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Distributed Relay Selection and Channel Choice in Cognitive Radio Network

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Abstract—In this paper, we study the cooperative communications where multiple cognitive radio (CR) transmit-receive pairs competitive maximize their own throughputs. In CR networks, the influences of primary users and the spectrum availability are usually different among CR users. Due to the existence of multiple relay nodes and the different spectrum availability, each CR transmit-receive pair should not only select the relay node but also choose the appropriate channel. For this distributed problem, we propose a game theoretic framework to formulate this problem and we apply a regret-matching learning algorithm which is leading to correlated equilibrium. We further formulate a modified regret-matching learning algorithm which is fully distributed and only use the local information of each CR transmit-receive pair. This modified algorithm is more practical and suitable for the cooperative communications in CR network. Simulation results show the algorithm convergence and the modified learning algorithm can achieve comparable performance to the original regret-matching learning algorithm.

Keywords—cognitive radio; cooperative communication; relay selection; channel choice; regret-matching learning; correlated equilibrium.

I. Introduction

In recent years, there has been an exponential growth of wireless devices and technologies, creating a dramatic increase in demand for the limited spectrum. However, today's spectrum is managed under a fixed assignment policy, which is highly inefficient in terms of spectrum utilization [1][2]. Different from traditional radios, cognitive radios are capable of sensing their environments and promptly reconfiguring their communication parameters based on their observations [3][4][5]. Cooperative communications have gained much attention as an emerging transmission strategy for future wireless networks. Cooperative communication exploits the spatial diversity inherent in multi-user systems by allowing users relay each other's data to the destination [6]. The relay selection of cooperative communication has been investigated in ref. [7,8,9,10,11]. In ref. [7], the authors propose a distributed relay selection scheme that requires limited network knowledge with instantaneous signal-to-nose ratio (SNR). In ref. [8], the relay assignment problem is solved for the multiuser cooperative communications. The authors of ref. [9,10] investigate the relay selection problem with focus on when to cooperate and which relay to cooperate with, which requires channel state information (CSI). In ref. [11], the authors propose a distributed game-theoretical framework over multiuser cooperative communication networks to achieve optimal relay selection and power allocation without knowledge of CSI.

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However, most existing work focus on centralized fashion and even the distributed game-theoretical framework still need negotiation among users. We carefully note that in CR network, the CR transmitter and receiver not only have difference in available spectrum, but also have distance in space. Therefore, the problem of relay selection is important in CR network. Furthermore, due to the variability of the CR network, the fully distributed relay selection is more practical. ref.[12,13] investigate the cooperative relay in CR networks. The authors in ref.[12] introduce the cognitive relay node into the secondary communication and propose a cooperative relay scheme to share the spectrum of relay nodes. However, the cognitive relay selection has not been investigated. The authors in ref.[13]propose an infrastructure-based secondary network architecture to increase the throughput of the whole CR network. In this centralized architecture, the relay node can be selected to bridge the source and the destination.

In CR network, due to the difference of available spectrum and the distance of space, the cognitive relay selection should not only choose the relay node but also choose the available spectrum. In addition, there are multiple transmit-receive pairs in the CR network and the collision of the CR relay node selection should be considered and avoided.

In this paper, we study the cooperative communications where multiple CR transmit-receive pairs competitive maximize their own throughputs and only depend on their local information. In this case, traditional centralized resource allocation is unpractical. The CR transmit-receive pairs should make the relay selection and channel choice simultaneously and separately. We propose a game theoretic framework to formulate this problem and we apply a regret-matching learning algorithm leading to correlated equilibrium. We further formulate a modified regret-matching learning algorithm which is fully distributed and each CR transmit-receive pair only uses its own realized payoffs and strategies. This modified algorithm is more practical and suitable in CR network.

The remaining part of the paper is organized as follows. In Section II, the system model is described and a game theoretic framework is proposed to formulate this problem. In Section III, we apply a regret-matching learning algorithm leading to correlated equilibrium and we further formulate a modified regret-matching learning algorithm which is fully distributed. In Section IV, the simulation results are presented and discussed. Finally, we conclude our work and point out the future work in Section V.

II. System model and Problem formulation

In this section, we first illustrate the system model of competitive relay selection and channel choice. Secondly, we propose a game theoretic framework to formulate this problem.

2.1 System model

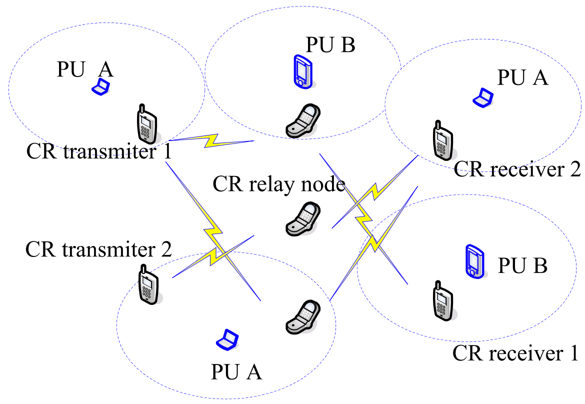

Fig. 1 Relay model of CR network.

One simple scenario is indicated in Fig. 1. As shown in Fig. 1, there are two CR transmit-receive pairs competitive choose the CR relay node for the data transmission. Furthermore, the CR network coexists with the multiple types of primary user (A and B) and should not affect the primary user. Note that the bandwidth of the spectrum can be different among the primary users. The available spectrums of CR relay nodes also constrained by the primary users. Therefore the CR transmit-receive pairs should do the relay selection and channel choice jointly to maximize their own throughputs. In addition, the multiple CR transmit-receive pairs can cause collision if the same channel is used simultaneously and the collided data transmissions fail. In another aspect, if more than one CR transmit-receive pairs choose the same CR relay node in the same time, the collision will happen and all the data transmissions will fail. Therefore, each CR transmit-receive pair should not only aware the environment of primary networks but also aware the environment in CR network.

The CR transmit-receive pairs should make the relay selection and channel choice jointly for maximizing their own throughputs. We assume each CR node can only transmit or receive on one channel. In addition, the multiple CR transmit-receive pairs can cause collision if the same channel or the same CR relay node is simultaneously used.

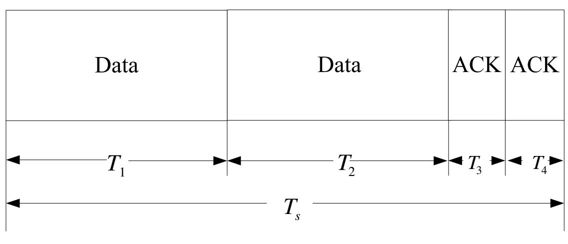

Fig. 2 Time slot structure.

In MAC layer, due to the characteristic of relay transmission, the time slot is divided as Fig. 2. The length of whole time slot is set as T_s. T_s is divided as T_1, T_2, T_3 and T_4. As shown in Fig. 2, T_1 is the transmission time of CR transmitter to the CR relay node. Similarly, T_2 is the transmission time of CR relay node transmitting to the CR receiver. In the period of T_3, the CR receiver should send ACK to the CR relay node if the data transmission is successful. In the period of T_4, the CR relay node should send ACK to the CR transmitter if the data transmission is successful. In this way, the CR transmitter can know the data transmission is success or not.

2.2 Problem formulation

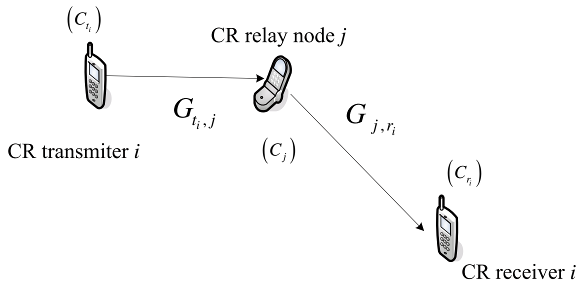

Fig. 3 CR relay model.

In this subsection, we propose a game theoretic framework to formulate this problem. Fig.3 shows the relay model of the CR transmits-receive pair i. $C_{t_i}$and C_{r_i} is the available spectrum set of the CR transmitter and receiver respectively. C_j is the available spectrum set of the CR relay node j. At the beginning of T_1, the CR transmitter of pair i should choose the relay node j and the channel $c_{t_i} \in C_{t_i}$ for the data transmission. If the collision not happen and c_{t_i} is the available channel of transmitter i, the data transmission is successful. Note that in this paper, we assume all nodes transmit with equal power P. We define as the channel gain from transmitter of pair i to the relay node j and is the noise power of CR network. In this way, the throughput from transmitter of pair i to the relay node j can be calculated as:

$$R_{t_i,j} = W_{c_{t_i}} \log_2(1 + \frac{PG_{t_i,j}}{N_0}), \quad (1)$$

where $W_{c_{t_i}}$ is the bandwidth of the channel c_{t_i}. In the similar way, at the beginning of T_2, the CR relay node j should choose the channel $c_j \in C_j$ for data relay transmission. If the collision is not happen and $c_j \in C_{r_i}$, the data relay transmission is successful and the throughput from the relay node j to the receiver of pair i can be calculated as:

$$R_{j,r_i} = W_{c_j} \log_2(1 + \frac{PG_{j,r_i}}{N_0}), \quad (2)$$

Note that and the throughput of the whole transmission pair i can be defined as:

$$R = \min\{R_{t_i,j}, R_{j,r_i}\}, \quad (3)$$

At the beginning of the data transmission, the CR transmitter of pair i can only know its own local available spectrum set C_{t_i}. The CR transmitter of pair i is absolutely unknown of the network environment and this is fully distributed. We assume there are N CR transmit-receive pairs and M CR relay nodes in CR network. The strategies of the CR transmitter of pair i can be defined as: $s_i \triangleq \{j, c_{t_i}, c_j\}$where $j \in M$, $c_{t_i} \in C_{t_i}$ and $c_j \in C_j$. Note that at the beginning of data transmission, the

CR transmitter of pair i does not know the available spectrum sets C_j and C_{r_i}. Therefore, the available set of s_i should include the whole channels in the CR network. Fortunately, once the transmission of the pair i is success, the ACK can be feed back from receiver to the transmitter and we assume the available spectrum sets C_j and C_{r_i} can also be feedback to the transmitter. In this way, after the first successful transmission, the CR transmitter of pair i can update the available strategy set S_i. The $S := \Pi_{i \in N} S_i$ denote the N-tuples strategies of the whole CR network. The utility function of the CR transmit-receive pair i can be defined as:

$$U_i(s_i, s_-i) = \begin{cases} \min\{R_{t_i,j}, R_{j,r_i}\}, & \text{success} \\ 0, & \text{or else} \end{cases}, \quad (4)$$

where s_{-i} denotes the strategy combination of all CR pairs except i (thus $s = (s_i, s_{-i})$).In this game theoretic framework, each CR transmit-receive pair aims for maximizing its own utility by learning the network environment and adjust its strategy insistently.

III. Learning Policies

In this section, we first introduce the concept of correlated equilibrium. Secondly, for the distributed relay selection and channel choice, we apply a regret-matching learning algorithm leading to correlated equilibrium. Finally, we further formulate a modified regret-matching learning algorithm which is fully distributed and each CR transmit-receive pair only uses its own realized utilities and strategies.

3.1 Correlated Equilibrium

Correlated equilibrium is more general than Nash equilibrium. A correlated equilibrium can be described as follows: assume that, before the game is played, each player receives a private signal. The player may then choose his action in the game depending on this signal. If the signals are (stochastically) independent across the players, it is a Nash equilibrium. But the signals could well be correlated, in which case correlated equilibrium may obtain [14]. It can be argued that correlated equilibrium may be the most relevant non-cooperative solution concept.

Definition 1: A probability distribution ψ on S is a correlated equilibrium of game Γ if, for every $i \in N$, every $j, k \in S_i$ we have

$$\sum_{s \in S} \psi(s)[U_i(k, s_{-i}) - U_i(j, s_{-i})] \leqslant 0, \quad (5)$$

Note that a Nash equilibrium is also a correlated equilibrium. Indeed, Nash equilibrium correspond to the special case where ψ is a product measure, that is, the play of the different players is independent. Furthermore, the set of correlated equilibrium is nonempty, closed and convex. It may include distributions that are not in the convex hull of the Nash equilibrium distributions.

3.2 Regret-matching Learning

In this subsection, we introduce a regret-matching learning algorithm for solving the problem of distributed relay selection and channel choice. For two different strategies $j, k \in S_i$ of the CR transmitter-receiver pair i, suppose pair i were to replace strategy j, which every time it was played in the past, by strategy k, we define the regret of pair i for not playing strategy k at time slot t as

$$R_i^t(j,k) := [D_i^t(j,k)]^+ = \max\{D_i^t(j,k), 0\}, \quad (6)$$

where$D_i^t(j,k) = \frac{1}{t} \sum_{\tau \leq t: s_i^\tau = j} [U_i(k, s_{-i}^\tau) - U_i(j, s_{-i}^\tau)]$ and $s^\tau = (s_i^\tau, s_{-i}^\tau)$ denotes the strategy combination of all CR pairs in the time slot τ. Then the probability distribution p_i^{t+1} used by pair i at time slot $t+1$ is defined as

$$\begin{cases} p_i^{t+1}(k) := \frac{1}{\mu} R_i^t(j,k), \text{for all } k \neq j, \\ p_i^{t+1}(j) := 1 - \sum_{k \in S_i: k \neq j} p_i^{t+1}(k), \end{cases}, \quad (7)$$

where $\mu > 0$ is a large enough number that guarantees $p_i^{t+1}(j) > 0$.

Definition 2: for every time slot t, let z^t be the empirical distribution of the N-tuples strategies played up to time slot t. That is, for every $s \in S$,

$$z^t(s) = \frac{1}{t} |\{\tau \leqslant t : s^\tau = s\}|, \quad (8)$$

is the relative frequency that s has been played in the first t time slots.

Theorem 1: If every CR transmit-receive pair plays according to (7), then the empirical distributions of z^t converge almost surely as $t \to \infty$ to the set of correlated equilibrium distributions of game Γ[14].

We can see that regret-matching learning algorithm requires CR transmit-receive pair i to know not only his own utility and the strategy history but also the utility of strategy k which was not realized in the past. That is, pair i observes the choices of the other pairs. Actually, this is impossible in practice.

3.3 Modified Regret-matching Learning

As the unpractical part of regret-matching learning mentioned above, we apply a modified regret-matching learning algorithm in this subsection. In this modified learning algorithm, each CR transmit-receive pair only needs to know his own realized utilities and strategies.

We modify the regret (6) as

$$D_i^t(j,k) = \frac{1}{t} \sum_{\tau \leq t: s_i^\tau = k} \frac{p_i^\tau(j)}{p_i^\tau(k)} U_i^\tau - \frac{1}{t} \sum_{\tau \leq t: s_i^\tau = j} U_i^\tau, \quad (9)$$

where p_i^τ and U_i^τ denotes the play probabilities of pair i and the utility of pair i at time slot τ respectively. We can see from (9), the regret $D_i^t(j,k)$ is estimated by the actual utilities which are obtained by CR transmit-receive pair i. This means in this modified learning algorithm, each CR transmit-receive pair only needs to know his own realized utility and strategies. In the next time slot $t+1$, the probability distribution p_i^{t+1} is defined as

$$\begin{aligned} p_i^{t+1}(k) &:= (1 - \frac{\delta}{t^\gamma}) \min\{\frac{1}{\mu} R_i^t(j,k), \frac{1}{|S_i| - 1}\} \\ &\quad + \frac{\delta}{t^\gamma} \frac{1}{|S_i|}, \text{for all } k \neq j \\ p_i^{t+1}(j) &:= 1 - \sum_{k \in S_i: k \neq j} p_i^{t+1}(k), \end{aligned} \quad (10)$$

where γ is a number strictly between 0 and $1/4$, $\mu > 0$ is a large enough number and $0 < \delta < 1$.

Theorem 2: If every CR transmit-receive pair plays according to the (10), then the empirical distributions of play z^t converge almost surely as $t \to \infty$ to the set of correlated equilibrium distributions of game Γ [15].

IV. Simulation Results and Discussion

In this section, we present simulation results to evaluate the performances of the two proposed learning algorithms.

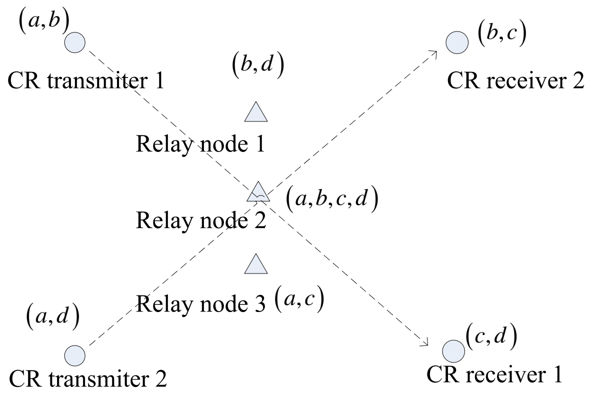

Fig. 4 Simulation model of CR network.

In our simulations, the number of CR transmitter-receiver pairs is set to be 2 and the CR relay nodes is set to be 3. Fig.4 shows the simulation model of the CR network. The CR network located in the area with $400m \times 400m$.The CR transmitter and receiver of pair 1 are located at coordinate $(0m, 400m)$ and $(400m, 0m)$ respectively. The CR transmitter and receiver of pair 2 are located at coordinate $(0m, 0m)$ and $(400m, 400m)$ respectively. The three CR relay nodes are located at coordinate $(200m, 300m)$, $(200m, 200m)$ and $(200m, 100m)$ respectively. The available channel set of each CR node is shown in Fig.4 and the bandwidths of the channels are defined as: $a = 0.6\text{MHZ}$, $b = 0.3\text{MHZ}$, $c = 0.5\text{MHZ}$,$d = 0.3\text{MHZ}$. The transmit power is set as $P = 10\text{mW}$ and the noise level is $N_0 = 10^{-8}\text{mW}$. The propagation factor is set to 2. The length of whole time slot is set as $T_s = 10\text{ms}$. We define $T_1 = T_2 = 4.5\text{ms}$, $T_3 = T_4 = 0.5\text{ms}$.

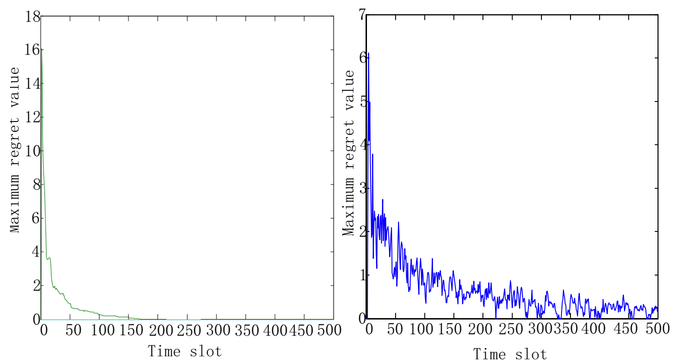

Fig. 5 Convergence of two learning algorithms.

We firstly study the convergence of the two learning algorithms proposed in this paper. Fig.5 shows the convergence of regret-matching and modified regret-matching learning algorithms. The maximum regret value of the two CR pairs indicates how close the CR network is to correlated equilibrium. We can see that the regret-matching converge within 200 periods in the left subfigure of Fig.5. In the right subfigure of Fig.5, the modified learning algorithm doesnt converge so fast, but the regret decreases with the periods. The reason for this difference is that the utility of strategy k can only be estimated in modified algorithm while in regret-matching algorithm, it can be calculated accurately.

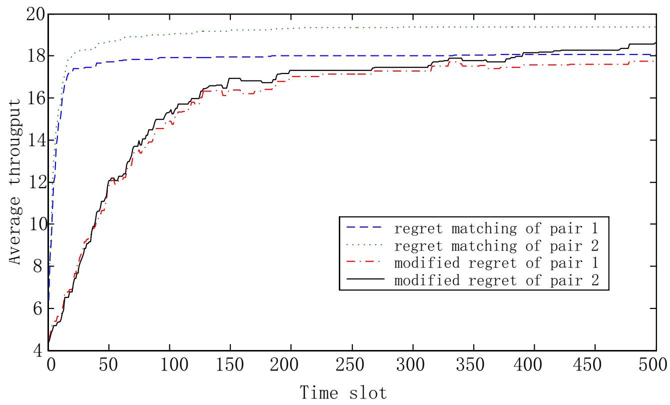

Fig. 6 Throughput of two learning algorithms.

In Fig.6, we plot the throughputs comparison between regret-matching and modified learning algorithm. As shown, the regret-matching performs better than the modified algorithm. This is due to the fact that in regret-matching algorithms, each CR transmitter-receiver pair can observe the strategies of others, but in modified regret-matching algorithm, each CR transmit-receive pair only know his own realized utilities and strategies. Therefore, the regret-matching is closer to the set of correlated equilibrium. However, with the increase of time slots, the performance of modified regret-matching algorithm approaches regret-matching and this is coincide with the convergence property in Theorem 2.

V. Conclusions

In this paper, we study the cooperative communications where multiple CR transmit-receive pairs competitive maximize their own throughputs. We propose a game theoretic framework to formulate this problem and we apply a regret-matching learning algorithm leading to correlated equilibrium. We further formulate a modified regret-matching learning algorithm which is fully distributed and each CR transmit-receive pair only uses its own realized utilities and strategies. Simulation results show the convergence properties of both two algorithms and the modified leaning algorithm approaches the regret-matching algorithm with the increase of time slots. In the future, we will extend our work to jointly consider the relay selection, channel choice and power control in the CR relay network.

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