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# Performance Enhancement for Device-to-Device Underlaying Cellular Network Using Coalition Formation Game

Amr Radwan†, Hoon Kim††

## ABSTRACT

Interference in device-to-device (D2D) communication underlaying cellular network needs to be elaborately investigated because of channel sharing. The objective is to improve the quality of D2D communications while maintaining high performance for cellular users. In this paper, we solve the above problem by jointly considering channel allocation and power control using coalition formation game. Our cooperative game theoric approach allows to enhance network-wide performance. We design a merge-and-split algorithm to deal with the complexity of the combinatorial structure in coalition formation problem. The analytical and numerical results show that our algorithm converges to a stable point which achieves high network performance.

**Key words:** Device-to-device, Power Control, Channel Allocation, Wireless Network.

## 1. INTRODUCTION

Because of the increasing demand for mobile data [1], radio bandwidth needs to be used more efficiently. The underlay mode of device-to-device (D2D) communication is designed to reuse the spectrum of the traditional cellular communication. In this communication mode, interference is a significant problem due to spectrum sharing. Two common approaches to deal with interference are power control and channel allocation. However, when these approaches are utilized separately, the joint effects between them are ignored. In this paper, we jointly consider them in a unified game theoric framework to improve the network-wide performance.

Join power control and channel allocation has the nature of a combinatorial problem. If we formulate a mix-integer problem, we need to deal with high complexity. Coalition formation game provides a cooperative framework which can be used to formulate the channel sharing problem. Moreover, to avoid the exponential growth of coalition partition, we use probability distribution to represent the possibility that a coalition merges with others. In this way, each user does not need to enumerate all the possible partitions of the network when making its decision.

In this paper, we jointly consider power control and channel allocation for D2D communication. We propose a merge-and-split algorithm for the user equipments (UEs) to form coalitions and share spectrum, then based on the coalition partition, the D2D users (DUs) decide their transmit power. We use coalition formation game in order to improve network-wide performance since this game be-

※ Corresponding Author : Hoon Kim, Address: (10380) Juhwa-ro 170, Ilsanseo-gu, Goyang-si, Gyeonggi-do, Korea, TEL : +82-31-910-7119, FAX : +82-31-910-7188, E-mail : megali@hanmail.net
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† Dept. of Information & Communication Eng., Inje University
(E-mail : amr_or@yahoo.com)
†† Dept. of Emergency Medicine, Inje University Ilsan Paik Hospital

longs to cooperative approach with non-selfish players. In other words, the players consider the system performance when making their own decision.

The summary of our contributions in this paper is expressed as follows

- We formulate a game theoric framework for joint power control and channel allocation in D2D underlaying cellular network. This framework addresses the general scenario when multiple DUs can share the same channel.
- We propose a coalition formation algorithm and prove that it converges to a stable solution. This algorithm is shown to enhance the quality of D2D communications while maintaining high performance of cellular users (CUs).

## 2. RELATED WORKS

There are several studies of channel allocation and power control in D2D underlaying cellular network. In [2] and [12], the coalition formation algorithms are developed for spectrum allocation of D2D communications. However, power control is not considered in these works. In [3], [4] and [5], the authors also used coalition formation algorithm for D2D resource allocation. The authors in [3] considered spectrum resource sharing with fixed transmit power. In [4], the transmit power of CUs is predefined by eNB and the transmit power of DUs is equally assigned on each channel. The authors in [5] supposed that the base station (BS) and the transmitters of the D2D pairs transmit with fixed power, and the transmit power that the BS allocated to each resource block for cellular data transmission is equal.

Some other approaches for jointly considering channel allocation and power control in D2D underlaying cellular system are [6], [7], [8] and [9]. The studies in [6] and [7] adopt bipartite matching while those in [8] use Stackelberg game and those in [9] utilize column generation. The authors in [8] adopted Stackelberg game which is non-cooperative approach while we use cooperative approach. In [9], a joint channel and power allocation problem is formulated as a mixed integer programming which has high complexity.

In this paper, we jointly consider power control and channel allocation for D2D underlaying cellular system using coalition formation game. We propose a merge-and-split algorithm which intends to improve the quality of D2D communications while maintaining high performance for CUs. We prove that this algorithm converges to the point that achieves high network performance.

## 3. NETWORK MODEL

In this paper, the term DU can be used to refer to a DU pair. In our D2D underlying cellular system, one CU can share channel with multiple DUs, on the other hands, one DU can reuse channel of at most one CU. Channel allocation and power of CU are predefined since in this system, the power control first intends to control the transmission power of DUs such that the interference from DUs to CUs can be throttled [10].

Channel state is assumed to be fixed in the time interest. We assume that the BS has channel state information of the network and feedbacks to DUs. We also assume a fully loaded cellular network scenario where the active CUs occupy all orthogonal channels in the cell and there is no spare spectrum. We consider uplink scenario since UEs are less capable of dealing with co-channel interference than BSs.

## 4. JOINT CHANNEL ALLOCATION AND POWER CONTROL COALITIONAL GAME

### 4.1 Game Formulation

We denote $C$ as the set of cellular users and $D$ as the set of D2D pairs. A coalition is denoted as $N$ while a coalition partition is denoted by $P$. We

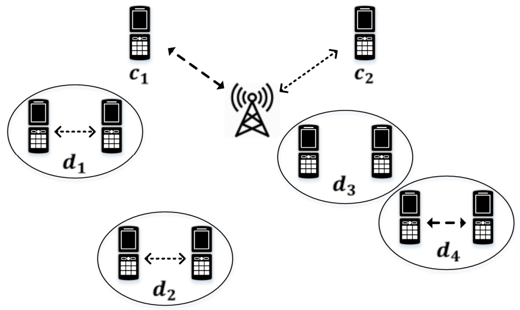



Fig. 1. An example of a partition with 2 coalitions: $\{c_1, d_4\}$ and $\{c_2, d_1, d_2\}$.

denote $N_C$ as the set of coalitions, each has one CU and zero or multiple DUs, $N_D$ as the set of singleton coalitions of one DU. Fig. 1 is an example of a partition with two coalitions. In order to avoid the exponential growth of combinatorial coalition formation, we proposed to use probability distribution to represent the possibility that a coalition merges with others.

In this paper, the coalition value/utility is represented by the SIR measurement. We first define the constructive and destructive power ratio which are used later in the definition of coalition value.

**Definition 1**

The *constructive power ratio* of $d$ in $N$ is the SIR of $d$ as

$$SIR(d,N) = \frac{\phi_d^N p_d^N g_d}{p_c g_{cd} + \sum_{d' \in N, d' \neq d} \phi_{d'}^N p_{d'}^N g_{d'd}},$$

where the *merging probability* $\phi_d^N$ denotes the probability that $d$ merges with $N$; $p_d^N$ and $p_c$ are the power of $d$ in $N$, power of $c$ in $N$, respectively; the symbols $g_d, g_{cd}$ and $g_{d'd}$ denote the channel gain of D2D pair $d$, gain from CU $c$ to the receiver of $d$ and gain from the transmitter of $d'$ to the receiver of $d$, respectively. The *destructive power ratio* of $d$ to $c$ in $N$ is defined as

$$IF(d,c,N) = \frac{p_c g_{cB} \phi_d^N p_d^N g_{dB}}{\left(\sum_{\hat{d} \in N} \phi_{\hat{d}}^N p_{\hat{d}}^N g_{\hat{d}B}\right)\left(\sum_{\hat{d} \in N'} \phi_{\hat{d}}^N p_{\hat{d}}^N g_{\hat{d}B}\right)},$$

where $g_{cB}, g_{dB}$ are gain from $c$ and $d$ to BS, respectively; the *destructive power ratio* of $d$ to other DUs in $N$ is defined as

$$IF(d,N) = \sum_{d' \in N} \frac{\phi_{d'}^N p_{d'}^N g_{d'} \phi_d^N p_d^N g_{dd'}}{\left(p_c g_{cd'} + \sum_{\hat{d} \in N, \hat{d} \neq d'} \phi_{\hat{d}}^N p_{\hat{d}}^N g_{\hat{d}d'}\right)\left(p_c g_{cd'} + \sum_{\hat{d} \in N', \hat{d} \neq d'} \phi_{\hat{d}}^N p_{\hat{d}}^N g_{\hat{d}d'}\right)},$$

where $N' = N \cup d$.

We can understand that the constructive power ratio represents the contribution of $d$ to the coalition $N$. In our game model, this contribution is measured by SIR of the DU $d$ in coalition $N$. In contrast, destructive power ratio of $d$ to CU and to other DUs represent interference of $d$ to CU and to other DUs, respectively. The intuition of the formulation of $SIR(d,N)$, $IF(d,c,N)$ and $IF(d,N)$ is shown in the Proposition 1 of the Section IV.B.

The value of the coalition $N$ is defined as the total value of users in this coalition. That value is given as

$$f(N) = f(c,N) + \sum_{d \in N} f(d,N),$$

where

$$f(c,N) = SIR(c,N) = \frac{p_c g_{cB}}{\sum_{d \in N} \phi_d^N p_d^N g_{dB}},$$

Initialize singleton coalitions: each user is a coalition
**for each** $N \in N_C$
  **for each** $d \in N_D$
    Initialize $\phi_d^N : \phi_d^N \propto v(d,N), \sum_{N \in N_C} \phi_d^N = 1$
  **end for**
**end for**
**while** $P$ is not $D_{hp}$-stable **do**
  Uniformly randomly select a DU $d, \{d\} \in N_D$
  Uniformly randomly select a coalition $N \in N_C$
  **if** $f(d,N) > 0$ **then**
    $N \leftarrow N \cup d$
  **end if**
  Uniformly randomly select a coalition $N \in N_C$ and a DU $d \in N$
  **if** $f(d,N) < 0$ **then**
    $N \leftarrow N \setminus \{d\}$
    $N_D \leftarrow N_D \cup \{d\}$
  **end if**
  Update $\phi_d^N$
  $\widehat{p_d^N} = argmax_{p_d^N} log \left(1 + \frac{p_d^N g_d}{p_c g_{cd} + \sum_{d' \in N, d' \neq d} \phi_{d'}^N p_{d'}^N g_{d'd}}\right)$
  $p_d^N = min \left\{\widehat{p_d^N}, \overline{p_d^N}\right\}$
**end while**

and

$f(d,N) = SIR(d,N) - IF(d,c,N) - IF(d,N)$.

Algorithm 1. Proposed merge-and-split algorithm

We can see that the value $f(d,N)$ represents the overall constructive and destructive power ratio of $d$ in $N$.

**Definition 2**

Merge rule: $d$ will merge with $N$ if $f(d,N) > 0$.

Split rule: an $d$ inside $N$ will split with $N$ if $f(d,N) < 0$.

The intuition behind the coalition game is that each user keeps on forming a coalition that gives a higher contribution to the system payoff of sum rate. The joint channel allocation and power control coalition formation algorithm is summarized in Alg. 1. Since this algorithm is performed at the base station (BS) in a centralized manner, we need to design an algorithm with low complexity. If the merge-and-split process is enumerated, the number of partitions will increase exponentially with the increase of UE's quantity. In a large network, the complexity will become intractable. We propose to use the merging probability $\phi_d^N$ in order to avoid this complexity. In the algorithm, this probability is first initialized in proportion with the value $v(d,N)$. This means each DU tends to merge with the coalition that provides high utility. In each iteration, a pair of coalitions $d,\{d\} \in N_D$ and $N \in N_C$ are randomly selected. The merge condition on these two coalitions is verified and performed. Similarly, a pair of coalitions is selected for split operation. After merge and split operations, the merging probability and transmit power are updated according to the new coalition partition. We note that $\overline{p_d^N}$ is the power threshold of $d$ in the coalition $N$; it is the maximum DUs' power that does not degrade cellular performance. In the algorithm, each $d,\{d\} \in N_D$ tries to merge with a cellular coalition in $N_C$, each $d \in N, N \in N_C$ tries to split with $N$.

### 4.2 Property Analysis

**Proposition 1**: The following expression is maximized within the last stage of Alg. 1

$$\sum_{N \in P_f} f(N). \tag{1}$$

Proof:

We denote $f(N')$ as the value of $N$ after $d$ merges with $N$.

- Merge case

After the merge-and-split process converges, we have that for all pair $d \in N_D$ and $N \in N_C$, there is no merge action, which means $f(d,N') \le 0$. We will prove that (1) is maximized within the last stage, that is $f(N), N \in P_f$ is maximized.

In fact, for each pair $d \in N_D$ and $N \in N_C$, we have

$f(d,N') \le 0$,

or

$$SIR(d,N') - IF(d,c,N') - IF(d,N') \le 0. \tag{2}$$

Based on the formulation of $SIR(d,N)$, $IF(d,c,N)$ and $IF(d,N)$ in the Definition 2, we also have

$$f(N') = f(N) + SIR(d,N') - [SIR(c,N) - SIR(c,N')] - \sum_{\hat{d} \in N} [SIR(\hat{d},N) - SIR(\hat{d},N')]$$

$$= f(N) + SIR(d,N') - \left[ \frac{p_c g_{cB}}{\sum_{\hat{d} \in N} \phi_{\hat{d}}^N p_{\hat{d}}^N g_{\hat{d}B}} - \frac{p_c g_{cB}}{\sum_{\hat{d} \in N'} \phi_{\hat{d}}^N p_{\hat{d}}^N g_{\hat{d}B}} \right] - \sum_{\hat{d} \in N} \left[ \frac{\phi_{\hat{d}}^N p_{\hat{d}}^N g_{\hat{d}}}{p_c g_{c\hat{d}} + \sum_{\tilde{d} \in N, \tilde{d} \ne \hat{d}} \phi_{\tilde{d}}^N p_{\tilde{d}}^N g_{\tilde{d}\hat{d}}} - \frac{\phi_{\hat{d}}^N p_{\hat{d}}^N g_{\hat{d}}}{p_c g_{c\hat{d}} + \sum_{\tilde{d} \in N', \tilde{d} \ne \hat{d}} \phi_{\tilde{d}}^N p_{\tilde{d}}^N g_{\tilde{d}\hat{d}}} \right]$$

$$= f(N) + SIR(d,N') - \left[ \frac{p_c g_{cB}}{\sum_{\hat{d} \in N} \phi_{\hat{d}}^N p_{\hat{d}}^N g_{\hat{d}B}} - \frac{p_c g_{cB}}{\sum_{\hat{d} \in N} \phi_{\hat{d}}^N p_{\hat{d}}^N g_{\hat{d}B} + \phi_d^N p_d^N g_{dB}} \right] - \sum_{\hat{d} \in N} \left[ \frac{\phi_{\hat{d}}^N p_{\hat{d}}^N g_{\hat{d}}}{p_c g_{c\hat{d}} + \sum_{\tilde{d} \in N, \tilde{d} \ne \hat{d}} \phi_{\tilde{d}}^N p_{\tilde{d}}^N g_{\tilde{d}\hat{d}}} - \frac{\phi_{\hat{d}}^N p_{\hat{d}}^N g_{\hat{d}}}{p_c g_{c\hat{d}} + \sum_{\tilde{d} \in N, \tilde{d} \ne \hat{d}} \phi_{\tilde{d}}^N p_{\tilde{d}}^N g_{\tilde{d}\hat{d}} + \phi_d^N p_d^N g_{d\hat{d}}} \right]$$

$$f(N) + SIR(d,N') - \left[ \frac{p_c g_{cB} \phi_d^N p_d^N g_{dB}}{\left(\sum_{\hat{d} \in N} \phi_{\hat{d}}^N p_{\hat{d}}^N g_{\hat{d}B}\right)\left(\sum_{\hat{d} \in N} \phi_{\hat{d}}^N p_{\hat{d}}^N g_{\hat{d}B} + \phi_d^N p_d^N g_{dB}\right)} \right] - \left[ \sum_{\hat{d} \in N} \frac{\phi_{\hat{d}}^N p_{\hat{d}}^N g_{\hat{d}} \phi_d^N p_d^N g_{d\hat{d}}}{\left(p_c g_{c\hat{d}} + \sum_{\tilde{d} \in N, \tilde{d} \ne \hat{d}} \phi_{\tilde{d}}^N p_{\tilde{d}}^N g_{\tilde{d}\hat{d}}\right)\left(p_c g_{c\hat{d}} + \sum_{\tilde{d} \in N, \tilde{d} \ne \hat{d}} \phi_{\tilde{d}}^N p_{\tilde{d}}^N g_{\tilde{d}\hat{d}} + \phi_d^N p_d^N g_{d\hat{d}}\right)} \right]$$

$$= f(N) + SIR(d,N') - IF(d,c,N') - IF(d,N').$$

Based on (2), we have

$f(N) \geq f(N')$.

This means that value of $S$ before $d$ joins is larger or equal to that value after $d$ joins. In other words, $f(N)$ is maximized within the last stage of the Alg. 1 with respect to merge operation.

- Split case

Prove similarly for the case of split, we have that the value of $S$ before $d$ leaves is larger or equal to that value after $d$ leaves. Therefore, $f(N)$ is maximized within the last stage of the Alg. 1 with respect to split operation.

**Proposition 2**: Starting from any initial partition, the Alg. 1 will converge to a final partition $P_f$ with probability 1. The resulting structure is $D_{hp}$-*stable*.

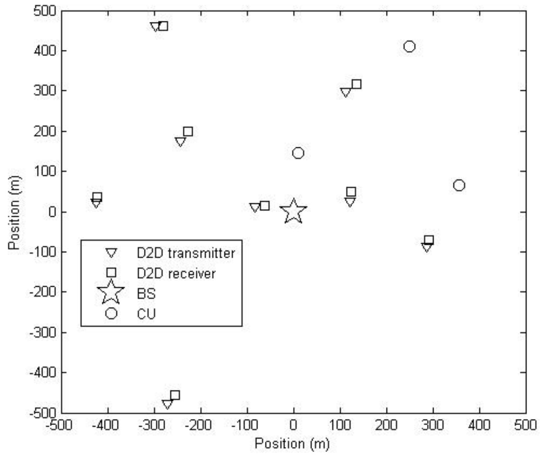
Proof:

Based on the Definition 2, every single merge or split operation results in a structure, which either is a new structure or remains unchanged from the previous structure. The number of partition of $D$ is $|C|+1$-th Bell number which is finite. It follows that the merge-split operations will terminate at $P_f$ with probability 1.

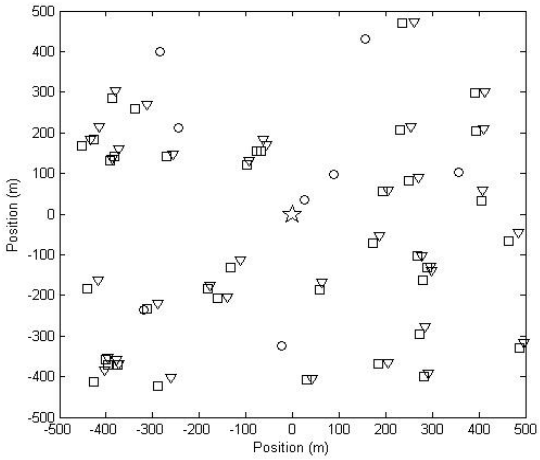
The resulting structure $D_f$ from Alg. 1 cannot be subject to any further merge or split. For instance, with any pair $d$ and $N$, we assume that $f(d,N) > 0$. Based on Definition 2, $P_f$ has a motivation to be changed through application of the merge operations on $d$ and $N$. Obviously, it contradicts the fact that $P_f$ is the final partition. Thus, we have proved that the final network structure $P_f$ resulting from Agl. 1 must be $D_{hp}$-stable.

## 5. EVALUATION

We evaluate the proposed coalition game by conducting simulation in Matlab. Fig. 2 illustrates the smallest and the largest scenario of the simulated networks. Their area is 500×500m with 1 BS in the center. Fig. 2a is the smallest scenario with 3 CUs and 8 D2D pairs while Fig. 2b is the largest scenario with 8 CUs and 38 D2D pairs. The locations of the CUs and D2D pairs are uniformly randomized within the cell area. Each D2D receiver must be located in close proximity with its transmitter, i.e., 30m. The channel gains are generated based on the large scale path loss. The initial transmit power is 25dBm while the default power threshold is 30dBm; the bandwidth used by each coalition is 180KHz. Since we use random approach, for each simulated scenario, we repeat the simulation by 10 times, each time with the same




(a)




(b)

Fig. 2. The simulated network of (a) 3 CUs, 8 DU pairs and (b) 8 CUs, 38 DU pairs.

number of UEs but different random positions.

We evaluate the proposed coalition game in four main measurements, namely, the number of merge/split operation, the individual data rate, the average data rate and the sum rate. The performance of the game is also compare with three other approaches: (1) the hierarchical matching approach (HIMA) [11], (2) the distributed resource and power allocation (REPA) [13], (3) the coalitional game for D2D resource allocation (CORA) [12], (4) the exhaustive search and (5) the random spectrum allocation. In [11], a channel can be used by (i) a group of D2D pairs or (ii) a group of CUs and D2D pairs. The authors establish a hierarchical matching market in order to find a Bayesian equilibrium with stable spectrum sharing. That equilibrium is achieved by the selfish users with their distributed algorithm. In [13], the authors maximize the number of underlay D2D users while maintaining high performance for prioritized cellular links. They formulate the joint optimization of power control and resource allocation. However, due to the computational complexity, instead of solving the problem analytically, they propose a Stackelberg game technique to find approximate solution. The study in [12] formulates the optimal resource allocation problem in D2D communication, then proposes a coalition formation game based algorithm that converges to the Nash-stable equilibrium. Differ from our approach, merging probability is not used while the merge-and-split process is performed concretely by the DUs until converged. In exhaustive search, the searching space grows exponentially with the number of users; therefore, we conduct its simulation only for 8 D2D pairs. In random spectrum allocation, the channels are assigned randomly, then each D2D transmitter decides its own transmit power.

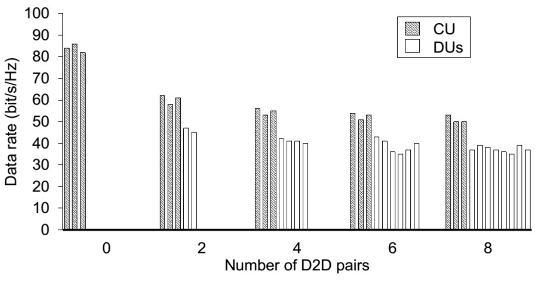



Fig. 3. User data rate in the network of 3 CUs.

To show the relationship among the performance of CUs and DUs, we depict the user data rate of a small network (Fig. 3). The network has 3 CUs and the number of DUs ranges from 0 to 8. In the figure, when there is zero DU, the CUs achieve high data rate since they are allowed to transmit at maximal power. When the DUs exist, the performance of CUs dramatically drops. Then that performancegradually reduces when the number of DUs increases. Due to the sharing of resource, when more D2D connections are established, the performance of DUs also drops.

The Fig. 4 depicts the number of merge-and-split operation of the proposed scheme and CORA. The simulations are conducted for 3 cases of the number of CUs, namely $|C|=5$, $|C|=7$ and $|C|=8$. We

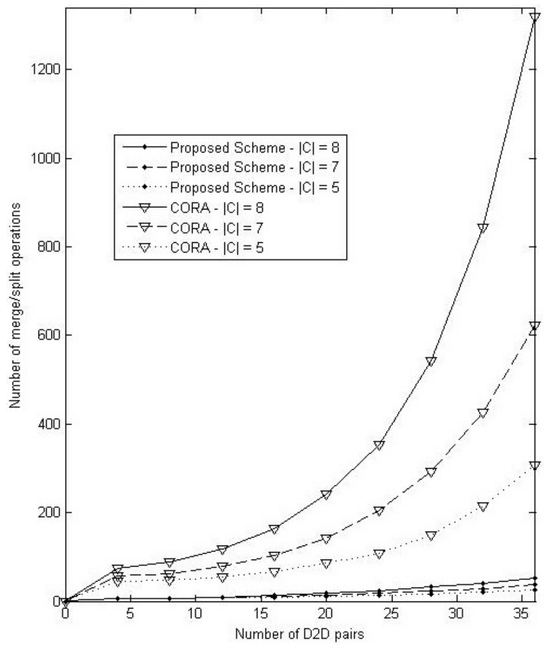



Fig. 4. Number of merge/split operation.

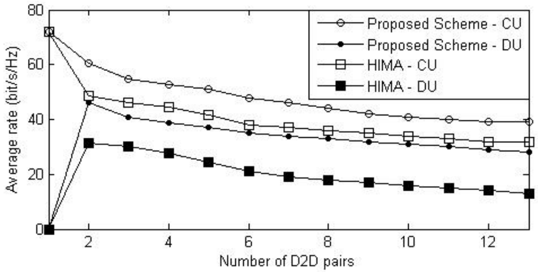



Fig. 5. Average data rate in the network of 3 CUs.

can see that when the number of CUs is high, more merge-and-split operations are required. Moreover, for both schemes, that number grows with the increase of the network size. However, CORA requires a significantly high number of operation and this number increases sharply with the network size. Since we propose to use merging probability, it is not necessary that the algorithm has to enumerate a large number of partitions. Therefore, the proposed algorithm requires a low number of merge-and-split operations. In this way, we can reduce the computation requirement for the central BS. Researchers generally try to design distributed algorithm for networking. However, by using the merging probability, the resource allocation can be computed by the BS in a centralized manner, allowing to reduce the network signalling.

In Fig. 5 and Fig. 6, we compare the average user data rate of the proposed algorithm with HIMA. Fig. 5 illustrates the simulation of small network with 3 CUs and the number of D2D pairs ranges from 0 to 13. Fig. 6 illustrates the larger network with 8 CUs and the number of D2D pairs ranges from 0 to 38. Similar to Fig. 3, the performance of CUs degrades with the increase of the number of DUs. Moreover, the two figures show that the proposed algorithm achieves higher performance than HIMA on both CUs′ and DUs′ rate. In Fig. 6, with the larger network, the performance of HIMA reduces significantly compared with ours. HIMA introduces a distributed algorithm with selfish DUs while the proposed algorithm is based on cooperative strategy in which the DUs consider the coalition payoff when making their decision. Moreover, in our approach, channel allocation and power control are jointly considered in a same coalitional game. In this way, we are able to achieve jointly improvable performance.

Fig. 6 also depicts the user data rate with respect to different values of $\overline{p_d^N}$. This means the proposed approach allows to adjust the cellular performance using that threshold. When this threshold is low, the DUs are not allowed to transmit with high power, the cellular links are protected and they achieve high performance. In contrast, when this threshold is high, the DUs are allowed to achieve high data rate at the cost of the CUs′ performance.

The sum rate of the proposed algorithm is compared with other approaches in a network of 3 CUs (Fig. 7) and a network of 8 CUs (Fig. 8). Since the exhaustive search is highly complex, it is simulated only for the small network in Fig. 7. On

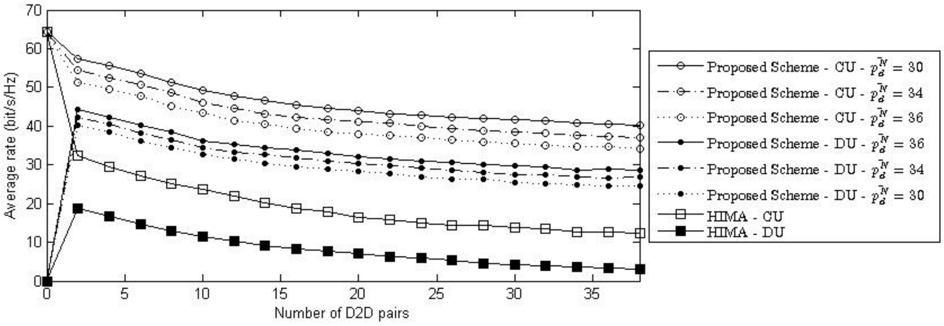



Fig. 6. Average data rate in the network of 8 CUs.

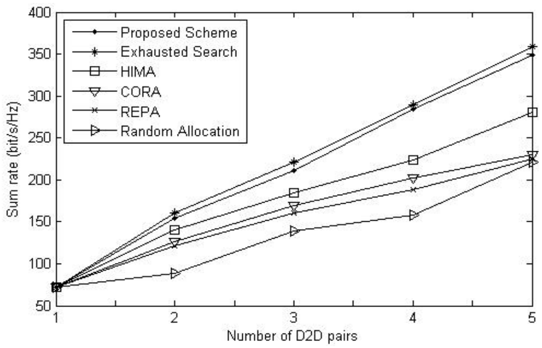



Fig. 7. Sum rate in the network of 3 CUs.

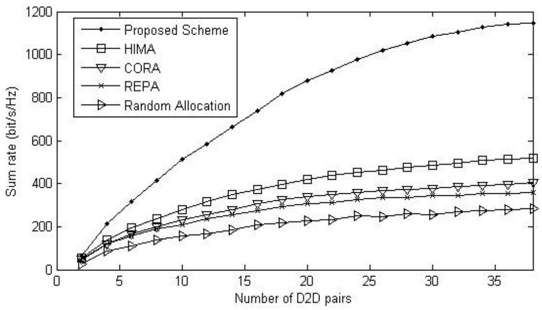



Fig. 8. Sum rate in the network of 8 CUs.

both figures, the proposed algorithm obtains significant improvement compared to other approaches. Especially, in Fig. 7, it asymptotically reaches the performance of exhaustive search. The proposed algorithm achieves higher performance than HIMA and REPA since these two algorithms uses non-cooperative approach where DUs act as selfish players. In non-cooperative game, the players maximize there own payoff; this may degrade the total system performance because of interference between DUs and CUs as well as among DUs. We note that in these simulations, the power threshold is selected so as to improve the system sum rate. In CORA, power control is not considered; this means that the transmit power of UEs can not be controlled to maximize the sum rate. Moreover, the transmit power can not be jointly optimized with the channel allocation.

## 6. CONCLUSION

In this paper, we formulate a coalition formation game for joint channel allocation and power control in D2D underlaying cellular network. We propose a merge-and-split algorithm with coalition probability distribution which is able to avoid exponential growth of coalition partition. Moreover, the analytical and numerical results show that our algorithm converges to a stable point which yields high network-wide performance. The numerical analysis also shows that our formulated game achieves higher average rate and sum rate than a Stackelberg game based approach.

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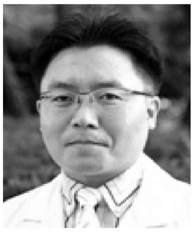
Amr Radwan

received his B.S. and M.S. degrees in Mathematics from Sohag University, Sohag, Egypt, in 1999 and 2005. He received the Ph.D. degree in Mathematics from Humboldt University zu Berlin, Germany in 2012. From Aug. 2012-Sep.2014, he worked as a lecturer at Mathematics Department, Faculty of Science, Sohag University, Egypt. Dr. Radwan was awarded an NRF Postdoctoral Research Fellowship (2014, Oct.-2015, Feb.), and joined Prof. Won-Joo Hwang's research group in the Department of Information and Communications Engineering at Inje University, where he worked problems related to wireless networks. Since Mar. 2015, he has been an assistant professor at Department of Information and Communications Engineering, Inje University, Gyeongnam, Korea. His research interests are in the area of nonlinear optimization, optimal control problem, automatic differentiation, evolutionary computing and wireless networks.



Hoon Kim

received the MSc Degree from Graduate School, College of Medicine, Inha University, Korea in 2006. He received his M. D. degree from Inha University, Republic of Korea in 2002. Since September 2010, he has been a professor at Inje University, Republic of Korea. His research interests are in Health Information System and International Cooperation in Healthcare.