Resource Allocation for Cognitive Networks with D2D Communication: An Evolutionary Approach

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***Abstract*—We consider how to efficiently employ D2D communications for secondary users (SUs) in a cognitive cellular network. In this network, primary users (PUs) transmit via base station normally, while SUs can employ multiple transmission modes. One is to transmit via base station (BS mode), and the other is to employ D2D communication (D2D mode) due to the scarce idle spectrum. The SUs who have the potential to transmit to each other using D2D mode form a group. Within this group, they can transmit to each other via BS mode or using D2D mode directly. Outside this group, only BS mode is available. To investigate how to employ D2D mode into this network, first we define the utilities of SUs employing BS mode and D2D mode respectively considering achieved data rate, power consumption, price of unit bandwidth and the impact of interference. Then we analyze the optimal power allocation for each mode. To optimize SUs' strategies of mode selection, we adopt replicator dynamics in evolution theory to model the behaviors of SUs. Furthermore, we prove the existence of SUs' evolutionary stable strategy (ESS) of the mode selection process. Based on our model, we finally propose a distributed protocol for SUs within a D2D group to converge to ESS automatically. Numerical results show that our proposed protocol is not only efficient to achieve ESS with improved network performance, but also robust in ESS.**

I. Introduction

Recently, the increasing application of wireless devices has stimulated dramatic demand for spectrum, which is a splendid challenge to the relatively scarce spectrum. To improve the utility of the scarce spectrum, more and more efforts are taken on cognitive radio and device-to-device (D2D) technology.

Akyildiz points out in [1] that the spectrum efficiency of the licensed users (primary users) is relative low, which motivates the unlicensed users (secondary users) to utilize the idle spectrum. Due to the low efficiency of licensed spectrum, even Federal Communications Commission (FCC) has been considering opening the under-utilized licensed spectrum to secondary users with the aid of cognitive radio technology [2]. Cognitive radio plays as a promising technology to improve the utility of the licensed spectrum, which dynamically provides services to primary users and secondary users [3] [4]. Since secondary users can only utilize the temporally idle spectrum to avoid collisions, resource allocation becomes a key issue. To deal with the problem of resource allocation in cognitive radio networks, many efforts have been made on game theory based approaches. Multi-stage auction game is adopted in [5] for spectrum sharing and power allocation. Zhang utilizes stackelberg game to optimize transmission slots among PUs and SUs in cognitive cooperative networks [6]. However, cognitive radio technology only improves spectrum efficiency from the perspective of time and channel, neglecting the potential optimization from space perspective, such as device-to-device (D2D) communication.

D2D communication shares the same resource with cellular communication under control of the cellular network, which improves the utility of spectrum from space perspective. Similar as cognitive radio system, D2D communication must not cause harmful interference to cellular network. Due to the benefit of D2D communication, IMT-Advanced systems, such as LTE-Advanced and WiMax, allow D2D communication as an underlay to the cellular network to increase the spectral efficiency. Doppler in [7] integrates D2D communication into LTE-Advanced networks. Jänis in [13] analyzes interference-aware resource allocation for D2D radio. Yu investigate power allocation for D2D communication [14]. Most of the work on D2D focus on how to employ D2D communication in cellular network with limited interference, but no effort has been made on cooperating D2D communication with cognitive radio technology to jointly optimize spectrum utility.

To jointly employ cognitive radio technology and D2D communication in cellular networks, we analyze the behaviors of secondary users using evolutionary game. The theory of evolutionary game was initially developed to model the behavior of biological agents, human beings in the society and entities in a market environment [9]. It has been previously applied in congestion control [10] and cooperative spectrum sensing [11]. In this paper, evolutionary game is employed on SUs' transmission strategies. The contributions of our work are as follows:

- We introduce D2D communications into cognitive cellular networks as an underlay to increase the spectrum efficiency. SUs can either utilize the idle spectrum to set up cellular communication via base station (BS mode) or employ D2D transmission using a certain PU's spectrum with constrained interference (D2D mode) due to the lack of idle spectrum.
- The problems of power allocation for BS mode and D2D mode are analyzed respectively.
- To evaluate SUs' strategies on transmission mode selection, we analyze the evolutionary process of SUs during which their strategies are updated by replicator dynamics

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and then derive the evolutionary stable strategy (ESS) of the game.
- Furthermore, based on our model we propose a distributed protocol to implement resource allocation among SUs of a certain D2D group, which can converge to ESS automatically. Numerical results show the efficiency and robustness of our protocol.

The rest of this paper is organized as follows: Section II describes our system model and formulates the problem. Section III analyzes the optimal power allocation for BS mode and D2D mode respectively. In Section IV, the dynamic behaviors of SUs are modeled as an evolutionary game and the evolutionary stable strategy (ESS) is analyzed. We propose a distributed protocol to converge to ESS in Section V and simulation results provided in Section VI prove the efficiency and robustness of our protocol. Finally conclusions are drawn in Section VII.

II. System model and problem Formulation

A. System Model

We consider a cognitive cellular system with multiple PUs and multiple SUs, shown in Figure 1. In this system, some of the SUs who can employ D2D communication as an underlay to transmit to each other form a D2D group, so there may be many such groups in a single cell. This kind of D2D groups may be the users who are accessing the datum stored in the same server, the search and rescue team members in the mountain, etc.. Note that D2D is usually short-range communication with limited power and D2D groups usually select spectrum of the PUs who are far away by sensing, so they seldom cause damaging interference to the PUs employing the same spectrum. Considering the usage scenario of D2D groups mentioned above, D2D groups are usually far away from each other so the interference between groups is small enough. For any SU in a D2D group, if he wants to communicate with the SU outside the group, he has to transmit via base station using cellular communication, just as what the common cognitive cellular system does. While if he intends to communicate with another SU within the same group, D2D communication is available and he can determine whether to transmit via base station (BS mode) or using D2D mode directly. Note that each SU makes such decision using a mixed strategy $Z = (z^{BS}, z^{D2D})$, where z^{BS} and z^{D2D} denote the probabilities to employ BS mode and D2D mode respectively. Obviously $z^{BS} + z^{D2D} = 1$. To achieve higher payoff, each SU updates his mixed strategy based on the current utilities of the two modes.

B. Problem Formulation

We consider the SUs in a certain D2D group. If SU_j decides to transmit via base station (BS mode), his income is the achieved data rate while the cost is mainly composed of two parts, one is the power consumption and the other is the cost of bandwidth charged by the base station. So the utility of

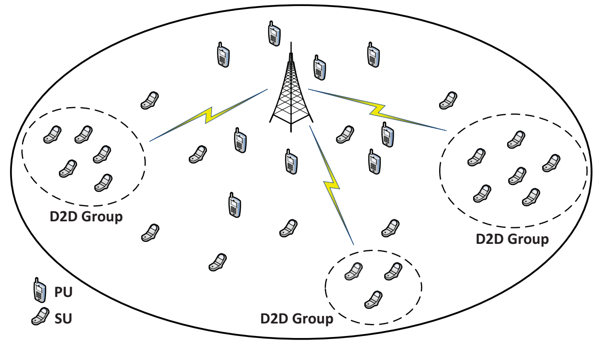

Fig. 1. A cognitive cellular network with D2D groups.

SU_j can be calculated as:

$$\begin{aligned} U_j^{BS} &= \lambda R_j - \pi P_j - p_1 B_j \\ &= \lambda B_j \log_2(1 + \frac{P_j G_j}{\sigma^2}) - \pi P_j - p_1 B_j, \end{aligned} \quad (1)$$

where B_j is the bandwidth used by SU_j, σ^2 is the power of noise, π is the cost of unit power, λ is the value of unit data rate, P_j and G_j are SU_j's transmit power and channel gain respectively. To facilitate analysis, we assume the SUs who transmit in BS mode equally share the current idle spectrum W supplied by the base station. If the demand from SUs is D, obviously B_j equals W/D. Note that SU_j must pay for the idle spectrum B_j with price p_1 which is closely related to the demand D from SUs and current total idle spectrum W supplied by the base station. If the demand D from SUs increses, the base station will raise the price p_1 so that some of the SUs may change their strategies into D2D mode for a higher utility. If no SU demands spectrum, the price will fall to zero and many SUs may come back to BS mode. Here we model the price p_1 exponentially increases with D/W, i.e.

$$p_1 = c_1[\exp(c_2 \cdot D/W) - 1], \quad (2)$$

where c_1 and c_2 are positive constants.

If SU_j decides to communicate with another SU within the group by D2D mode, he uses the sub-channel of a certain PU who is far away. In this case, the power of the PU who is utilizing the same sub-channel as SU_j becomes SU_j's interference and vice versa. To evaluate the utility of SU_j, we consider the achieved data rate as income, the power consumption and impact of interference as cost. Then SU_j's payoff of employing D2D mode can be written as:

$$\begin{aligned} U_j^{D2D} &= \lambda R_j - \pi P_j - p_2 \\ &= \lambda B_i \log_2(1 + \frac{P_j G_j}{\sigma^2 + P_i G_{ij}}) - \pi P_j - p_2, \end{aligned} \quad (3)$$

where B_i equals the bandwidth of sub-channel used by PU_i, P_j and P_i correspond to the power of SU_j and PU_i respectively, π is the cost of unit power, λ is the value of unit data rate, G_j is SU_j's channel power gain, gain G_{ij} corresponds to the undesired interference link of PU_i, and p_2 is the cost of interference caused by D2D communication. Since the licensed bandwidth is limited, too many SUs' employing D2D communication results in relative low signal to interference plus noise ratio (SINR), which has a negative impact on the data rate that can be achieved. To evaluate this impact, we define the price p_2 which increases with the percentage of D2D users:

$$p_2 = c_3[\exp(c_4 \cdot x_{D2D}) - 1], \tag{4}$$

where c_3 and c_4 are positive constants, and x_{D2D} is the percentage of SUs who employ D2D mode in the group.

For each SU who intends to establish data links with another SU in the same D2D group, he must make a decision on his transmission strategy based on the potential utilities of the two modes. For each transmission mode, he should adopt an optimal power for higher utility. How to allocate power and how to select transmission mode have close relationship with the payoff that can be achieved, and these problems will be discussed in the following sections.

III. Power Control Strategy

In this section, we derive SUs' optimal transmitting power of two transmission modes. Since power is limited, we assume the maximum power of PUs and SUs are P_{max} and P'_{max} respectively. Since SUs in D2D mode may decrease PUs' SINR, to guarantee PUs' QoS (quality of service) and priority, each PU should adopt a power not less than P_{min}.

A. Power Control in BS Mode

In BS mode, higher power means higher data rate that can be achieved, but it also means larger power consumption. For SU$_j$, we can work out the optimal power P_j^* by differentiating U_j^{BS} with respect to P_j, i.e.

$$\frac{\partial U_j^{BS}}{\partial P_j} = \frac{\lambda B_j G_j}{(\sigma^2 + P_j G_j)\ln 2} - \pi. \tag{5}$$

Lemma 1: The optimal power for SU$_j$ in BS mode is

$$P_j^* = \begin{cases} P'_{max} & \text{if } \pi < \mu_1 \\ 0 & \text{if } \pi > \mu_2 \\ \frac{\lambda B_j}{\pi \ln 2} - \frac{\sigma^2}{G_j} & \text{otherwise} \end{cases} \tag{6}$$

where $\mu_1 = \frac{\lambda B_j G_j}{(\sigma^2 + P'_{max} G_j)\ln 2}$ and $\mu_2 = \frac{\lambda B_j G_j}{\sigma^2 \ln 2}$.

Proof: The term on the right hand side of (5) strictly decreases in P_j. If $\pi < \mu_1$, $\frac{\partial U_j^{BS}}{\partial P_j}$ is always larger than 0. Considering $P_j \in [0, P'_{max}]$, we have $P_j^* = P'_{max}$. If $\pi > \mu_2$, we have $\frac{\partial U_j^{BS}}{\partial P_j} < 0$, so SU$_j$ should better not transmit. Otherwise, the optimal power can be obtained from $\frac{\partial U_j^{BS}}{\partial P_j} = 0$. ■

B. Power Control in D2D Mode

In D2D mode, SU$_j$ uses the same sub-channel as that of a certain PU far away (PU$_i$ for example). In this case, the power of SU$_j$ becomes the interference to PU$_i$ and vice versa. Note that D2D mode is only available within a group of SUs. These SUs may select the sub-channels with lower interference by sensing because the PUs who are using these sub-channels are usually farther away, so that interference can be controlled and not to cause dramatic damage to the transmission link. Based on the above analysis, the cost of power consumption mentioned in (3) is not the major concern of SUs, but the signal to interference plus noise ratio (SINR) to guarantee data rate. To facilitate analysis, we maximize the total data rates of PU$_i$ and SU$_j$ as the goal of power control strategy in D2D mode.

Let

$$\begin{aligned} \mathbb{R}(P_i, P_j) &= R_i + R_j \\ &= B_i \log_2(1 + \Gamma_i)(1 + \Gamma_j), \end{aligned} \tag{7}$$

where Γ_i and Γ_j are the SINR of PU$_i$ and SU$_j$ respectively, which can be represented as:

$$\begin{aligned} \Gamma_i &= \frac{P_i G_i}{\sigma^2 + P_j G_{ji}}, \\ \Gamma_j &= \frac{P_j G_j}{\sigma^2 + P_i G_{ij}}. \end{aligned}$$

Then the optimization problem of transmission power can be formulated as:

$$(P_i^*, P_j^*) = \arg \max_{(P_i, P_j) \in \Phi} \mathbb{R}(P_i, P_j) \tag{8}$$

$$\begin{aligned} s.t.\ \ \Phi = \{&(P_i, P_j) : P_{min} \le P_i \le P_{max}, \\ &0 \le P_j \le P'_{max}, \Gamma_i \ge \gamma_p, \Gamma_j \ge \gamma_s\}, \end{aligned}$$

where $\Gamma_i \ge \gamma_p$ and $\Gamma_j \ge \gamma_s$ constrain the interference caused by D2D communication.

Lemma 2: The optimal solution (P_i^*, P_j^*) for (8) only can be achieved on the boundary of Φ.

Proof: We prove this lemma by contradiction. Let $\Omega_1 = \{(P_i, P_j) : P_{min} \le P_i \le P_{max}, 0 \le P_j \le P'_{max}\}$ and $\Omega_2 = \{(P_i, P_j) : \Gamma_i \ge \gamma_p, \Gamma_j \ge \gamma_s\}$, shown in Figure 2 and Figure 3 respectively, then $\Phi = \Omega_1 \cap \Omega_2$. Since Ω_1 is a finite closed region, Φ is a finite closed region or empty set. Note that we can properly set parameters P_{max}, P_{min}, P'_{max}, γ_p and γ_s to guarantee Φ is not empty, so our discussion is based on the assumption that Φ is a non-empty finite closed region.

Let $\partial\Phi$ be the boundary of region Φ and $\Phi' = \Phi \backslash \partial\Phi$. Assuming $V_1(P_i^*, P_j^*) \in \Phi'$, shown in Figure 4, we can draw a ray starting from $V_1(P_i^*, P_j^*)$ with slope $\kappa = P_j^*/P_i^* > 0$, which intersects $\partial\Phi$ at $V_2(P_i^b, P_j^b)$. Let $P_i^b = \alpha P_i^* (\alpha > 1)$. Since $\kappa = \frac{P_i^b - P_i^*}{P_j^b - P_j^*}$, obviously $P_j^b = \alpha P_j^*$. Considering $\mathbb{R}(\alpha P_i^*, \alpha P_j^*) > \mathbb{R}(P_i^*, P_j^*), \forall \alpha > 1$ [8], which contradicts with the assumption that (P_i^*, P_j^*) is the optimal solution, thus $(P_i^*, P_j^*) \in \partial\Phi$ holds. ■

Lemma 3: The optimal solution (P_i^*, P_j^*) for (8) only exists on the corner points of Φ.

Proof: According to *Lemma 2*, $(P_i^*, P_j^*) \in \partial\Phi$. Note that the shape of region Φ changes with different values of the constrained parameters, so is the shape of $\partial\Phi$. However, $\partial\Phi$ is only composed of some of the following five lines: $l_1 : P_i = P_{min}$, $l_2 : P_i = P_{max}$, $l_3 : P_j = P'_{max}$, $l_4 : \Gamma_i = \gamma_p$

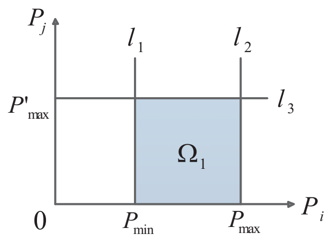

Fig. 2. Feasible region Ω_1.

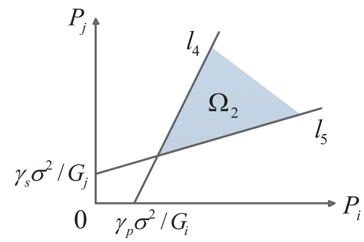

Fig. 3. Feasible region Ω_2.

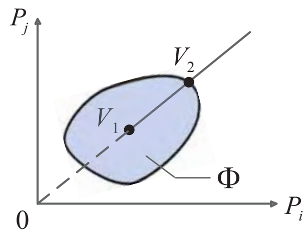

Fig. 4. Illustration of *Lemma 2*: Optimal power (P_i^*, P_j^*) is only achieved on the boundary of Φ.

and $l_5 : \Gamma_j = \gamma_s$. Let $l'_e = l_e \cap \partial\Phi$ $(e = 1, 2, 3, 4, 5)$ and $Q(P_i, P_j) = (1+\Gamma_i)(1+\Gamma_j)$. Applying the conclusion in [8], if $(P_i, P_j) \in l'_1 \cup l'_2$, $\frac{\partial^2 Q}{\partial P_j^2} \geq 0$. At the same time $\frac{\partial^2 Q}{\partial P_i^2} \geq 0$, if $(P_i, P_j) \in l'_3$. So $Q(P_i, P_j)$ is convex when $(P_i, P_j) \in l'_1 \cup l'_2 \cup l'_3$. Then (P_i^*, P_j^*) only has the possibility to exist on the end points of l'_e $(e = 1, 2, 3)$. According to [14], if $(P_i, P_j) \in l'_4 \cup l'_5$, Q is monotonically increasing in P_i or P_j. So (P_i^*, P_j^*) only has the possibility to be obtained on the end points of l'_e $(e = 4, 5)$. Based on the above analysis, *Lemma 3* holds. ■

Note that there are at most five corner points in feasible region Φ, so we can derive the optimal solution to (8) simply by traversing the corner points.

IV. Mode Selection

In this section, the behaviors of SUs within a D2D group are modeled by evolutionary game. For each SU within a certain D2D group, he selects his transmission strategy according to the utilities of different transmission modes. During the selection process, the percentage of SUs, also known as population share, using a certain pure strategy may change. Such evolutionary process of population share can be characterized by *replicator dynamics* in evolutionary game.

Definition 1: *Replicator Dynamics*. Let $\mathbb{Z}$ be the set of pure strategies, and x_k be the population share of strategy $z_k \in \mathbb{Z}$. If the utility of an SU only depends on the strategy employed but not who is playing the strategy, the evolution dynamics of x_k is given by the following differential equation [12]:

$$\dot{x}_k = \epsilon[\bar{U}(z_k, x_{-z_k}) - \bar{U}(x)]x_k, \tag{9}$$

where x_{-z_k} is the population share who employ strategies other than z_k, $\bar{U}(z_k, x_{-z_k})$ is the average utility of the population who are playing strategy z_k, $\bar{U}(x)$ is the average utility of the total population and ϵ is a constant representing the evolutionary speed. Equation (9) gives an intuition that if strategy z_k results in a higher utility than the average level, more SUs intend to adopt strategy z_k next time.

During the evolutionary process, each SU's strategy may approach a stable state, defined as *evolutionary stable strategy (ESS)*.

Definition 2: *Evolutionary Stable Strategy (ESS)*. Strategy z^* is ESS if and only if the following conditions hold,

- $U(z, z^*) \leq U(z^*, z^*)$,
- If $U(z, z^*) = U(z^*, z^*)$, $U(z, z) < U(z^*, z)$.

Let $Z_j = (z_j^{BS}, z_j^{D2D})$ be the mixed strategy of SU$_j$, that is, SU$_j$ selects BS mode with probability z_j^{BS} and D2D mode with probability z_j^{D2D}. According to previous assumptions, a D2D group is usually small and far away from base station as well as interferential PUs, and SUs within a D2D group follow uniform distribution, so channel gains of SUs within a group are almost equal. In this case, the payoff of a certain SU only depends on the strategy employed, not on who is playing the strategy. Then we can omit j from Z_j. We further assume SUs' strategy Z is decided by the current population share. If the current population share of BS mode and D2D mode are x^{BS} and x^{D2D} respectively, where $x^{BS} + x^{D2D} = 1$, we have $z^{BS} = x^{BS}$ and $z^{D2D} = x^{D2D}$. Thus any SU's mixed strategy Z can be rewritten as $Z = (z^{BS}, z^{D2D})$.

Since each SU employs the mixed strategy Z, the population share may be changing, modeled as

$$\dot{x}^{BS} = \epsilon[\bar{U}^{BS} - \bar{U}]x^{BS}, \tag{10}$$
$$\dot{x}^{D2D} = \epsilon[\bar{U}^{D2D} - \bar{U}]x^{D2D}, \tag{11}$$

where $\bar{U}^{BS}$ and $\bar{U}^{D2D}$ are the expected utilities of SUs using BS mode and D2D mode respectively, and $\bar{U}$ is the utility expectation of all SUs calculated by

$$\bar{U} = x^{BS}\bar{U}^{BS} + x^{D2D}\bar{U}^{D2D}. \tag{12}$$

Substituting (12) into (10), equation (10) can be rewritten as

$$\dot{x}^{BS} = \epsilon x^{BS}(1 - x^{BS})(\bar{U}^{BS} - \bar{U}^{D2D}). \tag{13}$$

Based on this equation, we can get the condition for ESS.

Lemma 4: In a certain D2D group, ESS is achieved if the following condition holds:

$$\bar{U}^{*BS} = \bar{U}^{*D2D}. \tag{14}$$

Proof: In equilibrium, no SU will deviate from ESS, indicating $\dot{x}^{*BS} = 0$ or $\dot{x}^{*D2D} = 0$. Since $\dot{x}^{BS} + \dot{x}^{D2D} = 0$, $\dot{x}^{*BS} = 0$ and $\dot{x}^{*D2D} = 0$ are equivalent to each other. According to (13), $\dot{x}^{*BS} = 0$ indicates $x^{BS} = 1$, $x^{BS} = 0$ or $\bar{U}^{BS} = \bar{U}^{D2D}$. If $x^{BS} = 1$, all of the SUs employ BS mode to compete for the limited idle spectrum W, resulting a huge price for unit spectrum. If $x^{BS} = 0$, too many SUs utilize D2D mode which not only cause great interference on PU's sub-channels, but waste the idle spectrum W with relatively low price for unit bandwidth. Based on the above analysis, we can

A.	Resource Allocation for SUs in a D2D Group

```
1:  Initialize:
2:  each SU randomly choose a back-off window from Ψ
3:  each SU employs an initial mixed strategy Z_init = (z_init^BS, z_init^D2D)
4:  Loop:
5:  for j = 1 to N_s
6:    if ψ_j == 0
7:      select transmission mode according to Z
8:      if BS mode is employed
9:        adopt optimal power P_j^* according to Lemma 1
10:       upload U_j^BS through uplink signaling channel
11:     else
12:       adopt optimal power P_j^* according to Lemma 3
13:       upload U_j^D2D through uplink signaling channel
14:     end if
15:     reset back-off window ψ_j ∈ Ψ
16:     update Z according to (10) and (11)
17:   else
18:     ψ_j = ψ_j − 1
19:   end if
20: end for
21: repeat Step 5 to Step 20
```

make the conclusion that ESS is achieved if $\bar{U}^{*BS} = \bar{U}^{*D2D}$. ■

V. Convergence to ESS

In this section, we propose a distributed protocol to implement selection of transmission modes, which can converge to ESS automatically.

In our protocol, transmission time is slotted with τ and each transmission only starts (or stops) at the very beginning (or end) of a certain time slot. To guarantee mode selections are adopted in a distributed manner, each SU, SU_j for example, maintains a back-off window $\psi_j \in \Psi$, where Ψ is the set of available values of back-off windows. At the beginning of mode selection-and-transmission process, SU_j randomly chooses a back-off window ψ_j from Ψ. After ψ_j time slots, a new process of selection and transmission is triggered, at the same time the value of ψ_j is updated. Following the above procedures, SUs behave in a distributed manner during mode selection.

Note that each cell maintains an uplink as well as a downlink signalling channel (e.g. PUCCH and PDCCH in LTE-Advanced system). Using uplink signaling channel, each SU uploads his current utility immediately after mode selection completed. With the received utilities from SUs, the base station calculates the average utility of BS mode $\bar{U}^{BS}$, the average utility of D2D mode $\bar{U}^{D2D}$ and the average utility of total SUs $\bar{U}$, then periodically broadcasts these parameters through downlink signaling channel. So each SU can utilize these parameters to update his mixed strategy Z when mode selection is triggered.

Table A shows the pseudocode of the proposed distributed protocol which can converge to ESS automatically. Note that N_s in Table A represents the number of SUs in a certain D2D group.

VI. Numerical Results and Analysis

In this section, we provide the numerical results for resource allocation in D2D cellular networks using our proposed distributed protocol. Since D2D groups are independent with each other, our analysis mainly focus on the simulation results of a certain D2D group.

We conduct a D2D group with 50 SUs uniformly distributed in a $500m \times 500m$ area which locates far away from the base station. Each SU in this group has the potential to set up D2D communication with SUs within the same group. The length of transmission slot τ is set as $0.5ms$ according to LTE-Advanced system.

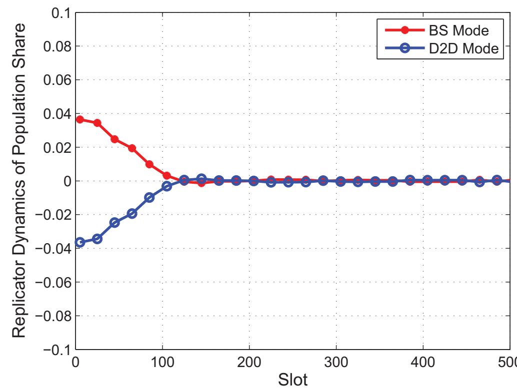

Fig. 5. The replicator dynamics of population share.

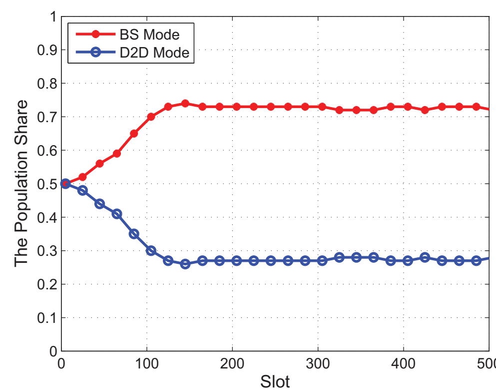

Fig. 6. The population share of SUs.

Figure 5 and Figure 6 shows the replicator dynamics and population share of the D2D group respectively. In these two figures, the red line with stars represents the BS mode while the blue line with circles represents the D2D mode. The initial mixed strategy of SUs is set as $Z = (0.5, 0.5)$, that is, each SU selects transmission modes with equal probability, which is shown in Figure 6. Then each SU changes his mixed strategy when his back-off window ψ reaches zero. Since $\dot{x}^{BS} > 0$ and $\dot{x}^{D2D} < 0$ in the beginning, SUs' mixed strategy $Z = (z^{BS}, z^{D2D})$ changes with population share $X = (x^{BS}, x^{D2D})$ and many SUs turn to BS mode for higher payoff. After about 110 slots ($55ms$), x^{BS} (or x^{D2D}) varies little with $|x^{BS}(t) - x^{BS}(t+\tau)| \leq 0.02$, which indicates ESS is achieved at $Z = (0.73, 0.27)$.

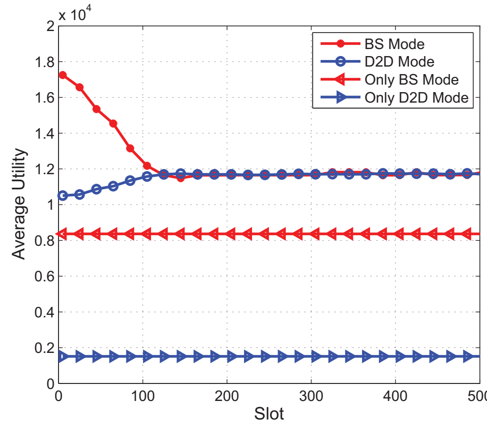

Fig. 7. The average utilities.

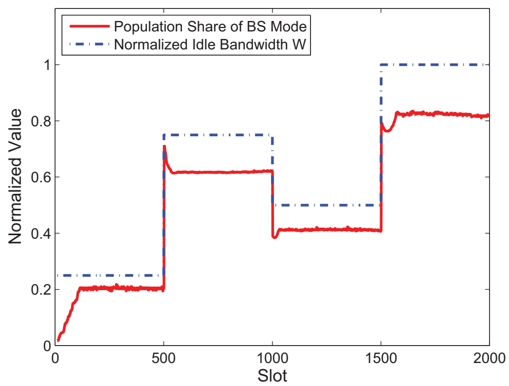

Fig. 8. The system converge to ESS efficiently when W changes.

Figure 7 shows the average utility of BS mode $\bar{U}^{BS}$, D2D mode $\bar{U}^{D2D}$, total SUs $\bar{U}$, and average utility if all SUs employ BS mode or D2D mode respectively. Initially all of the SUs employ the mixed strategy $Z = (0.5, 0.5)$, with which the average utility of BS mode $\bar{U}^{BS}$ is much larger than that of D2D mode $\bar{U}^{D2D}$, therefore quite a lot of SUs turn to BS mode for higher payoff. With the decreasing idle bandwidth that each SU in BS mode obtained and the increasing price of unit idle bandwidth p_1, $\bar{U}^{BS}$ decreases while $\bar{U}^{D2D}$ increases. About 110 slots later, $\bar{U}^{BS} \doteq \bar{U}^{D2D}$, indicating ESS is achieved. Besides, from this figure we can see our proposed protocol achieves higher overall utility than pure BS mode and pure D2D mode.

In actual cellular system, the idle bandwidth W varies from time to time due to the change of PUs' transmission requirements. Figure 8 shows that the population share of BS mode changes with the current idle bandwidth W at the state of ESS. Based on our proposed protocol, ESS can be quickly achieved even though W frequently changes, which proves the robustness of our protocol.

VII. Conclusion

In this paper, we study the problem of resource allocation in a cognitive cellular network with D2D communication. Secondary users within a D2D group can set up communications employing either BS mode or D2D mode. For each mode, SUs' optimal power is analyzed and each SU selects transmission mode using the mixed strategy which is updated by replicator dynamics within the framework of evolutionary game theory. Furthermore, we propose a distributed protocol to implement our model and simulation results prove the efficiency and robustness of our protocol. Besides, our proposed protocol can be applied in large scale wireless networks [15][16][17].

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References

[1] I. Akyildiz, W. Lee, M. Vuran and S. Mohanty, "NeXt Generation Dynamic Spectrum Access Cognitive Radio Wireless Networks: A Survey," 2006.

[2] Federal Communications Commission, "Spectrum Policy Task Force Report," FCC Document ET Docket No. 02-155, Nov. 2002.

[3] Q. Zhao and B. M. Sadler, "A Survey of dynamic Spectrum Access," *IEEE Signal Processing Magazine*, vol. 24, no. 3, pp. 79-89, May 2007.

[4] J. Mitola III and G. Maguire Jr., "Cognitive Radio: Making Software Radios More Personal," *IEEE Personal Communications*, vol. 6, pp. 13-18, Aug. 2007.

[5] J. Huang, R. Berry, and M. Honig, "Auction-based Spectrum Sharing," *Mobile Networks and Applications*, 11(3):405C408, Jun. 2006.

[6] J. Zhang, Q. Zhang, "Stackelberg Game for Utility-Based Cooperative Cognitive Radio Networks," in *Proc. ACM Mobihoc'09*, 2009.

[7] K. Doppler, M. Rinne, C. Wijting, C. Ribeiro and K. Hugl, "Device-to-Device Communication as an Underlay to LTE-Advanced Networks," *IEEE Communications Magazine*, vol. 47, pp. 42-49, Dec. 2009.

[8] A. Gjendemsjo, D. Gesbert, G.E. Oien, and S.G. Kiani, "Optimal Power Allocation and Scheduling for Two-Cell Capacity Maximization," in *International Symposium on Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks*, pp. 1-6, Apr. 2006.

[9] C. Alós-Ferrer, A. B. Ania, and K. R. Schenk-Hoppé, "An Evolutionary Model of Bertrand Oligopoly," *Games and Economic Behavior*, vol. 33, pp. 1-19, 2000.

[10] E. H. Watanabe, D. S. Menasché, E. de Souza e Silva, and R. M. Leão, "Modelling Resource Sharing Dynamics of VoIP Users Over A WLAN Using A Game-Theoretic Approach," in *Proc. IEEE INFOCOM'08*, Apr. 2008.

[11] B. Wang, K. J. Ray Liu and T. C. Clancy, "Evolutionary Cooperative Spectrum Sensing Game: How to Collaborate?" *IEEE Transactions on Communications*, vol. 58, pp. 890, Mar. 2010.

[12] J.W. Weibull, Evolutionary Game Theory, *MIT Press*, 1995.

[13] P. Jänis, V. Koivunen, C. Ribeiro and J. Korhonen, "Interference-Aware Resource Allocation for Device-to-Device Radio Underlaying Cellular Networks," in *Proc. IEEE VTC'09*, 2009.

[14] C. Yu, O. Tirkkonen, K. Doppler, and C. Ribeiro, "Power Optimization of Device-to-Device Communication Underlaying Cellular Communication," in *Proc. IEEE ICC'09*, Jun. 2009.

[15] X. Wang, L. Fu, and C. Hu, "Multicast Performance with Hierarchical Cooperation," in *IEEE/ACM Transactions on Networking*, vol. 20, no. 3, 2011. DOI:10.1109/TNET.2011.2170584

[16] X. Wang, W. Huang, S. Wang, J. Zhang, and C. Hu, "Delay and Capacity Tradeoff Analysis for MotionCast," in *IEEE/ACM Transactions on Networking*, vol. 19, no. 5, pp. 1354-1367, Oct. 2011.

[17] X. Wang, Y. Bei, Q. Peng, and L. Fu, "Speed Improves Delay-Capacity Tradeoff in MotionCast," in *IEEE Transactions on Parallel and Distributed Systems*, No. 99, pp. 729-742, 2011.