S1000-9361(11)60425-1

because these bands are open to all the users.

Game theory is a mathematical tool used to analyze the strategic interactions among multiple decision makers. It is quite desirable to study CRNs in a game theoretic framework when centralized control is not available or flexible self-organized approaches are necessary [3]. The unlicensed spectrum sharing problem can be modeled as a repeated game because of the long-term interactions among the players. A repeated game is composed of several stages, and each of them is a repetition of the same strategic-form game. The number of the stages can be finite or infinite.

Therefore, we analyze the unlicensed spectrum sharing game between LEO satellites and terrestrial CRNs with game theory, and provide a solution to the efficient allocation as well. The solution can provide the extra spectrum resources so that the LEO satellite can keep communicating even in the crowded spectrum. This will improve the reliability of the LEO satellite communication system. Furthermore, we will explain in Section 2 that the environmental variation will not degrade the performance seriously.

Some previous works have been devoted to the unlicensed spectrum sharing game. In Ref. [4], the achievable rate in the game was obtained with the assumption that the game is infinitely repeated and the Gaussian interference channels (GICs) are time-invariant. The strategy suggested to all the players was Grim-trigger. This work was extended to prevent the players from cheating with the “punish-and-forgive” strategy [5]. With this strategy, the game stays in cooperation stage until the opponent defects. Then the game jumps into the punishment for the next $T-1$ time slots and cooperation resumes from the Tth time slot. For an N-player infinite game [6], a strategy based on carrot-and-stick strategy was also designed. With the strategy the cooperation only recovers when all the players defect. Furthermore, the access probability was introduced to affect the players’ utility in Ref. [7].

Although these unlicensed spectrum sharing schemes have improved the spectrum usage efficiency, they can only be applied to the particular infinitely repeated games in which any player in the game has mutual interference with anyone else. Furthermore, these schemes cannot overcome the observation noise. However, for the unlicensed spectrum sharing problem between LEO satellites and terrestrial CRNs, the repeated game is quite different: the number of the stages is finite and the interference among the players is “spatially-distinguished”. And we will take into account the observation noise as well. Therefore, this new problem should be modeled and formulated, and the corresponding spectrum sharing scheme should be developed.

There are many recent developments in the research of the spatial prisoner’s dilemma [8-13], which seems to be similar to the game formulated in Section 3 for our problem, i.e., the “partially-blind” (PB) finitely repeated prisoner’s dilemma. However, the neighbors in the spatial game will just need to cooperate, namely they do not need to coordinate as the CRN players in a PB game to reuse the frequency band. Moreover, the LEO satellites in the PB game can move fast by a pre-selected route while the other players are almost fixed in most cases. Therefore, we need to develop the new method to solve this problem.

2. System Model

As we focus on the small LEO satellite constellation, the LEO satellites cannot cover any particular area all the time. That is to say, for our problem, the main difference between the small constellation and the single LEO satellite is the duration of the gaps between passes. Therefore, it is reasonable to reduce the small constellation to a single LEO satellite for a simpler system model. As a result, we consider a situation where one single LEO satellite coexists with the terrestrial CRN users in the same area and competes for the same unlicensed spectrum band. We assume that the band is totally $2W$ as shown in Fig. 1. An LEO satellite BS1 passes by the area where two terrestrial CRN users BS2 and BS3 exist. The satellite can interfere with the two users. However, none of the two terrestrial CRN users can interfere with the other one or sense the other’s existence in many practical cases since the signals can be deeply attenuated within a short range. It is because of the slow fading and fast fading caused by the obstacles between transmitters and receivers such as buildings, mountains, etc. We call this property “spatially-distinguished-interference” (SDI) which will lead to low spectrum efficiency. From Fig. 1 we can see that BS2 and BS3 occupy different bands without any coordination. Then, BS1 will definitely interfere with the terrestrial CRN users whichever band it chooses. This spectrum allocation is quite inefficient since BS2 could have reused the frequency with BS3 which is remotely located. Therefore the inefficient frequency reuse due to SDI causes the inefficient spectrum sharing.

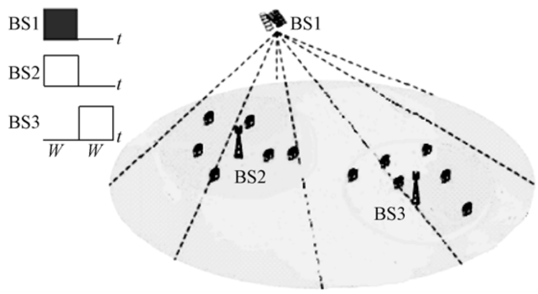

Fig. 1 Model of unlicensed spectrum sharing game between LEO satellites and terrestrial CRNs.

Furthermore, the LEO satellite exists in this area only for a short period because it moves at very high speed. This period is typically of 10 min with an orbital height of 1 000 km and an elevation of 5°. The short interaction period will lead to a finitely repeated game and possibly a bad equilibrium of the game in the end.

We assume that the CR users share the same band by piece-wise constant power allocation. For example, if a CR user has sensed that there are M−1 users to interfere with, it will choose to occupy multiples of 1/M of the band. This assumption is reasonable since each player can be aware of the number of the competitors. Each player would be willing to broadcast its existence if there is an efficient equilibrium to arrive at. The further explanation can be found in Section 4.

Finally, we assume that the channels are flat fading with Gaussian interference. It is reasonable to assume that the channels are flat fading because the propagation of the radio between satellites and terrestrial CRN users is line-of-sight in most cases. We also assume that the users use random Gaussian codebook to achieve the channel capacity, and thus each user can treat the received interference as white noise [4].

We model a situation in which each system is formed by a single transmitter-receiver pair. Each pair could be called a user here. For an M-user flat fading Gaussian interference channel in discrete time, the received signal of user i at time n is

$$y_i[n]=\sum_{j=1}^{M} h_{j,i}x_j[n]+z_i[n] \qquad (i=1,2,\cdots,M) \tag{1}$$

where y_i is the received signal of user i, $h_{j,i}$ the channel gain from user j to user i, x_j the transmitted signal or interference from user j, and the noise process is independently identical distributed over time with the zero mean Gaussian distributed random variables z_i. M is the number of all the users, which should be greater than one.

Under these assumptions, we can determine the maximum rate that user i can achieve over specific power allocations (R_i , b/s) as

$$R_i=\int_0^{2W}\log_2\left(1+\frac{c_{i,i}p_i(f)}{N_0+\sum_{j\neq i}c_{j,i}p_j(f)}\right)\mathrm{d}f \tag{2}$$

where $c_{j,i} = |h_{j,i}|^2$, which represents the channel power gain from player j to i. N_0 is the noise density, and the power spectral density of the transmitted signal of user i, $p_i(f)$, is restricted by the maximum transmitted power Pt_i:

$$\int_0^{2W} p_i(f)\mathrm{d}f \le \mathrm{Pt}_i \tag{3}$$

According to SDI, for BS1-BS3 in Fig. 1 we can assume $c_{i,i}$ = 1, $c_{1,2} = c_{2,1} = c_{1,3} = c_{3,1}$ = 1/4, $c_{2,3} = c_{3,2}$ = 0, W = 1 (2W in total) , N_0 = 1, $\mathrm{Pt}_1 = \mathrm{Pt}_2 = \mathrm{Pt}_3 = P$.

We also assume that the power is uniformly distributed, i.e., $p_i(f) = P$ for player i occupying W and $p_i(f) = P/2$ for 2W.

This model will be extended without loss of generality in Section 3 to the case of one satellite and two pairs of terrestrial CRN players sharing the spectrum.

Moreover, it is worth mentioning that the environmental variation will not degrade the scheme performance seriously, because the environment does not change frequently. The CRN base stations are practically assumed to work permanently in most cases. Furthermore, the terrestrial CRN users covered by the satellite do not change rapidly as the satellite moves, since the area covered is very large. For example, a typical LEO satellite, such as the satellite in Iridium, is 780 km high and has each beam more than 600 km in diameter. Thus, we assume the smallest beam and the following results can be obtained.

The velocity of the satellite v is about 7.45 km/s, and the velocity of the projection on the ground v_{p} is about 6.65 km/s. Therefore, as the satellite moves, the varying rate of the covered area $\delta A/\delta t$ is about 1 995 km^2/s, namely 0.7% of the whole area per second.

One of the worst cases is that the CRN base stations are uniformly distributed, such that the change is sustained. Thus, we can assume that the base stations are uniformly distributed and the following results can be obtained.

The time required for the environment to vary for 10% is about 14 s.

However, this time can be much larger in practice since most of the terrestrial CRN users gather in cities or towns [2]. And, the change will affect the equilibrium of the spectrum sharing game only if the satellite enters the cities or towns. When the satellite leaves, the interference decreases, and the satellite does not need to change its channel.

Therefore, this channel variation will not degrade the performance seriously since the services provided by small LEO satellite constellations are mainly burst transmissions, which are non-real-time and last only for several seconds to several tens of seconds.

3. Problem Formulation

In this section, we formulate the problem as a special game. We assume that all the players are rational. In other words, players would try to selfishly maximize their own interest, but they would not be malicious. We first prove that the single stage spectrum sharing game with SDI is actually a prisoner's dilemma. Then, we attribute the multi-stage game to the finitely repeated prisoner's dilemma due to the short interaction period. Finally, considering the effect of SDI on the observation, we formulate the problem as a PB finitely repeated prisoner's dilemma.

3.1. *Single stage game*

In a single stage game, all the players only care about their current payoffs. The set of strategies ($s_1^*, s_2^*, \cdots, s_i^*, \cdots, s_K^*$) is called a Nash equilibrium [14] if and only if for all possible strategies, the strategy utilities always satisfy:

$$U_i(s_1^*, s_2^*, \cdots, s_i^*, \cdots, s_K^*) \ge U_i(s_1^*, s_2^*, \cdots, s_i', \cdots, s_K^*) \tag{4}$$

The Nash equilibrium provides a stable point from which no individual would have any incentive to deviate.

For the spectrum sharing game, the critical issue is to make an agreement on how to share the spectrum among the players. The specific channel allocation will be easily implemented if all the players have reached such an agreement. With the agreement, each player will just take its share and occupy the corresponding vacant spectrum.

In our model, the players in Fig. 1 have the available strategies of occupying either only one band (W) or all the two bands ($2W$). Occupying more bands can bring higher capacity, but it will also introduce more interference at the same time. We prove that the single stage game with SDI is actually a prisoner's dilemma [14].

Deduction 1 With the assumptions in Section 2, we formulate the single stage problem with three primary components:

1) Set of players: $N = \{\text{BS1, BS2, BS3}\}$.

2) Strategy space: $S = \{W, 2W\}$.

3) Payoff utility function: $U_i = 2^{R_i}$ (i = 1, 2, 3), where

$$R_i = \int_0^{2W} \log_2 \left(1 + \frac{p_i(f)}{1 + \sum_{j \neq i} c_{j,i} p_j(f)}\right) \mathrm{d}f \tag{5}$$

The capacity R_i could be replaced by its monotonic increasing function U_i for simplicity.

The capacities approximate the upper bounds as the power P approaches infinity. Therefore, we can get the utility bounds of all the strategy sets. For example, if the strategies are $\{W, W, 2W\}$, satellite BS1 will avoid interfering with BS2 but have to interfere with BS3. We can calculate the utility bound of BS3:

$$R_3 = \lim_{P \to \infty} [\log_2 (1 + \frac{P/2}{1 + P/4}) + \log_2 (1 + P/2)] =$$
$$\log_2 (3) + \log_2 (1 + P/2) = \log_2 (3 + 1.5P)$$
$$U_3 = 2^{R_3} = 3 + 1.5P$$

Therefore, we can calculate all the payoff utility bounds according to the system model, and use two 2-player game matrices in Fig. 2 to represent the game of three players ($P \to \infty$).

(a) BS1=W

BS2 \ BS3	W	$2W$
W	$1+P, 1+P, 1+P$	$9, 1+P, 3+1.5P$
$2W$	$9, 3+1.5P, 1+P$	$5, 3+1.5P, 3+1.5P$

(b) BS1=$2W$

BS2 \ BS3	W	$2W$
W	$2+P$, 9, 9	11.7, 8, 16
$2W$	11.7, 16, 8	9, 25, 25

Fig. 2 The 3-player game model with SDI.

The Nash equilibrium of this game is the non-cooperative strategy set $\{2W, 2W, 2W\}$ with the utility set {9, 25, 25}. This stable outcome is inefficient for all the players. However, the Pareto optimal strategy set is $\{W, W, W\}$. Therefore, this single stage game can be attributed to the prisoner's dilemma [14].

3.2. Finitely repeated prisoner's dilemma

Different from the rational players in an infinitely repeated prisoner's dilemma, those in a finitely repeated prisoner's dilemma have no incentive to cooperate in any single stage. This result can be inferred from the backward induction [15].

In a finitely repeated game, there is an end in the game. At the final stage, each rational player will certainly spread its power over all the $2W$ band since defecting dominates cooperating when there is no future payoff. Then in the next to the last stage, defecting does better than cooperating again because the choice at this stage cannot affect the outcome at the final stage. Thus, defecting will also be adopted by the players in the third stage from the end. As a result, the players will defect in each stage.

3.3. PB game

In normal games, we assume that players can observe the other players' strategies. However, in Fig. 1 either BS2 or BS3 cannot observe the other's strategies because of SDI. Furthermore, the satellite will enter the game without any information in advance if the satellite does not broadcast its entrance, so the terrestrial CRN players cannot observe the satellite's entrance. Therefore we call it the PB observation.

The PB observation can be further illustrated in Fig. 3, which can be regarded as an extension of the model in Fig. 1. There are four pairs of people and an additional person talking in Fig. 3. Pairs A, B and pairs C, D are separated by a soundproofing wall, and E is at the end of the wall. Suppose that people can avoid interference only by talking in a different tone. When E is not talking, people at the same side can cooperate by equally dividing the available tones. However, when E suddenly starts to talk, any pair cannot tell whether it is the other pair's defecting at their side or E's entrance. In the first case the interference will definitely lead to the deviation from the cooperation, but in the second case the players could establish a new cooperation state with E. Moreover, the two pairs at each side should reuse the same tones so as to leave some free tones for E if the players would like to communicate without any interference to achieve larger capacities. The frequency reuse may lead to some coordination overhead, and we need to design a scheme to avoid the overhead as much as possible.

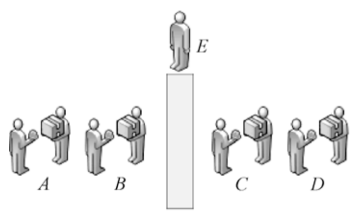

Fig. 3 PB observation model.

Therefore, this problem is formulated as a PB finitely repeated prisoner's dilemma.

4. Spectrum Sharing Schemes

In this section, we propose the optimal spectrum sharing scheme refreshing-contrite-tit-for-tat (R-CTFT) for the game. This scheme contains the strategies that are based on tit-for-tat (TFT). Tit-for-tat is an English saying meaning "equivalent retaliation". The strategy TFT includes the following four items:

1) Unless provoked, the player will always cooperate.

2) If provoked, the player will retaliate.

3) The player is quick to forgive.

4) The competition continues long enough for repeated punishment and forgiveness.

TFT was designed for the finitely repeated prisoner's dilemma in the game theory, whereas grim-trigger [4] was designed for the infinite one. TFT can be viewed as an improved version of grim-trigger because grim-trigger only has the first and second items in the list. And TFT is more practical since there is not any infinite game in the real world.

TFT is a strikingly simple and quite natural strategy, but it emerged as the most efficient strategy for the finitely repeated prisoner's dilemma [15]. The dilemma will be self-enforced to an efficient equilibrium [15] if some players in the game take this strategy. Then all the players will take TFT strategy and cooperate with the others at this equilibrium.

One of the possible processes is described as follows with which the terrestrial CRN players (without any satellite) can arrive at the efficient equilibrium and share the unlicensed spectrum efficiently:

We first assume that each terrestrial CRN base station possesses an identification (ID) number to construct a network. The ID numbers can be related to some reputation information. It is proposed that each CRN player would be willing to broadcast its ID number since there is an efficient equilibrium to arrive at. On the other hand, each CRN player would be willing to take TFT in order to cooperate with the other known competitors because most terrestrial CRN base stations are supposed to keep working for a period that is long enough to meet the fourth item in the requirement list of TFT, and the efficient equilibrium is beneficial to all the players. With this process, the base stations with good reputations can cooperate with the others once they begin to work.

However, things are different when it comes to the unlicensed spectrum sharing game between LEO satellites and terrestrial CRN users. Firstly, LEO satellites may not be willing to broadcast their ID numbers since most of them are intended for some special use such as the military use. Secondly, terrestrial CRN players may not be willing to cooperate with LEO satellites since the period of the interaction between them is so short that it may not meet the fourth item in the requirement list of TFT. Thirdly, they cannot arrive at the efficient equilibrium even if the satellites broadcast their ID numbers and the terrestrial CRN players are willing to cooperate. This is because the frequency cannot be efficiently reused due to SDI and the corresponding PB observation. Although the PB observation can be overcome by the coordination among satellites and terrestrial CRN users, the overheads will severely degrade the performance of the LEO satellites.

Therefore, it is a crucial problem to enforce the efficient unlicensed spectrum sharing between LEO satellites and terrestrial CRN users without a specific ID number and overcome the PB observation without any coordination overhead as well.

Moreover, TFT is an efficient strategy, but the performance can be easily lowered by the observation noise. Contrite-tit-for-tat (CTFT) and generous-tit-for-tat (GTFT) are the most efficient general versions of TFT that can be used to cope with the observation noise in the game theory [16]. Therefore, we should also take the observation noise into consideration in our game.

We first design the scheme refreshing-tit-for-tat (R-TFT) which can help enforce the efficient spectrum sharing under the noiseless PB observation. This scheme can help enforce the efficient frequency reuse to overcome the PB observation without any satellite ID number or coordination overhead. In R-TFT, the "refreshing" process is added before the efficient equilibrium is approached. Furthermore, in order to overcome the observation noise, we suggest two promising spectrum sharing schemes refreshing-generous-tit-for-tat (R-GTFT) and R-CTFT which are based on GTFT and CTFT. Finally, we prove that R-CTFT dominates R-GTFT with noisy PB observation in our game. Therefore we propose that R-CTFT is the optimal scheme for our problem.

4.1. Noiseless PB observation

The establishment of the efficient equilibrium carried out by R-TFT can be illustrated as shown in Fig. 4, which is later named as the "refreshing" process. The satellite player first spreads its power all over the unlicensed spectrum since its entrance (Figs. 4(a)-4(b)). It keeps spreading until the previous cooperation state breaks (Fig. 4(c)). Then it begins to cooperate and broadcast its entrance in order to setup a new cooperation state (Figs. 4(d)-4(e)). On the other hand, the terrestrial CRN players just take the normal strategy (TFT here) (Fig. 4). They regard the satellite entrance as some other terrestrial CRN players' defection because they have no prior knowledge about it. Thus they defect in Fig. 4(c), and will return to cooperation after the satellite cooperates and broadcasts its entrance (Fig. 4(e)).

Here an ID number is not necessary for the satellite to broadcast its entrance. This is because the ID numbers are used to convey some reputation information before the player enters the game. But the satellite has built up a good reputation immediately by its behavior after cooperating regardless of the others' actions.

Therefore, the satellite BS1 can successfully enforce the frequency reuse by "refreshing" the cooperation state and finally share the unlicensed spectrum efficiently without any coordination overhead. The terrestrial CRN players also benefit from this scheme since the sooner they set up the new cooperation state, the less interference from the satellite they will receive. After the establishment of the efficient equilibrium, all the players can just take the normal strategies (TFT here) to maintain the cooperation. Therefore the scheme R-TFT is an efficient and stable solution to the efficient spectrum sharing under the PB observation.

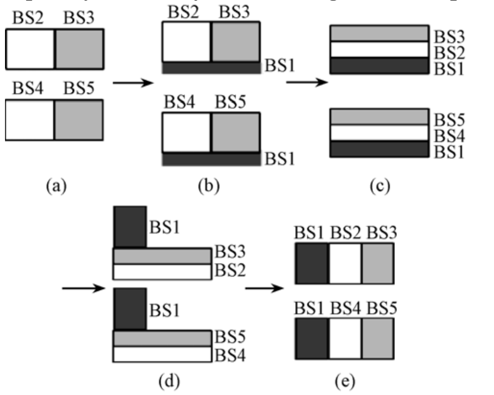

Fig. 4 Efficient equilibrium carried out by R-TFT.

4.2. Noisy PB observation

GTFT and CTFT are the general versions of TFT, which can be used to cope with the observation noise most efficiently [16].

GTFT is the same strategy as TFT except that it allows the player to forgive the opponent with a probability even if it is provoked.

CTFT has three states, i.e., content, provoked and contrite.

1) Content: the player begins in content with cooperation and stays there unless there is a unilateral defection.

2) Provoked: if the player is the victim while the content state is broken, it becomes provoked and defects until cooperation from other players causes it to become content.

3) Contrite: if it is the defector while the content state is broken, it becomes contrite and cooperates.

This strategy is based on the idea that one should not be provoked by the other player's response to one's own unintended defection. It can be figured out whether the defection was unintended or not just by watching the outcome, i.e., the payoff utility.

The simulation in Ref. [16] shows that GTFT is better than CTFT at lower noise levels, but when the noise is greater than 1%, CTFT is better.

We propose two schemes, R-GTFT and R-CTFT, to enforce the frequency reuse under the noisy PB observation. The strategies in the schemes are mainly based on GTFT and CTFT. In R-GTFT and R-CTFT, the same "refreshing" process is added as in R-TFT before the efficient equilibrium is approached. After the establishment of the efficient equilibrium, all the players can just take the normal strategies (GTFT or CTFT here) to maintain the cooperation.

We first prove that R-CTFT is more efficient than R-GTFT for the terrestrial CRN players. Next, we show that the satellite players also prefer R-CTFT. Thus, R-CTFT is the optimal scheme for our problem.

Deduction 2 We assume that for the terrestrial CRN players, the opponent, namely the other player in the pair in Fig. 3, has the perfect observation. That is to say the terrestrial CRN opponent has no observation noise.

From Fig. 2 we can see that the single stage game is a prisoner's dilemma for all the players, even if there is a satellite that has already entered the game. However, the game is different when there is a satellite entering the game. In the "refreshing" process, the satellite will keep spreading its power over the whole spectrum until the previous cooperation state breaks. Then, before all the players' defecting, the game is not a prisoner's dilemma. In this game, defecting dominates cooperating, and it is optimal for all the players to defect. Thus, they would like to defect as quickly as possible.

Therefore, the exact number of the players will not affect the results of the games, namely either all defecting or all cooperating. We can simplify the games by separating the players into two groups that will choose to cooperate or defect. Each player could choose to join either group at each game stage.

Moreover, we can simplify the games by replacing the exact utility values with some values that can represent the characteristics more clearly. The prisoner's dilemma can be represented by the left matrix in Fig. 5, and the other game can be represented by the right matrix.

(a) No-entering	Cooperate	Defect
Cooperate	3, 3	0, 5
Defect	5, 0	1, 1

(b) Entering	Cooperate	Defect
Cooperate	−4, −4	−4, −1
Defect	−1, −4	1, 1

Fig. 5 Utility table.

We also have

1) False observation probability: p.

2) Forgiving probability in R-GTFT: q.

3) Opponent's false observation probability: 0.

4) Satellite entering probability: e.

The state transition diagram of the spectrum sharing game can be shown in Fig. 6, where P_i stands for the

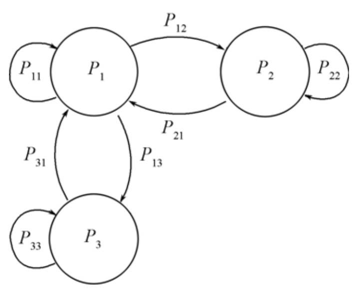

Fig. 6 State transition diagram of the spectrum sharing game.

probability of the state S_i, $P_{i,j}$ the probability of the transition from S_i to S_j. In most practical situations, the terrestrial CRN players are cooperating when the satellite enters. Thus we reduce the transitions between S_2 and S_3 for simplicity. Define the states:

1) Opponent cooperating without entrance: S_1.
2) Opponent defecting without entrance: S_2.
3) Satellite entering: S_3.

Calculate the steady state probabilities:

$$\begin{bmatrix} P_1 \\ P_2 \\ P_3 \end{bmatrix} = \begin{bmatrix} P_{11} & P_{21} & P_{31} \\ P_{12} & P_{22} & 0 \\ P_{13} & 0 & P_{33} \end{bmatrix} \begin{bmatrix} P_1 \\ P_2 \\ P_3 \end{bmatrix} \tag{6}$$

The mean utility can be calculated as

$$\text{Mean} = \text{Mean}(S_1)P_1 + \text{Mean}(S_2)P_2 + \text{Mean}(S_3)P_3 \tag{7}$$

In R-GTFT, we have the transition probabilities:

$$\begin{cases} P_{11} = (1-e)(1-p+pq) \\ P_{12} = (1-e)p(1-q) \\ P_{13} = e \\ P_{21} = P_{33} = (1-p)q + p \\ P_{22} = P_{31} = (1-p)(1-q) \end{cases} \tag{8}$$

The mean values of the state utilities are

$$\begin{cases} \text{Mean}(S_1) = (1-e)\{3[(1-p)+pq]+5p(1-q)\} + 0\cdot e \\ \text{Mean}(S_2) = (1-p)(1-q) + 0\cdot[(1-p)q+p] \\ \text{Mean}(S_3) = -4[(1-p)q+p] + (1-p)(1-q) \end{cases} \tag{9}$$

While in R-CTFT, the transitions are more predictable. The terrestrial CRN players have three states, namely content, provoked and contrite. In the provoked or the contrite state, the players will keep defecting or cooperating until the state transits. Therefore, the transition probabilities in R-CTFT are

$$\begin{cases} P_{11} = (1-e)(1-p) \\ P_{12} = (1-e)p \\ P_{13} = e \\ P_{22} = P_{33} = p \\ P_{21} = P_{31} = 1-p \end{cases} \tag{10}$$

The mean values of the state utilities are

$$\begin{cases} \text{Mean}(S_1) = (1-e)[3(1-p)+5p] + 0\cdot e \\ \text{Mean}(S_2) = p + 0\cdot(1-p) \\ \text{Mean}(S_3) = -4p + (1-p) \end{cases} \tag{11}$$

Thus, we can plot the utility curves of R-GTFT and R-CTFT given a certain false observation probability in Figs. 7-8. When there is no satellite entering, the performance of R-GTFT can be improved by increasing the forgiving probability. In that case, R-GTFT can perform better than R-CTFT as shown in Fig. 7. However when the satellite entering probability is nonzero, increasing the utilities in state S_1 and S_2 of R-GTFT by increasing the forgiving probability comes at the price of decreasing the utility in state S_3, and vice versa. It means that the performance of R-GTFT is limited by the trade-off between the non-satellite state utility and the satellite entering state utility. This trade-off curve is represented by the utility curve of R-GTFT in Fig. 8. The trade-off curve shows that the utility curve of R-GTFT is bounded and cannot be higher than that of R-CTFT. Therefore, R-CTFT is strictly better than R-GTFT for the terrestrial CRN players.

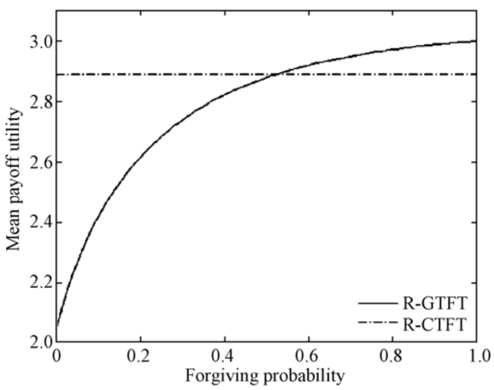

Fig. 7 Utility curves without satellite entrance (e = 0) with the false observation probability 0.01.

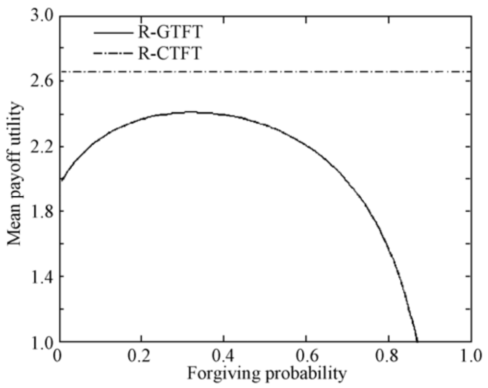

Fig. 8 Utility curves with satellite entrance (e = 0.05) with the false observation probability 0.01.

On the other hand, the satellite players will also prefer R-CTFT. We can setup the new cooperation sate in a more efficient way by R-CTFT rather than R-GTFT, since the probability of the transition from S_3 to S_1 is larger in R-CTFT. Moreover, after the establishment of the new cooperation state, the satellite can be regarded as a terrestrial CRN player and it will also prefer R-CTFT.

Therefore, R-CTFT is proposed as the optimal spectrum sharing scheme for our game. This scheme can be viewed as the equilibrium, from which no player would like to deviate, and the players in R-CTFT can share the spectrum efficiently and stably.

5. Simulation Results

In this section, we conduct numerical simulations to evaluate the proposed spectrum sharing schemes. The payoff utilities corresponding to the strategies are the same as shown in Fig. 5. But the state transitions are not the same as shown in Fig. 6. The transitions between S_2 and S_3 are included here for more accurate results.

We first look into the problem with the noiseless PB observation. There are two terrestrial CRN players and one satellite player in the game. We assume that the players are taking R-TFT scheme. Figure 9 shows a terrestrial CRN player's payoffs. The variation of the payoffs reflects the interactions among the players. The satellite enters when the payoff falls down to −4, whereas the cooperation state is successfully "refreshed" when the payoff grows back to 3. Therefore, according to the simulation, R-TFT can be used to deal with the noiseless PB observation and enforce the frequency reuse among the terrestrial CRN players.

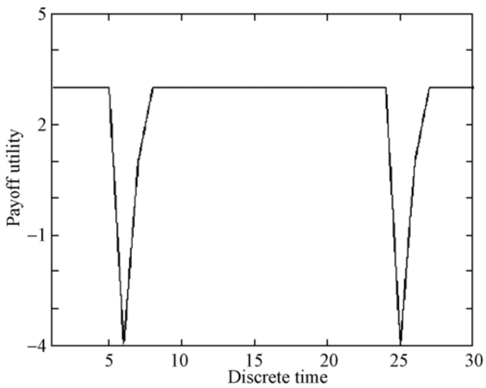

Fig. 9 Illustration of R-TFT with noiseless PB observation.

Then, we take into consideration the observation noise. The effect of the observation noise on R-TFT is, however, shown in Fig. 10. The payoff will swing between peaks and valleys after the false observation. And the game may converge to a less efficient equilibrium which has a payoff of 1 instead of 3.

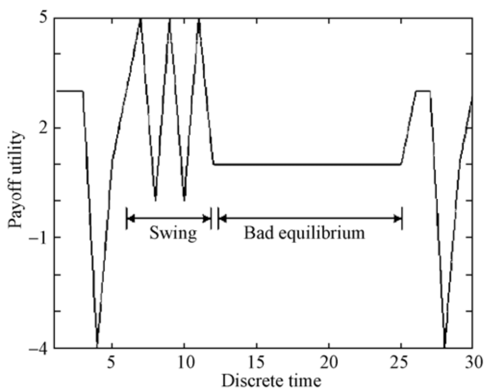

Fig. 10 Illustration of R-TFT with noisy PB observation.

Therefore, we design two schemes, R-GTFT and R-CTFT, which are based on the most efficient anti-noise strategies. Figures 11-12 show the payoffs of R-GTFT and R-CTFT with the noisy PB observation. The swing due to the noisy observation is removed in these schemes. It means that these schemes are successful in coping with the noise.

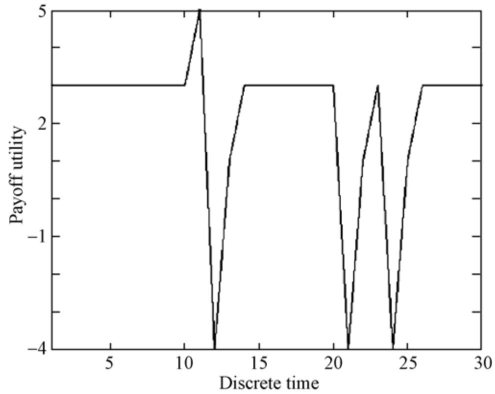

Fig. 11 Illustration of R-GTFT with noisy PB observation.

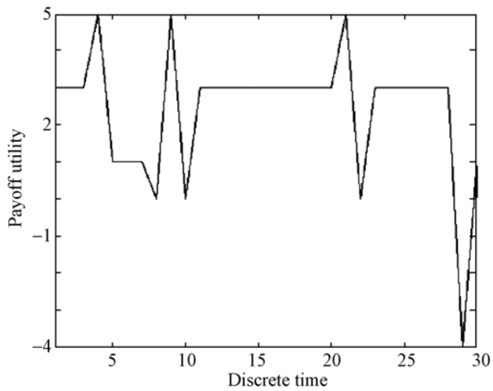

Fig. 12 Illustration of R-CTFT with noisy PB observation.

Next, we compare these two schemes for the terrestrial CRN players with a certain noise level and satellite entering probability. Figure 13 shows the payoffs without any satellite entrance, whereas Fig. 14 shows the payoffs with a nonzero satellite entering probability. The payoffs of R-GTFT can be higher than those of R-CTFT with a large forgiving probability when there is no satellite entrance. However, the performance of R-GTFT is restricted when there is a satellite entering the game at some time. In Fig. 14, R-GTFT is dominated by R-CTFT and the performance of R-GTFT cannot be improved by increasing the forgiving probability.

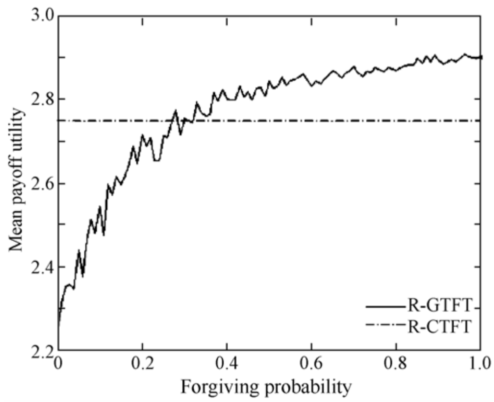

Fig. 13 Comparison for terrestrial CRN players without satellite entrance.

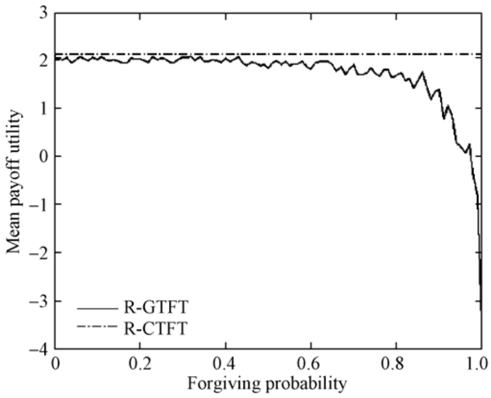

Fig. 14 Comparison for terrestrial CRN players with satellite entrance.

We also conduct simulations for spectrum sharing with different noise levels (i.e., different false observation probabilites) and satellite entering probabilities to further explore the performance of R-GTFT and R-CTFT. It can be shown in Figs. 15-16 that R-CTFT dominates R-GTFT with different false observation probabilities or satellite entering probabilities.

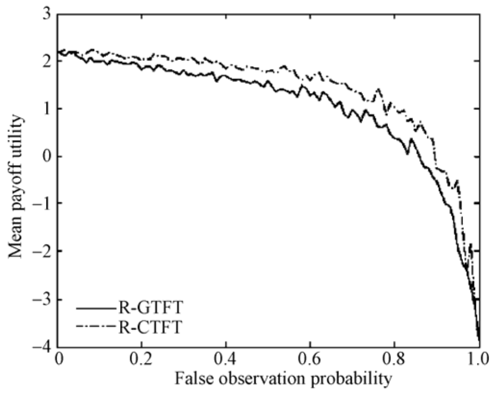

Fig. 15 Comparison for terrestrial CRN players with different false observation probabilities.

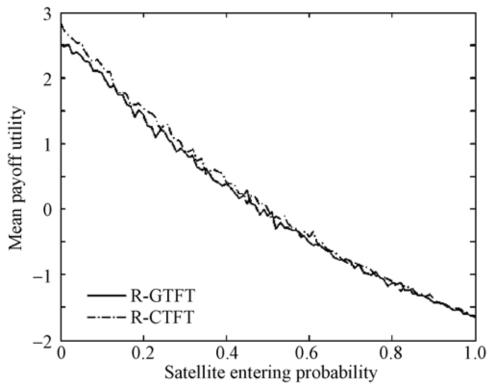

Fig. 16 Comparison for terrestrial CRN players with different satellite entering probabilities.

Finally, we verify that R-CTFT is better for the satellite players as well. In Fig. 17, R-CTFT is faster than R-GTFT in the "refreshing" process of the cooperation state whatever the observation noise is. After the establishment of the new cooperation state, the satellite will evaluate the strategy in the same way as the terrestrial CRN players. Therefore, both the terrestrial CRN players and the satellite players prefer R-CTFT, and they will not deviate from the scheme. By R-CTFT, all the players in the game can share the unlicensed spectrum efficiently and stably.

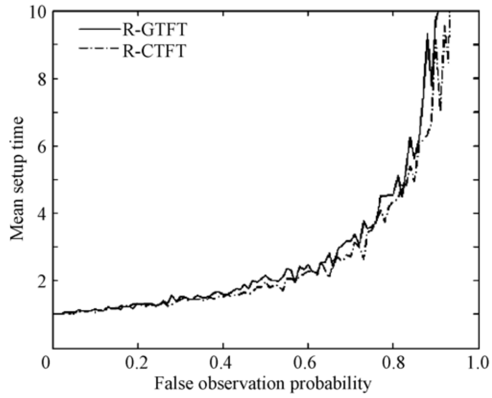

Fig. 17 Comparison for satellite players with different false observation probabilities.

6. Conclusions

We have proposed a novel spectrum sharing scheme to stably improve the efficiency of the unlicensed spectrum sharing game between LEO satellites and terrestrial CRN players. We model the problem, explore two special properties of the problem and formulate the problem as a PB finitely repeated prisoner's dilemma. Then, we propose that R-CTFT is the optimal spectrum sharing scheme for the game. This scheme can be used to enforce the frequency reuse among the remotely located terrestrial CRN players without any coordination overhead as well as to overcome the observation noise. Simulation results verify that the proposed scheme has stably improved the spectrum usage in the most efficient way.

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