Mode Selection for Energy-Efficient D2D Communications in LTE-Advanced Networks: A Coalitional Game Approach

Khajonpong Akkarajitsakul, Phond Phunchongharn, Ekram Hossain, and Vijay K. Bhargava

***Abstract*—We consider the problem of mode selection for device-to-device (D2D) communications in LTE-advanced networks. We propose a solution based on a coalitional game among D2D links to select their communications modes. The solution is given by three coalitions which represent the groups of D2D links using cellular mode, reuse mode, and dedicated mode of transmission. The D2D links in the same coalition cooperatively select the subchannels and use the corresponding transmission mode such that the total power is minimized while their rate requirements are satisfied. The D2D links can make a decision to leave and join a coalition based on their individual transmission costs. The individual transmission cost of each D2D link is a function of the transmission power and the price of channel occupancy which depends on the D2D link's communications mode. We find stable coalitions as the solution of the mode selection problem. The stable coalitions represent the system states in which no D2D link can change its communication mode and have lower transmission cost without making others worse off. A discrete-time Markov chain-based analysis and a distributed algorithm are presented to obtain the stable coalitions.**

Keywords: Device-to-device (D2D) communications, mode selection, cooperative game, coalition formation.

I. Introduction

Two major requirements for LTE-Advanced (Long Term Evolution-Advanced) standard as a candidate of the 4G (Fourth Generation) cellular wireless networks are to improve spectrum efficiency and to enhance network throughput. Device-to-device (D2D) communications technology is a promising add-on component of LTE-Advanced systems to satisfy those requirements. The concept of D2D communications is to allow the direct communications among the user equipments (UEs) by reusing the cellular resources rather than using the uplink or downlink resources of the cellular networks. D2D communications can achieve four types of gains [1], namely, the proximity gain, hop gain, reuse gain, and pairing gain. In D2D communications, the UEs can operate in one of three modes as follows (Fig. 1): i) *Reuse mode*: D2D UEs directly transmit data among each other by reusing some radio resources used by cellular UEs to enhance the spectrum utilization. ii) *Dedicated mode*: D2D UEs directly transmit data between each other by using a dedicated portion of spectrum to avoid interference with cellular UEs. iii) *Cellular mode*: Similar to the cellular UEs, the D2D UEs relay their data through the base station.

One key question here is how to select a transmission mode for each D2D link. In the cellular mode, more resources (e.g., the number of time slots) may be required for transmitting data to the receiver compared to those used in the the reuse mode or dedicated mode; however, it is easier to manage interference with cellular users. The reuse mode can achieve a higher spectrum efficiency but D2D communications in this mode may interfere with cellular users and other D2D users using the cellular mode. On the other hand, the dedicated mode can completely avoid interference since some resources are reserved for the D2D communications; however, the spectrum utilization can be very poor in this mode.

In [2], a mode selection algorithm was proposed for both single-cell and multiple-cell scenarios where each cell includes one D2D link and one cellular link. The algorithm selects the mode that can achieve the highest sum-rate while satisfying the SINR constraints of the cellular network. In [3] and [4], the problem of mode selection with power control was studied in a single cell with one D2D link and one cellular link. The transmission mode and corresponding transmission power are chosen to maximize the sum-rate of the cellular and D2D communications.

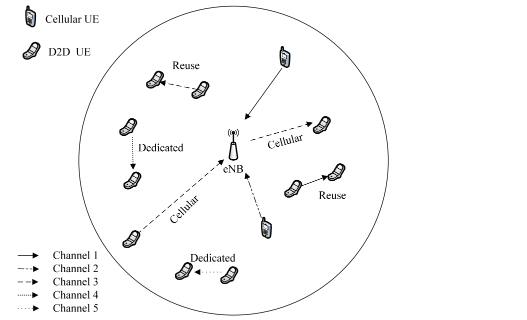

Fig. 1. A single cell with multiple cellular links and D2D links using different D2D communications modes.

In [5], the problem of sum-rate maximization for multiple cellular links and D2D links was formulated as a mixed-integer non-linear program with SINR constraints for cellular and D2D communications. In [6], a heuristic algorithm was proposed to jointly allocate power and subcarrier and to select transmission mode and modulation for multiple D2D links and multiple cellular links. The objective of the algorithm is to minimize the overall transmission power subject to the rate constraints. However, [6] considered only dedicated and cellular modes for the D2D links. Moreover, the key assumption in all these work is that the UEs always cooperate to achieve the globally optimal solution. However, the assumption may not be always true since each UE is of self-interest and may have its own communication requirement which is different from that of the others. Depending on their requirements, different D2D links can use different transmission modes, and the links using the same transmission mode may cooperate with each other. In this context, the coalitional game theory can be applied to analyze the formation of cooperative groups of UEs. The coalitional game theory has been used to model and analyze the resource allocation problem in wireless networks.

In this paper, we study the problem of mode selection and cooperative transmission for D2D communications via coalitional game theory where coalitions are formed for transmission mode selection such that the cooperation among users in a coalition provides benefits to the D2D users (e.g., reduces transmission cost). The cooperation here implies that the D2D links within a coalition use orthogonal channels for transmission so that they do not experience any interference from the other D2D links in the same coalition. We define an appropriate *transmission cost* for each user in terms of transmission power and the price of channel occupancy. Since each user is rational, she may not want to cooperate with other users in a group or coalition if she is unable to achieve a lower transmission cost even if the overall transmission power of the group is minimized. Thereby, the assumption that all users always cooperate to use a single transmission mode to achieve the global optimality is relaxed. The stable solution for such a coalition formation process can be considered as the solution for the mode selection problem in D2D communications.

The rest of this paper is organized as follows. Section II describes the system model and assumptions. The coalitional game model is presented in Section III. Section IV presents the stable coalition formation process. Section V presents the numerical results for the proposed mode selection approach.

II. System Model and Assumptions

We consider N cellular links and M D2D links sharing $\mathcal{L}$ subchannels in a cell (Fig. 1). Each cellular link $i \in \mathcal{N} = \{1, \cdots, N\}$ is a connection between a cellular UE and the eNB (i.e., the base station) and has a rate requirement of R_i. Each D2D link $j \in \mathcal{M} = \{1, \cdots, M\}$ is a connection between the transmitter of a D2D UE and the receiver of a D2D UE which are in the same cell and has a rate requirement of R_j. We assume that all the subchannels have the same bandwidth of B Hz. The cellular users use orthogonal subchannels to communicate with the eNB. Denoting either a cellular link or a D2D link by k, we define $g^l_{kk'}$ as the channel power gain between the transmitter of link $k^{'}$ and the receiver of link k on channel l. g^l_{Bk} and g^l_{kB} are defined as the channel power gains between the transmitter of link k and the eNB and the channel power gain between the eNB and the receiver of link k, respectively. Let p^l_k denote the transmission power used for transmitting data from the transmitter of link k to the receiver of link k on subchannel l. Also, let p^l_{kB} and p^l_{Bk} denote the transmission powers used for transmitting data from the transmitter of link k to the eNB and from the eNB to the receiver of link k on subchannel l, respectively. Next, let N_k and N_B denote the additive white Gaussian noise power at the receiver of link k and at the eNB, receptively, which is assumed to be constant over all the subchannels.

Each D2D link tries to choose the communication mode which gives the lowest transmission cost in terms of transmission power and cost of channel occupancy while the QoS requirements of the communication links are satisfied. We use the concept of coalitional game theory to determine which communication mode should be used by each D2D link. We assume that the channel state information for all the involved links is known by a coordinator at the base station. Then, the coordinator can distribute this information to all the links. In this coalitional game, the D2D links in the same coalition will not interfere with each other (e.g., by cooperatively using orthogonal subchannels) but they may interfere with links in different coalitions (i.e., the same subchannel can be used by multiple links in different coalitions at the same time).

III. Coalitional Game Model

In this section, we present a non-transferable utility (NTU) coalitional game where M D2D links are *players*. The coalitions of players are denoted by $\mathcal{S}_c$, $\mathcal{S}_r$, $\mathcal{S}_d \subseteq \mathcal{M}$, where $\mathcal{S}_c$, $\mathcal{S}_r$, and $\mathcal{S}_d$ are coalitions of D2D links using the cellular mode, the reuse mode, and the dedicated mode, respectively. Since each link can use only one mode at a time, we have $\mathcal{S}_c \cup \mathcal{S}_r \cup \mathcal{S}_d = \mathcal{M}$ and $\mathcal{S} \cap \mathcal{S}^{'} = \emptyset$ for any $\mathcal{S}, \mathcal{S}^{'} \in \{\mathcal{S}_c, \mathcal{S}_r, \mathcal{S}_d\}$ and $\mathcal{S} \neq \mathcal{S}^{'}$.

A. Rates of Links

Let $r_j(\mathcal{S}_c)$, $r_j(\mathcal{S}_r)$, and $r_j(\mathcal{S}_j)$ denote the rates of D2D link j when it is in the coalition using the cellular mode, the reuse mode, and the dedicated mode, respectively. We can find the rate of each D2D link when it is using each different communications mode as follows.

Since in the cellular mode the eNB (i.e., base station) needs to relay packets transmitted from the transmitter to the receiver of link j and the same subchannel is used for both uplink and downlink transmissions, the rate $r_j(\mathcal{S}_c)$ is half of the minimum value between the uplink rate from the transmitter of link j to the base station and the downlink rate from the base station to the receiver of link j. That is, $r_j(\mathcal{S}_c)$ is given by (1), where $j \in \mathcal{S}_c$ and $j' \in \mathcal{S}_r$.

Moreover, since a subchannel can be assigned to only one D2D link in each coalition, there may be interference from a D2D link using the reuse mode. Note that $p^{l(up)}_{j'}$ is the transmission power used for transmitting data from the transmitter to the receiver of link j' using the reuse mode while the transmitter of D2D link j in the cellular mode is transmitting data to the base station with transmission power p^l_{jB}. Similarly, $p^{l(down)}_{j'}$ is the transmission power used for transmitting data from the transmitter to the receiver of link $j^{'}$ using the reuse mode while the receiver of D2D link j is receiving data which is relayed from the base station with transmission power p^l_{Bj}. Then, the average transmission power of D2D link j can be calculated as $p^l_j = \frac{1}{2}(p^l_{jB} + p^l_{Bj})$.

In the reuse mode, D2D link j reuses a subchannel which is already used by either a cellular link or a D2D link using the cellular mode. Then, the cellular or D2D link using the

$$r_j(\mathcal{S}_c) = \frac{1}{2}B\min\left\{\log_2\left(1+\frac{g^l_{Bj}p^l_{jB}}{N_B+g^l_{Bj'}p^{l(up)}_{j'}}\right), \log_2\left(1+\frac{g^l_{jB}p^l_{Bj}}{N_j+g^l_{jj'}p^{l(down)}_{j'}}\right)\right\}. \quad (1)$$

$$r_j(\mathcal{S}_r) = \begin{cases} \frac{1}{2}B\left(\log_2\left(1+\frac{g^l_{jj}p^{l(up)}_j}{N_j+g^l_{jj'}p^l_{j'B}}\right)+\log_2\left(1+\frac{g^l_{jj}p^{l(down)}_j}{N_j+g^l_{jB}p^l_{Bj'}}\right)\right), & \text{if subchannel } l \text{ is occupied by a D2D link using the cellular mode.} \\ B\log_2\left(1+\frac{g^l_{jj}p^l_j}{N_j+g^l_{ji}p^l_i}\right), & \text{if subchannel } l \text{ is occupied by a cellular link.} \end{cases} \quad (2)$$

cellular mode may interfere with the transmission of link j using the reuse mode. If subchannel l is occupied by D2D link j' using the cellular mode, the rate of D2D link j is the average rate of the rate obtained by D2D link j' in its uplink transmission (i.e., $B\log_2\left(1+\frac{g^l_{jj}p^{l(up)}_j}{N_j+g^l_{jj'}p^l_{j'B}}\right)$) and the rate obtained by the D2D link j' in its downlink transmission (i.e., $B\log_2\left(1+\frac{g^l_{jj}p^{l(down)}_j}{N_j+g^l_{jB}p^l_{Bj'}}\right)$). We assume that D2D link j needs to keep the rate requirement R_j constant by adjusting its $p^{l(up)}_j$ and $p^{l(down)}_j$ (i.e., $B\log_2\left(1+\frac{g^l_{jj}p^{l(up)}_j}{N_j+g^l_{jj'}p^l_{j'B}}\right) = B\log_2\left(1+\frac{g^l_{jj}p^{l(down)}_j}{N_j+g^l_{jB}p^l_{Bj'}}\right) = R_j$). Therefore, the required SINRs for both the cases are same. Moreover, the average transmission power of D2D link j can be calculated as $p^l_j = \frac{1}{2}(p^{l(up)}_j + p^{l(down)}_j)$ when l is a subchannel shared with a D2D link using the cellular mode. The rate of D2D link j when it is in coalition $\mathcal{S}_r$ (i.e., using the reuse mode) is shown in (2), where $j \in \mathcal{S}_r$, $j' \in \mathcal{S}_c$, and $i \in \mathcal{N}$.

The rate of D2D link j when it is in coalition $\mathcal{S}_d$ (i.e., using the dedicated mode) is

$$r_j(\mathcal{S}_d) = B\log_2\left(1+\frac{g^l_{jj}p^l_j}{N_j}\right), \quad \text{where } j \in \mathcal{S}_d. \quad (3)$$

Since in the dedicated mode D2D link j uses a reserved channel, there is no interference from any other transmitter. Next, the rate of each cellular link i denoted by r_i can be obtined from

$$r_i = \begin{cases} B\log_2\left(1+\frac{g^l_{Bi}p^l_{iB}}{N_B+g^l_{Bj'}p^l_{j'}}\right), & \text{for uplink transmission} \\ B\log_2\left(1+\frac{g^l_{iB}p^l_{Bi}}{N_i+g^l_{ij'}p^l_{j'}}\right), & \text{for downlink transmission} \end{cases} \quad (4)$$

where $i \in \mathcal{N}$.

B. Strategies of the D2D Links

In each coalition $\mathcal{S} \in \{\mathcal{S}_c, \mathcal{S}_r, \mathcal{S}_d\}$, the members of the coalition choose subchannels that minimize the sum of transmission powers while their rate requirements are satisfied as shown in (5), where $\mathcal{A}_\mathcal{S}$ is the set of available subchannels for each coalition $\mathcal{S} \in \{\mathcal{S}_c, \mathcal{S}_r, \mathcal{S}_d\}$ which are denoted by $\mathcal{A}_{\mathcal{S}_c}$, $\mathcal{A}_{\mathcal{S}_r}$, and $\mathcal{A}_{\mathcal{S}_d}$, respectively, and p^l_j is the transmission power of D2D link j on subchannel l.

$$\begin{aligned} &\text{minimize} \quad \sum_{l\in\mathcal{A}_\mathcal{S}}\sum_{j\in\mathcal{S}} p^l_j \\ &\text{subject to} \quad r_j \geq R_j, \quad \forall j \in \mathcal{S}. \end{aligned} \quad (5)$$

Let $\mathcal{A}_\mathcal{N}$ denote the set of subchannels occupied by the cellular links. Next, D2D links using the cellular mode choose subchannels from the set of available subchannels, i.e., $\mathcal{A}_{\mathcal{S}_c} \subseteq \mathcal{L}\backslash\mathcal{A}_\mathcal{N}$. Then, D2D links using the reuse mode will choose the subchannels already occupied by either cellular links or D2D links using the cellular mode, i.e., $\mathcal{A}_{\mathcal{S}_r} \subseteq \mathcal{A}_\mathcal{N} \cup \mathcal{A}_{\mathcal{S}_c}$, and the D2D links using the dedicated mode will choose unoccupied subchannels which is denoted by $\mathcal{A}_{\mathcal{S}_d} \subseteq \mathcal{L}\backslash(\mathcal{A}_\mathcal{N}\cup\mathcal{A}_{\mathcal{S}_c})$. Note that when the subchannels are reused by D2D links, the other links which are using these subchannels (i.e., cellular links or D2D link using the cellular mode) need to adjust their minimum transmission powers such that their rate requirements are satisfied.

In coalition $\mathcal{S}$, a given subchannel l can be assigned to only one D2D link $j \in \mathcal{S}$. Then, $p^l_{j'}$ = 0, for all other j' different from j (i.e., $j \neq j'$). R_j is the rate requirement at the receiver of D2D link j.

According to (1)–(4) and the given rate requirement R_j of each D2D link j, the corresponding SINR requirement of D2D link j denoted by γ_j can be found as follows:

$$\gamma_j = \begin{cases} 2^{(R_j/B)} - 1, & \text{if } j \in \mathcal{S}_r \text{ or } \mathcal{S}_d \\ 2^{(2R_j/B)} - 1, & \text{if } j \in \mathcal{S}_c. \end{cases} \quad (6)$$

Also, given the rate requirement R_i of each cellular link i, the corresponding SINR requirement of cellular link i denoted by γ_i is given by

$$\gamma_i = 2^{(R_i/B)} - 1. \quad (7)$$

Hence, the rate requirement of each link k, which is either a cellular link or a D2D link, can be rewritten in terms of its SINR requirement as follows:

$$\mu_k \geq \gamma_k \quad (8)$$

where μ_k is the achievable SINR.

Let $\mathcal{H}_l$ denote the set of all the links sharing the same subchannel l and $\mathbb{P}$ denote a column vector whose element P_h is the transmission power of each link $h \in \mathcal{H}_l$. We can then find the transmission powers for all the links using the same subchannel that satisfy their SINR requirements as follows:

$$(\mathbb{I} - \mathbb{F})\mathbb{P} = \mathbb{U} \quad (9)$$

where $\mathbb{I}$ is an identity matrix, $\mathbb{U}$ is a column vector which can be written as

$$\mathbb{U} = \left(\cdots, \frac{\gamma_h N_h}{g_{hh}^l}, \cdots \right)^T, \quad \forall h \in \mathcal{H}_l \tag{10}$$

where T is the vector transpose. $\mathbb{F}$ is an $|\mathcal{H}_l| \times |\mathcal{H}_l|$ matrix ($|\mathcal{H}_l|$ is the number of links sharing subchannel l) whose (h, h')-th element is

$$F_{h,h'} = \begin{cases} \gamma_k \frac{g_{hh'}^l}{g_{hh}^l}, & \text{if } h \neq h' \\ 0, & \text{if } h = h'. \end{cases} \tag{11}$$

Note that the transmission powers given by (9) can be obtained distributively by using the power control algorithm proposed in [7].

C. Cost Function

The transmission cost of D2D link j when it is a member of coalition $\mathcal{S} \in \{\mathcal{S}_c, \mathcal{S}_r, \mathcal{S}_d\}$ is defined as a function of transmission power and the cost associated with using the subchannel as follows:

$$u_j(\mathcal{S}, l) = \delta_j p_j^l(\mathcal{S}) + \alpha_j c_j^l(\mathcal{S}) \tag{12}$$

where $p_j^l(\mathcal{S})$ is the transmission power of link i on subchannel l (in mW) which can be obtained from the minimization problem in (5) and $c_j^l(\mathcal{S}) \geq 0$ is the price of using subchannel l when D2D link j is in coalition $\mathcal{S} \in \{\mathcal{S}_c, \mathcal{S}_r, \mathcal{S}_d\}$. Since the price of using a dedicated subchannel $c_j^l(\mathcal{S}_d)$ has to be higher than the price of using a shared channel $c_j^l(\mathcal{S}_c)$ and $c_j^l(\mathcal{S}_r)$, we assume $c_j^l(\mathcal{S}_c), c_j^l(\mathcal{S}_r) \leq c_j^l(\mathcal{S}_d)$. In (12), δ_j and α_j are the positive weight constants of the transmission power and the price of subchannel occupancy, respectively. Each D2D link aims at minimizing its transmission cost.

IV. Coalition Formation

Each D2D link or player j makes a decision to leave its current coalition and join another coalition if in the new coalition, player j will incur a lower transmission cost and all the other players will not incur higher transmission costs than the ones incurred when they are in their current coalitions, i.e.,

$$\begin{aligned} u_j(\mathcal{S}' \cup \{j\}) &< u_j(\mathcal{S}), j \in \mathcal{S} \\ u_{j'}(\mathcal{S}' \cup \{j\}) &\leq u_{j'}(\mathcal{S}'), \forall j' \in \mathcal{S}' \end{aligned} \tag{13}$$

where $\mathcal{S}, \mathcal{S}' \in \{\mathcal{S}_c, \mathcal{S}_r, \mathcal{S}_d\}$, $\mathcal{S} \neq \mathcal{S}'$, and $j \neq j'$.

To find the solution of stable coalition formation [8] and analyze stable coalition structures, we can formulate a discrete-time Markov chain (DTMC). The state space of the DTMC can be expressed as the set of all the coalition structures denoted by $\Upsilon = \{\mathcal{S}_c, \mathcal{S}_r, \mathcal{S}_d\}$. The transition from one state to another state depends on the decisions of the players to leave and join the coalitions. Based on the probability that player j leaves its coalition $\mathcal{S}$ and joins another coalition $\mathcal{S}'$, the transition probability from state Υ to Υ' can be found as in (15), where $\frac{1}{M}$ is the probability that D2D link or player j is selected to make her decision to leave and join, $\frac{1}{2}$ is the probability that player i selects one of the remaining two coalitions, i.e., other two D2D communications modes, $\varphi_x(\Upsilon'|\Upsilon)$ is the probability that each player in the new coalition $\mathcal{S}' \cup \{j\}$ will accept the change which makes the coalition structure change from Υ to Υ', i.e.,

$$\varphi_x(\Upsilon'|\Upsilon) = \begin{cases} 1, & u_x(\mathcal{S}' \cup \{j\}) < u_x(\mathcal{S}) \\ 0, & \text{otherwise} \end{cases} \tag{14}$$

where $\mathcal{S}, \mathcal{S}' \in \Upsilon$ and $\mathcal{S} \neq \mathcal{S}'$. The stable coalitions correspond to the absorbing states of the DTMC [8].

Given the transition matrix $\mathbf{Q}$ whose elements are $\rho_{\Upsilon,\Upsilon'}$, the stationary probability vector $\vec{\boldsymbol{\pi}}$ can be obtained by solving the following equation:

$$\vec{\boldsymbol{\pi}}^T \mathbf{Q} = \vec{\boldsymbol{\pi}}^T \tag{16}$$

where $\vec{\boldsymbol{\pi}}^T \vec{\mathbf{1}} = 1$, and $\vec{\mathbf{1}}$ is a vector of ones, $\vec{\boldsymbol{\pi}} = \begin{bmatrix} \pi_{\Upsilon_1} & \cdots & \pi_{\Upsilon_q} & \cdots & \pi_{\Upsilon_{3^M}} \end{bmatrix}^T$, and π_{Υ_q} is the probability that the coalition structure Υ_q will be formed.

The solution for the DTMC can be obtained in a centralized manner. There can be multiple stable coalitional structures (i.e., multiple absorbing states) as shown in Fig. 2. A stable coalitional structure can be selected randomly by using the proposed distributed algorithm (as shown in **Algorithm 1**) to find the solution based on the individual leave-and-join decision of each D2D link j. Note that we can adapt the algorithm in order to select a specific stable coalitional structure (e.g., a stable coalitional structure giving the lowest total cost).

Algorithm 1 Distributed coalition formation algorithm

Initialize $\phi = 0$ and $\Upsilon(\phi)$
loop
  At time ϕ, D2D link j is randomly selected to make a decision to leave $\mathcal{S}(\phi)$ and join any coalition $\mathcal{S}'(\phi)$.
  D2D link j randomly selects $\mathcal{S}'(\phi)$, one of two other modes (i.e., coalitions).
  D2D link j sends its request to the central coordinator to join $\mathcal{S}'(\phi)$ and required information is exchanged for solving the minimization problem.
  All D2D links $j' \in \mathcal{S}'(\phi)$ compute and send their transmission costs $u_{j'}(\mathcal{S}'(\phi) \cup \{j\})$ to the central coordinator.
  D2D link j computes its transmission cost $u_j(\mathcal{S}'(\phi) \cup \{j\})$.
  if $u_j(\mathcal{S}'(\phi) \cup \{j\}) < u_j(\mathcal{S}(\phi))$ is true
    if $u_{j'}(\mathcal{S}'(\phi) \cup \{j\}) < u_{j'}(\mathcal{S}'(\phi)), \forall j' \in \mathcal{S}'(\phi)$ is true
      D2D link j joins $\mathcal{S}'(\phi)$
      $\Upsilon(\phi+1) = ((\Upsilon(\phi) \setminus \{\mathcal{S}(\phi)\}) \setminus \{\mathcal{S}'(\phi)\}) \cup (\{\mathcal{S}'(\phi) \cup \{j\}\} \cup \{\mathcal{S}(\phi) \setminus \{j\}\})$
    else
      $\Upsilon(\phi + 1) = \Upsilon(\phi)$
    end
  else
    $\Upsilon(\phi + 1) = \Upsilon(\phi)$
  end
  $\phi = \phi + 1$
end loop when a stable coalition structure Υ^* is obtained (i.e., no D2D link prefers to move to another coalition).

$$\rho_{\Upsilon,\Upsilon'} = \begin{cases} \frac{1}{M} \times \frac{1}{2} \prod_{x \in \mathcal{S}' \cup j} \varphi_x(\Upsilon'|\Upsilon), & \Upsilon \neq \Upsilon' \& \Upsilon' = ((\Upsilon \setminus \{\mathcal{S}\}) \setminus \{\mathcal{S}'\}) \cup (\{\mathcal{S}' \cup \{j\}\} \cup \{\mathcal{S} \setminus \{j\}\}) \\ 1 - \sum_{\Upsilon' \in \Omega, \Upsilon' \neq \Upsilon} \rho_{\Upsilon,\Upsilon'}, & \Upsilon = \Upsilon' \\ 0, & \text{otherwise.} \end{cases} \quad (15)$$

V. Numerical Results

Using Matlab, we simulate a single cell system with 4 cellular links coexisting with 4 D2D links in a rectangular area of 300m $\times$ 300m. The base station is located at the center of the area. The locations of cellular UEs are uniformly distributed within the range of 50m from the base station. For the randomly located D2D links, the distance between a transmitter and a receiver is uniformly distributed within the range of 100m. The path-loss is calculated from $PL(k,k')[\text{dB}] = PL(d_0)[\text{dB}] + 10n_{SF}\log\left(\frac{d_{k,k'}}{d_0}\right)$ with $n_{SF} = 4$ and the measured line-of-sight (LOS) path-loss at $d_0 = 1$m, $PL(d_0) = 37.7$ dB, and $d_{k,k'}$ being the distance between the transmitter and the receiver of link k. The noise power at the base station and all the D2D receivers is 10^{-10} W. The required transmission rate for all the cellular and D2D links are set to 128 kbps. The number of subchannels is 10 each with bandwidth of 180 kHz. The values of δ_j and α_j are set to 20 and 10, respectively. The price of using a dedicated subchannel is set to be $c_j^l(\mathcal{S}_d)$ is 5 and the price of using a shared channel is set to be $c_j^l(\mathcal{S}_c) = c_j^l(\mathcal{S}_r)$ is 0 for all the D2D links and the subchannels.

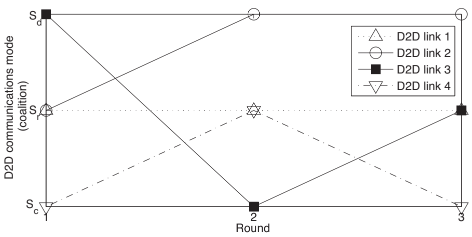

Fig. 2. Stable coalitional structure obtained from the distributed algorithm which is composed of D2D links in coalition $\mathcal{S}_c$ using the cellular mode, coalition $\mathcal{S}_r$ using the reuse mode, and coalition $\mathcal{S}_d$ using the dedicated mode.

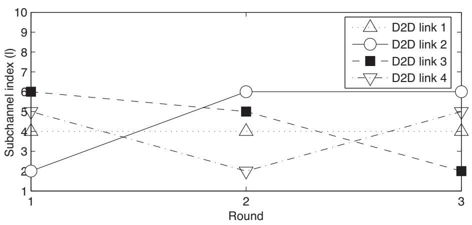

Fig. 3. Subchannels occupied by D2D links when they are in different coalitions as shown in Fig. 2.

Fig. 2 shows how the stable coalition structures are obtained from the proposed distributed algorithm. As the algorithm executes, we observe different stable coalition structures which are $\Upsilon^* = \{\mathcal{S}_c, \mathcal{S}_r, \mathcal{S}_d\} = \{\{4\},\{1,2\},\{3\}\}$, $\{\{3\},\{1,4\},\{2\}\}$, and $\{\{4\},\{1,3\},\{2\}\}$ for each round, respectively. Using the DTMC analysis, the stationary probabilities for the stable states (i.e., stable coalition structures) $\Upsilon^* = \{\{4\},\{1,2\},\{3\}\}$, $\{\{3\},\{1,4\},\{2\}\}$, and $\{\{4\},\{1,3\},\{2\}\}$ are obtained with probabilities 0.109, 0.123, and 0.122, respectively. Fig. 3 shows the subchannels occupied by the D2D links when they are using different D2D communications modes. The subchannels are assigned to the D2D links according to the minimization problem in (5).

TABLE I
Average transmission cost ($E[u_j]$) and transmission power ($E[p_j]$) of each D2D link

D2D link	Average cost	Average transmission power in mW
1	6.84	9.6
2	17.53	162.0
3	10.77	18.1
4	9.39	106.7

Table I shows the average cost and transmission power of each D2D link, which are calculated as follows:

$$E[u_j] = \sum_{q=1}^{D_M} \pi_{\Upsilon_q} u_j(\mathcal{S}), \quad \text{for } j \in \mathcal{S} \text{ and } \mathcal{S} \in \Upsilon_q \quad (17)$$

$$E[p_j] = \sum_{q=1}^{D_M} \pi_{\Upsilon_q} p_j(\mathcal{S}), \quad \text{for } j \in \mathcal{S} \text{ and } \mathcal{S} \in \Upsilon_q \quad (18)$$

where D_M is the number of coalition structures and π_{Υ_q} can be found from (16).

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