Joint Mode Selection and Radio Resource Allocation for D2D Communications Based on Dynamic Coalition Formation Game

(Invited Paper)

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***Abstract*—Device-to-Device (D2D) communication makes large benefit on users' data rate due to the proximity between potential D2D transmitters and receivers. However, the data rate is restricted by the co-channel interference between underlaying D2D links and traditional cellular users (CUs). In this paper, we investigate how to leverage D2D communication to improve overall system data rate via joint mode selection and radio resource allocation. We first formulate a problem to maximize the sum of users' data rate with interference and power constraints for both D2D links and CUs. Furthermore, we adopt the coalition formation game with transferable utility (TU) to solve the formulated problem. In the game model, the D2D links and CUs that share the same Resource Block (RB) form a coalition and the coalition formation decisions are determined by a best-reply rule. Simulation results show that the proposed scheme outperforms the scheme with heuristic greedy algorithm in terms of average users' data rate and fairness.**

***Keywords*—Device-to-device (D2D), coalition formation game, transferable utility (TU), mode selection, resource allocation, data rate, fairness.**

I. INTRODUCTION

Device-to-device (D2D) communication is listed in 3GPP Release 12 as a critical technology of LTE-Advanced (LTE-A) because of the three types of promising gains: 1) the proximity gain, 2) the reuse gain, and 3) the hop gain [1], [2], [3]. Besides the traditional communication via the base station, called evolved NodeBs (eNBs) in the LTE-A infrastructure, D2D users may be enabled to communicate directly bypassing the eNB [4]. This can be either under the control of the eNB or without it. In any case, the co-channel interference becomes a challenge when D2D are allowed operating in underlay mode, i.e., using the same frequency allocated to the regular cellular links. Recently, many works have dealt with this problem through proper mode selection and smart radio resource allocation.

The user equipments (UEs) in network-assisted D2D links remain controlled by the eNBs and keep cellular operation, and hence, UEs can switch between direct (D2D mode) and traditional cellular communications (cellular mode). If the co-channel interference caused by spectrum sharing deteriorates the system performance, D2D users may engage in cellular mode. In [5], an optimal mode selection scheme for D2D users in a multi-cell scenario was proposed. The eNB estimates the expected throughput based on the Signal to Interference plus Noise Ratio (SINR) and selects communication mode with the highest throughput. Simulation results showed that there was a 50% cell throughput gain. In [6], the authors proposed a scheme based on a coalitional game to select the transmission modes for D2D users, and the selection criteria was based on the power consumption. In [7], the work focused on the optimized cell rate by mode selection for D2D communications. The numerical results showed substantial gains from D2D communications handling local traffic.

Since the system performance can be improved by choosing proper resource sharers for D2D users, radio resource allocation is also a very important issue. In [8], a greedy heuristic Resource Block (RB) allocation algorithm was proposed where any CU with higher channel quality could share RBs with the D2D user that had lower channel quality. The performance of this algorithm can be further improved by considering more factors as it only used the interference channel gain as the factor to choose resource sharers for D2D users. In [9], the authors proposed two algorithms to allocate radio resources to D2D users. The two algorithms were based on interference mitigation between cellular and D2D users using interference tracing and tolerable interference broadcasting mechanisms, respectively. The simulation results showed that the overall throughput performance could be improved by 41%. In [10], the authors proposed a resource allocation scheme consisting of three steps, i.e., access admission, optimal power control and resource allocation, to find the optimal solution of the formulated problem. Numerical results showed that the overall network throughput could be significantly improved.

From the above, mode selection and radio resource allocation, when applied alone, are efficient approaches to improve system data rate. However, in the aforementioned works, they have never been jointly considered. In this paper, we propose a new joint mode selection and radio resource allocation scheme for D2D communications based on the coalition formation game in a distributed manner. We consider uplink (UL) resource sharing between D2D and CUs as the UL resources are under-utilized as compared to the downlink (DL) resources. In addition, the interference is easier to be controlled and mitigated in UL resources since the victim of interference by D2D communications is the immobile eNB. The coalition formation game is adopted because users can choose their transmission modes and spectrum reusing partners autonomously, which relieves the eNB from heavy signaling overhead and high computational complexity. In the game model, the D2D links

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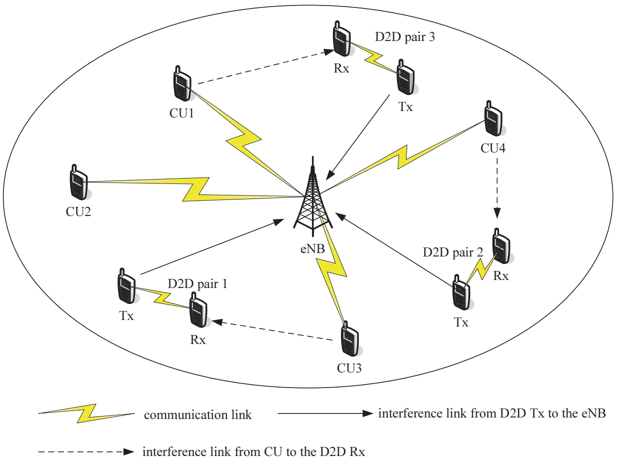

Fig. 1: System model of D2D communications as an underlay of cellular networks (uplink)

and CUs that share the same RB form a coalition and the coalition formation decisions are determined by a best-reply rule. We also adopt the concept "experimentation" which gives users the capability to destabilize the prevailing structure.

This paper is organized as follows. Section II introduces the system model and problem formulation. The coalition formation game model is presented in Section III. Section IV illustrates the numerical results for the proposed algorithm. Section V concludes the paper.

II. SYSTEM MODEL AND PROBLEM FORMULATION

We consider a single cell scenario, which includes multiple CUs and D2D pairs, as illustrated in Fig. 1. All D2D pairs constitute the set $\mathcal{D} = \{D_1, ..., D_i, ...\}$ and $|\mathcal{D}| = M$. The transmitter and receiver of D_i are represented by D_{Ti} and D_{Ri}, respectively. The D2D pairs can choose to transmit in either D2D mode or traditional cellular mode. The CUs can only transmit via the eNB in cellular mode and constitute the set $\mathcal{C} = \{C_1, ..., C_j, ...\}$ with $|\mathcal{C}| = N$.

We consider the LTE-A uplink employing Single Carrier FDMA (SC-FDMA) where the radio resources are allocated in units of RBs and each user has been granted one RB for transmission in a random manner in advance. The total system bandwidth is B and is divided into K orthogonal RBs. Each D2D pair can choose to communicate in either traditional cellular mode or D2D mode. If D2D operations are enabled, a D2D pair chooses a CU and shares its RB. Intuitively, when D2D transmitters and receivers locate in proximity with each other, employing D2D modes will achieve higher data rate compared to transmitting via the eNB. However, spectrum reuse may cause additional co-channel interference, thus lowering the data rates of users. To control the intra-cell interference in a reasonable range, we assume that one D2D pair can only share one existing CU's RB, while the RB of an existing CU can only be reused by one D2D pair.

Based on the selected transmission modes of D2D pairs, the data rate expressions of users can be calculated in the following two cases:

(i) When D_i chooses the D2D mode and reuses the RB of C_j, the received signal-to-interference-plus-noise (SINR) of D_{Ri} is given by

$$\xi_{D_i} = \frac{p_{D_i} G_{D_i}}{p_{C_j} G_{C_j,D_i} + N_0}, \tag{1}$$

and the received SINR for C_j on the eNB is

$$\xi_{C_j} = \frac{p_{C_j} G_{C_j,B}}{p_{D_i} G_{D_i,B} + N_0}, \tag{2}$$

where G_{D_i}, $G_{D_i,B}$ are the channel gains between D_{Ti} and D_{Ri} and between D_{Ti} and the eNB, respectively. The channel gains between C_j and D_{Ri} and between C_j and the eNB are denoted by G_{C_j,D_i} and $G_{C_j,B}$, respectively. Moreover, p_{D_i} is the transmission power of D_{Ti}, and p_{C_j} is the transmission power of C_j, $N_0 = B_{RB}\sigma^2$ is the additive white Gaussian noise power, where B_{RB} is the bandwidth of a RB which equals to 180KHz and σ^2 is the power spectral density. The data rates of D_i and C_j are given by

$$R_{D_i} = B_{RB} \log_2(1 + \xi_{D_i}), \tag{3}$$

and

$$R_{C_j} = B_{RB} \log_2(1 + \xi_{C_j}), \tag{4}$$

respectively.

(ii) When the spectrum reuse between D2D pairs and CUs causes severe co-channel interference, D2D pairs may choose to communicate via exclusive spectrum in the traditional cellular mode. In this scenario, the eNB needs to relay packets transmitted from the D2D transmitter to the receiver and the same RB is used for both uplink and downlink transmissions. Therefore, the achievable data rate is half of the minimum of uplink and downlink transmissions. The data rate of a D2D pair that communicates via the eNB is given by

$$R_{D_i} = \frac{B_{RB}}{2} \min\{\log_2(1+\mathrm{SNR_{up}}), \log_2(1+\mathrm{SNR_{dw}})\}, \tag{5}$$

where $\mathrm{SNR_{up}} = p_{D_i,B} G_{D_i,B}/N_0$ and $\mathrm{SNR_{dw}} = p_{B,D_i} G_{B,D_i}/N_0$ are the UL and DL SNR values, respectively. The transmission power of D_{Ti} to the eNB is expressed as $p_{D_i,B}$, and the transmission power of eNB to D_{Ri} is expressed as p_{B,D_i}.

It is assumed that the transmission power of the eNB can be adjusted to guarantee that the downlink data rate is higher than the uplink data rate. Therefore, the achievable data rate of the D2D pair in cellular mode can be written by

$$R_{D_i} = \frac{B_{RB}}{2} \log_2(1 + \frac{p_{D_i B} G_{D_i,B}}{N_0}). \tag{6}$$

The data rates of CUs that do not share their RBs with D2D pairs are given by

$$R_{C_j} = B_{RB} \log_2 \left(1 + \frac{p_{C_j} G_{C_j,B}}{N_0}\right). \tag{7}$$

In this work, the objective is to maximize the sum of users' data rate. The problem formulation is expressed as

$$\max \left(\sum_{i=1}^{M} R_{D_i} + \sum_{j=1}^{N} R_{C_j} \right), \tag{8}$$

$$s.t. \begin{cases} p_{D_i} G_{D_i,C_j} \le I_{C_j}^{thr}, & \forall C_j \in \mathcal{C}, \\ p_{C_j} G_{C_j,D_i} \le I_{D_i}^{thr}, & \forall D_i \in \mathcal{D}, \\ 0 < p_{C_j} \le p_{C_j}^{max}, & \forall C_j \in \mathcal{C}, \\ 0 < p_{D_i} \le p_{D_i}^{max}, & \forall D_i \in \mathcal{D}, \end{cases} \tag{9}$$

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The first two constraints in Eq. (9) restrict the interference caused to CUs and D2D pairs. The peak interference constraint can be calculated based on the SINR threshold, i.e., $I^{thr} = p_r/\xi^{thr} - N_0$, where p_r is the received power at the receiver. The last two constraints in Eq. (9) restrict the transmission power of users. The transmission power needs to be a positive value and lower than users' maximum transmission power. To relieve the eNB's high computational complexity, we adopt the dynamic coalition formation game with TU to solve this problem.

III. DYNAMIC COALITION FORMATION GAME

In the game model, a set of players seek to form cooperative groups, i.e. coalitions, to strengthen their positions in the game. If the coalition value which quantifies the worth of a coalition depends solely on the members of that coalition, with no dependence on how the players in other coalitions are structured, this coalitional game is in the characteristic form. In our work, we define a coalition formation game as ($\mathcal{S}$, v, U) with the player set $\mathcal{N} = \mathcal{D} \cup \mathcal{C}$, where $\mathcal{S}$ denotes the coalition structure satisfying $\mathcal{S} = \{S_1, ..., S_p, ...S_P\}$ with S_p being a coalition, and for $\forall p' \neq p$, $S_{p'} \cap S_p = \emptyset$, we have $\cup_{p=1}^{P} S_p = \mathcal{N}$, the characteristic function quantifying the gain of S_p is represented by $v(S_p)$, and $U = \{u_1, ..., u_x, ...\}$ is the payoff allocation vector of players.

According to the mode that each D2D pair chooses, we can categorize the coalitions into the following three cases:

(1) Case 1: A coalition contains one D2D pair and one cellular user, i.e., $S_p = \{D_i, C_j\}$. In this case, D_i chooses the D2D mode and reuses the RB of C_j.

(2) Case 2: A D2D pair forms a singleton set, i.e., $S_p = \{D_i\}$. In this case, D_i chooses the traditional cellular mode and uses an exclusive RB.

(3) Case 3: A CU forms a singleton set, i.e., $S_p = \{C_j\}$. In this case, C_j does not share its RB with any D2D pair.

In a coalitional game, the transferable utility (TU) property implies that the total utility of the coalition can be divided in any manner between the coalition members, while the nontransferable utility (NTU) property implies that the payoff that each player in a coalition receives is dependent on the joint actions that the players in the same coalition select. The distributed mode selection and resource allocation process in our model is defined as a coalitional TU game. The characteristic function of our game is

$$v(S_p) = \sum_{n \in S_p} R_x, \tag{10}$$

where x can be either a D2D pair or a CU in the coalition S_p, and R_x is the corresponding data rate achieved by the user.

Coalition collection is defined as a set of disjoint coalitions. In this game model, the coalitions, which contain D2D pairs, form the D2D collection $\mathcal{A}_D$; while the singleton coalitions, each of which contains only one CU, form the cellular collection $\mathcal{A}_C$. The coalition structure changes when a D2D pair chooses to leave the current coalition and joins in a coalition of the cellular collection or forms a singleton coalition.

The initial state of the game is the set of singleton coalitions, where all D2D pairs are assumed to communicate in traditional cellular mode. Each user's payoff is the coalition value at the initialized step. In the following steps, D2D pairs will be chosen randomly to select the proper modes and spectrum reusing partners. If a D2D pair finds that communicating in cellular mode can achieve higher total data rate, it will choose to stay in the singleton coalition.

We assume that a D2D pair D_i is selected to revise her strategy, then all the other players keep their strategies, i.e. for $x \neq D_i$, $S^{t+1}(x) = S^t(x)$, and $u_x^{t+1} = u_x^t$, where $S^t(x)$ represents the coalition in which the player x exists, and u_x^t is the payoff of x at time t. Since all the players are myopic, the best-reply rule guarantees that players can select the coalition that promises her the highest payoff. Then, the payoff of D_i at time $t+1$ can be calculated based on the best-reply rule as:

$$u_{D_i}^{t+1} = \max\{\max_{S_m \in \mathcal{A}_C \cup \emptyset} (v(S_m \cup \{D_i\}) - u_{C_j}^t), u_{D_i}^t\}, \tag{11}$$

$$S^{t+1}(D_i) = \begin{cases} \{\arg \max\limits_{S_m \in \mathcal{A}_C \cup \emptyset} (v(S_m \cup \{D_i\}) - u_{C_j}^t)\} \cup \{D_i\} \\ \qquad\qquad\qquad\qquad , u_{D_i}^{t+1} \neq u_{D_i}^t, \\ S^t(D_i) \qquad\qquad\qquad , u_{D_i}^{t+1} = u_{D_i}^t, \end{cases} \tag{12}$$

where S_m is an empty set or a coalition of the cellular collection. If S_m is an empty set, we have $u_{C_j}^t = 0$; otherwise, $u_{C_j}^t$ is the payoff of the CU in coalition S_m at time t. It should be noted that Eq. (11) and Eq. (12) exist only with the constraints in Eq. (9) are satisfied.

For a TU game, the payoff allocation vector U is said to be blocked by a coalition S_b if $\sum_{x \in S_b} u_x < v(S_b)$. The core of a game is defined by the set of all feasible payoff allocations that cannot be blocked by any coalition [11].

It should be noted that the players can only switch between existing coalitions, therefore, it is possible that there exists a blocking coalition that cannot be formed directly based on the current coalition structure. This is the reason why "experimentation" was introduced in [12], where it provides players with the capability to destabilize the prevailing structure. Players are allowed to take random actions (with a small probability) whenever they are members of a potentially blocking coalition even though the new coalition is a suboptimal one. This is consistent with the psychological phenomenon, where a player will tend to get 'fed up' with the current situation and might do something irrational if she realizes that she is performing poorly, just in order to induce some changes. Thus, "experimentation" does not require any higher degree of rationality, or farsightedness for players.

The algorithm for joint mode selection and resource allocation problem based on the best-reply process with "experimentation" is described in **Algorithm 1**.

IV. NUMERICAL RESULTS

In this section, we evaluate the performance of the distributed joint mode selection and resource allocation algorithm for D2D communications. The benchmark is a modified joint mode selection and resource allocation scheme based on the greedy heuristic algorithm proposed in [8]. In the heuristic algorithm [8], the eNB selects the cellular uplink with highest channel gain to share resource with the D2D pair with the lowest interference channel gain. Different from the algorithm in [8], we allow the D2D pairs that did not find a proper spectrum reusing partner to transmit in cellular mode rather than leave them idle in the benchmark.

We assume that the frequency band is frequency flat. The channel gain between D_{Ti} and D_{Ri} is modeled as $G_{D_i} =$

Algorithm 1 Distributed Joint Mode Selection and Resource Management Algorithm

```
Initialise $t = 0$;
The initial state is the set of singleton coalitions. All singleton sets of D2D pairs constitute the D2D collection $\mathcal{A}_D^t$, i.e., $\mathcal{A}_D^t = \{\{D_0\}, ..., \{D_M\}\}$, while all singleton sets of CUs constitute the cellular collection $\mathcal{A}_C^t$, i.e., $\mathcal{A}_C^t = \{\{C_0\}, ..., \{C_N\}\}$;
loop
    At time $t > 0$, randomly select a coalition $S^t(D_i) \in \mathcal{A}_D^t$ to revise $D_i$'s strategy, where $S^t(D_i)$ is the coalition that the player $D_i$ exists at time $t$. Other players keep their strategies, i.e., $S^{t+1}(x) = S^t(x)$, $u_x^{t+1} = u_x^t$, for all $x \neq D_i$;
    If there exists a coalition $S_b(D_i)$ blocking the current payoff allocation, then $D_i$ will take the best-reply process with probability $1 - \varepsilon$ and "experiment" with probability $\varepsilon$. Otherwise, $D_i$ takes the best-reply process with probability 1.
    - - - - - - Best-reply Process
    Calculate the maximum expected payoff obtained by $D_i$ based on the current coalition structure, i.e.,
        $u_{D_i}^e = \max_{S_m \in \mathcal{A}_C \cup \emptyset} \left( v(S_m \cup \{D_i\}) - u_{C_j}^t \right)$    (13)
    where $u_{D_i}^e$ is the expected payoff.
    if $u_{D_i}^e > u_{D_i}^t$ and all the constraints in Eq. (9) are satisfied then
        $S^{t+1}(D_i) = \{\arg \max_{S_m \in \mathcal{A}_C \cup \emptyset} (v(S_m \cup \{D_i\}) - u_{C_j}^t)\} \cup \{D_i\}$, $\mathcal{A}_D^{t+1} = \{\mathcal{A}_D^t \setminus \{S^t(D_i)\}\} \cup \{S^{t+1}(D_i)\}$, $\mathcal{A}_C^{t+1} = \{\mathcal{A}_C^t \setminus \{S^{t+1}(D_i) \setminus \{D_i\}\}\} \cup \{S^t(D_i) \setminus \{D_i\}\}$;
    else
        $S^{t+1}(D_i) = S^t(D_i)$, $\mathcal{A}_D^{t+1} = \mathcal{A}_D^t$, $\mathcal{A}_C^{t+1} = \mathcal{A}_C^t$;
    end if
    $t = t + 1$;
    - - - - - - Experimentation
    $D_i$ randomly chooses a coalition $S_r$ from the cellular collection with equal probability to join in as long as constraints in Eq. (9) are all satisfied;
    $S^{t+1}(D_i) = S_r \cup \{D_i\}$, $\mathcal{A}_D^{t+1} = \{\mathcal{A}_D^t \setminus \{S^t(D_i)\}\} \cup \{S^{t+1}(D_i)\}$, $\mathcal{A}_C^{t+1} = \{\mathcal{A}_C^t \setminus \{S_r\}\} \cup \{S^t(D_i) \setminus \{D_i\}\}$;
    $t = t + 1$;
end loop when a stable state is obtained.
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$(L_{D_i})^{-\alpha}\beta$, where L_{D_i} is the distance between D_{Ti} and D_{Ri} and β is the system constant; α is the path loss exponent, which is set to be 4. Similarly, we can get the channel gains $G_{D_i,B}$, G_{C_j,D_i} and $G_{C_j,B}$. Radius of the cell is 500m, and the eNB is centered in the cell. CUs and D2D pairs locate randomly in the cell, with the radial and angular coordinates of the users following the uniform distribution. Other simulation parameters are listed in TABLE I.

TABLE I: Simulation Parameters

Transmission power of devices	250mW(24dBm)
D2D SINR Threshold	2dB
CU SINR Threshold	4dB
Bandwidth of each RB	180kHz
ε	0.01
β	0.01
Noise level	-98dBm
Users' maximum transmission power	23dBm

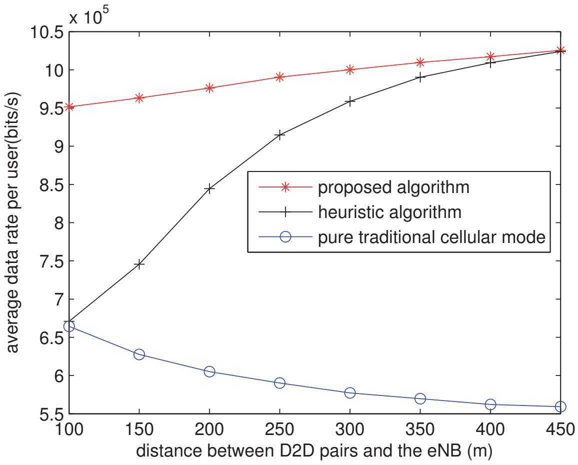

Fig. 2: Average throughput for different distances between D2D pairs and the eNB, where number of D2D pairs=10, number of CUs=50 and D2D cluster radius=20m.

Fig. 2 shows the effect of the distance between D2D pairs and the eNB on the average throughput. With the increment of distance between D2D pairs and the eNB, the interference from D2D pairs to the cellular uplink gets smaller. Therefore, the average data rate of users is improved. When the distance gets to a certain large value, the interference is small enough, thus the increasing rate of energy efficiency gets slower. We can conclude from this figure that the proposed algorithm outperforms the heuristic one. When the distance between D2D pairs and the eNB is large enough, the interference from D2D pairs to all CUs is controlled under a small value, thus the effect of choosing the best spectrum reuse partner is not obvious any more. It can be seen in the figure that the difference between the two algorithms gets smaller when the distance is large enough. On the contrary, the achievable data rate of the scenario where all D2D pairs transmit in cellular mode becomes smaller with the increase of the distance because of the increased path loss.

Fig.3 shows the average data rate ratio between the proposed and heuristic algorithms for different number of D2D pairs. It can be found that the ratio is larger with more D2D pairs. This is because the effect of choosing the best spectrum reusing partner gets more obvious when the number of D2D pairs increases.

Fig. 4 shows the average data rates of users for different D2D cluster radii, i.e., the distance between the D2D transmitter and receiver. We can find that the proposed algorithm outperforms the heuristic one for any D2D cluster radius. The average data rate decreases with the increment of D2D cluster radius because of the improved path loss.

Fig. 5 illustrates the fairness of the proposed and heuristic algorithms. We adopt the Jain's fairness index to do the evaluation, and the index is calculated by: $\mathcal{J} = (\sum_{x=1}^{n} r_x)^2/(n \times \sum_{x=1}^{n} {r_x}^2)$. The results range from $\frac{1}{n}$ (worst case) to 1 (best case), and it is maximum when all users get the same value. From this figure, we can find that the proposed algorithm achieves better fairness compared to the heuristic one. In

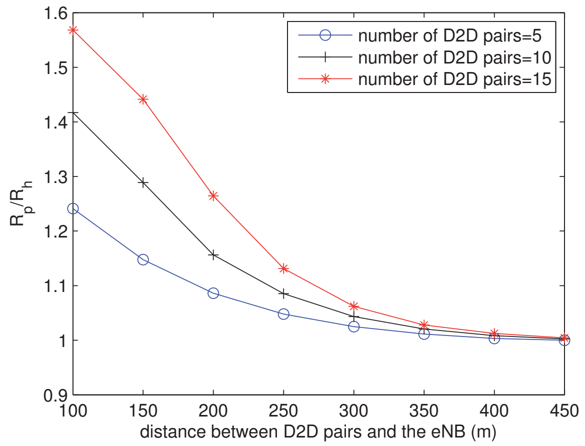

Fig. 3: Average data rate ratio between proposed and heuristic algorithms for different number of D2D pairs, where number of CUs=50, D2D cluster radius=20m.

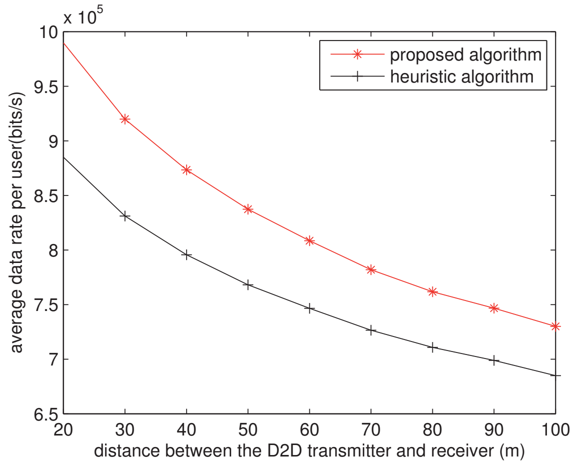

Fig. 4: Average throughput for different D2D cluster radii, where number of D2D pairs=10, number of CUs=50, and the D2D pairs locate randomly in the cell.

the heuristic algorithm, the eNB selects the CU with highest channel gain of the CU-BS link to share resource with the D2D pair with the lowest interference channel gain of the D2D-eNB link, which restricts the fairness performance. For the proposed algorithm, D2D pairs are selected randomly to find a proper transmission mode.

V. CONCLUSIONS

In this paper, we have proposed a joint mode selection and radio resource allocation algorithm for network-assisted D2D communications based on the dynamic coalition formation game to improve the overall system throughput. The coalition formation process is determined by the best-reply rule with “experimentation”. Simulation results demonstrate that the proposed algorithm outperforms the greedy heuristic algorithm in terms of both network throughput and fairness.

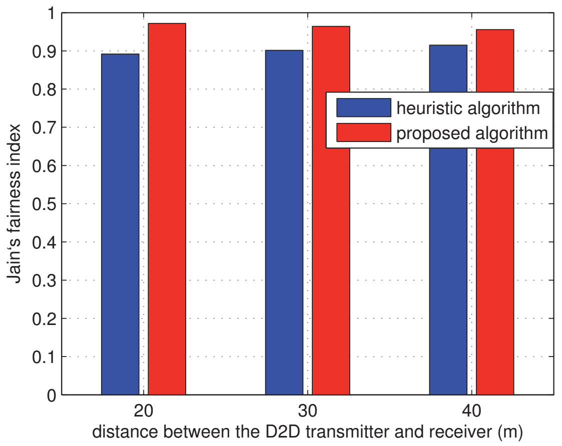

Fig. 5: Jain’s fairness index of D2D pairs’ rates, where number of D2D pairs=10, number of CUs=50, and the D2D pairs locate randomly in the cell.

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