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A Game-Theoretic Resource Allocation Approach for Intercell Device-to-Device Communications in Cellular Networks

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Abstract—Device-to-Device (D2D) communication is a recently emerged disruptive technology for enhancing the performance of current cellular systems. To successfully implement D2D communications underlaying cellular networks, resource allocation to D2D links is a critical issue, which is far from trivial due to the mutual interference between D2D users and cellular users. Most of the existing resource allocation research for D2D communications has primarily focused on the intracell scenario while leaving the intercell settings not considered. In this paper, we investigate the resource allocation issue for intercell scenarios where a D2D link is located in the overlapping area of two neighboring cells. Specifically, We present three intercell D2D scenarios regarding the resource allocation problem. To address the problem, we develop a repeated game model under these scenarios. Distinct from existing works, we characterize the communication infrastructure, namely Base Stations (BSs), as players competing resource allocation quota from D2D demand, and we define the utility of each player as the payoff from both cellular and D2D communications using radio resources. We also propose a resource allocation algorithm and protocol based on the Nash equilibrium derivations. Numerical results indicate that the developed model not only significantly enhances the system performance including sum rate and sum rate gain, but also sheds lights on resource configurations for intercell D2D scenarios.

Index Terms—Device-to-Device (D2D), resource allocation, intercell, repeated game.

1 Introduction

Last years have witnessed the advancement of cellular communication systems, which reshapes the way people interact [1], [2]. As current cellular infrastructures evolve toward Long Term Evolution (LTE), Device-to-Device (D2D) communication is emerged as a disruptive innovation to significantly improve the performance of cellular systems [3], [4], [5]. D2D enables devices of proximity to communicate with each other directly, thus mitigating the system overhead, increasing the spectrum utilization, and improving the cellular coverage [6]. Due to these gains, D2D has been attracting considerable interests from both academia and industries recently. For instance, the Third Generation Partnership Project (3GPP) [7], LTE as well as LTE-Advanced (LTE-A) [8] projects consider to employ D2D as the potential solution for supporting growing communication demands. Therefore, D2D technology plays a crucial role in improving the performance of cellular system, and it is expected to be an indispensable technology in the next generation wireless communication systems [9].

D2D communication sharing cellular spectrum raises a great challenge to the co-existing of D2D and cellular communication due to mutual interference. In most of the existing works in D2D communications, they focus on the scenario where D2D communications operate in the same cell with the cellular communication, and thus the former only poses interference to the later located in the same cell. This is commonly referred to intracell interference. However, in practice, D2D pairs may reuse common resources of multiple neighboring cells.

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Consequently, when such D2D pairs communication with each other, it will produce interferences to cellular communications in multiple cells. This is referred to as intercell interference and has been largely ignored in literature. In an intercell scenario, intercell interference, which needs to be coordinated among multiple cells and among the cellular and the D2D user equipment (UE), is more challenging to support D2D communications [10] and deserve in-depth investigations. In this paper, we particularly study the intercell scenario and notice that the intercell interference situations can be different and more severe due to the presence of D2D, for instance, when the D2D link utilizes downlink cellular resources, a D2D transmitter may cause strong interference to a cellular UE in the neighbor cell receiving downlink traffic using the same resource. Likewise, when a D2D pair utilizes uplink resources, the D2D receiver may suffer high interference from a cellular UE in the neighbor cell transmitting uplink traffic to its serving BS.

To address the interference between cellular and D2D users, there have been many radio resource management schemes proposed to manage the interference between cellular and D2D users, which can be generally classified into four categories: resource allocation [11], [12], power control [13], [14], model selection [15], [16], and pairing [17]. Among these schemes, resource allocation is the initial step toward efficient interference coordination. However, previous studies on resource allocation mainly focused on the intracell scenario while leaving the intercell settings untouched, and thus they cannot comprehensively reflect behaviors and performance at the level of entire cellular system.

In the existing D2D resource allocation solutions, game theory is widely applied to characterize the interactions and competitions among D2D communications. Game theory offers a mathematical basis for the analysis of interactive decision making processes, which provides tools for predicting what might (and possibly what should) happen when rational players with conflicting interests interact [18]. Typically, D2D pairs in previous works are modeled as players competing for the resources, where the utility of each player is defined as the function of achievable data rate and generated interference. Based on the utility function, the equilibrium, i.e., the optimal resource allocations, can be obtained through analyzing the player's best reaction function.

From an interference perspective, these above mentioned approaches can be extended to handle the intercell case by simply incorporating interference from another cells. However, they fail to determine the resource configuration when D2D exploits the commonly shared spectrum of two neighboring cells. Taking a practical case as an example, when the user equipments, named UE1 and UE2, are proximal but scattered in the overlapping area of two neighboring cells. UE1 and UE2 should be capable of establishing a direct link as long as they are using the common spectrum of two cells. Hence, the game model must be redesigned to facilitate this case.

To fill the gap, this paper investigates the resource allocation problem for intercell D2D communications underlaying cellular networks. Unlike previous approaches, we consider the situations that D2D link is located in the overlapping region of two neighboring cells. To the best of our knowledge, this work is an early attempt to address the resource allocation problem for a D2D link locating in the common area of two cells. The contributions made in this paper are summarized as follows.

- We present three intercell D2D communication scenarios with cellular infrastructures: 1) the cellular links in both cells use uplink resources; 2) the cellular link in one cell uses downlink resources while that in another cell uses uplink resources; and 3) the cellular links in both cells use downlink resources. For each dedicated scenario, we define the sum rates of BSs and formulate the resource allocation problem.
- We develop a static *Cournot* game to address the problem, which is inspired by [19] that aims primarily at the secondary users competing for the spectrum shared by the primary user in cognitive radio networks. Unlike existing works that modeled the D2D pairs as players, this static game characterizes the BSs as players competing for resource quota of D2D demand, and defines the utility of each player as the payoff collected from both cellular and D2D communications using the resources. With this game, we then analyze its Nash Equilibrium/Equilibria (NE) properties and propose a repeated version. By enabling the static game to repeat, the payoffs of BSs can be improved, and thus the repeated model is more preferable for the considered scenarios than the static one.
- We propose a resource allocation algorithm and a protocol according to the NE derivation and analysis. The protocol determines the communication scenario and guides the BSs to allocate resources to D2D link. If the NE of the game exists, the resource allocation as NE is; otherwise, the resource allocation from each BS is the half of D2D resource demand.
- We examine the sensitivity factors of the model and system performance through extensive numerical experiments. The results verify that the model developed in this paper considerably improve the system performance in terms of sum rate and sum rate gain, which further provides a systematic insight on resource allocation for intercell scenarios.

The remainder of this paper is organized as follows. Section 2 briefly reviews the related work. Section 3 presents the system model including three D2D communication scenarios. In Section 4, we develop a repeated game and analyze the equilibrium to address the resource allocation problem. A resource allocation algorithm and a protocol on the basis of equilibrium analysis is also proposed in this section. Section 5 presents the numerical results and we conclude the paper in Section 6.

2 Related Work

Resource allocation for D2D communication is a critical issue that deserves a thorough consideration in order to coordinate the interference efficiently. Various works have been proposed to address this issue, most of which formulated the problem from an optimization perspective: they share the same objective in mitigating the interference while improving the Quality-of-Service (QoS) performance of the system.

The joint resource allocation schemes with resource reuse, model selection, and power control were proposed in [20], [21], and [22], respectively. In [23], authors considered to maximize the spatial reuse of radio resources and proposed a suboptimal greedy algorithm. A Partial Time-frequency Resource Allocation (PRA) framework for D2D communications was provided by [24]. [25] presented an algorithm that restricted the mutual interference under the constraints by adopting the interference limited area control method. A two-phase solution approach was proposed in [26], where resource allocation for cellular flows with max-min fairness was performed in the first phase and resource allocation for D2D flows was conducted in the second phase. [27] provided a resource allocation method that D2D can reuse the resources of more than one cellular user. Authors in [28] considered a scenario of D2D communications overlaying a cellular network and proposed a spectrum sharing protocol. The protocol allowed the D2D users to communicate bi-directionally with each other while assisting the two-way communications between the cellular base station and the cellular user.

Recently leveraging game theory to allocate D2D resources has become an active research topic since the game theory can provide an insightful understanding to the complex interactions among independent rational players. The game model for D2D resource allocation can be generally classified into two categories: non-cooperative and cooperative. In the former type, D2D UEs are commonly viewed as players competing for the resources. [29], [30], [31], and [32] addressed the D2D resource allocation using auction games. In particular, [29] took the energy efficiency into the optimization objective account. [30] presented a sequential second price auction where all the spectrum resources were considered as a set of resource units auctioned off by groups of D2D pairs in sequence. A non-monotonic descending price auction algorithm was presented by [31]. The utility function in this game factored the channel gain from D2D and the costs for the system. In [17], authors developed a Stackelberg game, in which a cellular UE and a D2D UE to form a leader-follower pair. Then a joint scheduling and resource allocation scheme to improve the performance of D2D communication was proposed.

In addition to the above non-cooperative games, cooperative game for D2D resource allocation has also been explored. In [33], a coalitional game with transferable utility is developed. In this game, each D2D user attempts to maximize its own utility and has the incentive to cooperate with other users to form a strengthened user group. As such, user can increase the opportunity to win its preferred spectrum resources.

Our work differs aforementioned works from following aspects. First, all of these works investigated the D2D resource allocation in a single cell, while we design a game to formulate the intercell scenarios where the D2D link is located in the common area of two neighboring cells. Second, unlike the above works that characterized the D2D users to be players as usual, we model the BSs as players instead.

3 System Model and Assumptions

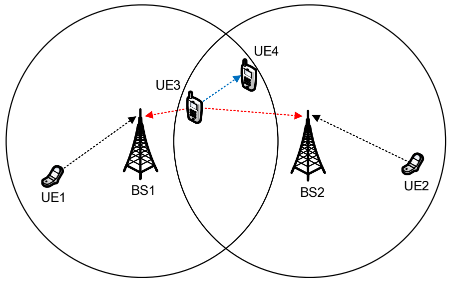
We consider the scenario that two D2D users are located in the overlapping area of two neighboring cells using uplink resources for communications. In each cell, there is a cellular user that is communicating with the base station. We assume that the D2D pair reuses the uplink resources with cellular users while cellular communications utilize either uplink or downlink resources, thus they are able to work with coordination from BSs. The scenario can be formulated as three cases illustrated in Fig. 1, where UE3 (transmitter) and UE4 (receiver) are the D2D pair, UE1 and UE2 are cellular users.

- **Case 1**. Cellular communications (dark arrowed lines) in both cells use uplink resources. In this case, the D2D pair (blue arrowed dot line) causes interference (red arrowed dot line) to both BSs as shown in Fig. 1(a)
- **Case 2**. Cellular communications in the left hand cell use downlink resources, while those in the right hand cell use uplink resource. D2D communications only cause interference to BS2 in this context as shown in Fig. 1(b).
- **Case 3**. Cellular communications in both cells use downlink resources, where D2D pair causes no interference to any BS as shown in Fig. 1(c).

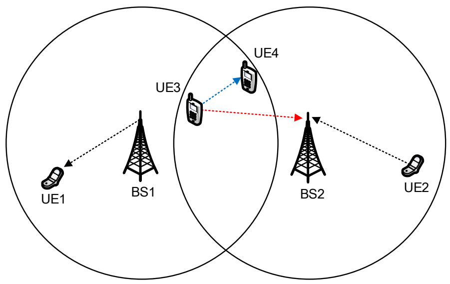
We define the sum rate of BS for above three cases. Let G_{ij} be the channel power gain between the transmitter i and the receiver j over either the cellular link or the D2D link, G_{3BS_1} be the gain between UE3 and BS1, G_{3BS_2} be the gain between UE3 and BS2. Denoting the power of transmitter i by p_i, the sum rate of m-th BS in Case n by R_m^n, the noise power of additive white gaussian noise (AWGN) at the receiver by N_0. Consequently, for Case 1, it yields

$$R_1^1 = B_1 \cdot \log_2 \left(1 + \frac{G_{1BS_1} p_1}{N_0 + G_{3BS_1} p_3}\right), \quad (1)$$

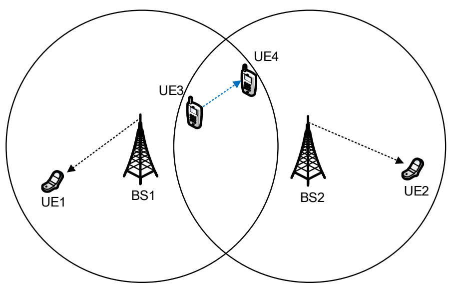
$$R_2^1 = B_2 \cdot \log_2 \left(1 + \frac{G_{2BS_2} p_2}{N_0 + G_{3BS_2} p_3}\right). \quad (2)$$



(a) Case 1



(b) Case 2



(c) Case 3

Fig. 1. D2D communications across two neighboring cellular networks.

where B_1 and B_2 are the bandwidth of BS1 and BS2, respectively.

Similarly, for Case 2, we have

$$R_1^2 = B_1 \cdot \log_2 \left(1 + \frac{G_{BS_1 1} p_{BS_1}}{N_0}\right), \tag{3}$$

$$R_2^2 = B_2 \cdot \log_2 \left(1 + \frac{G_{2BS_2} p_2}{N_0 + G_{3BS_2} p_3}\right). \tag{4}$$

For Case 3, we have

$$R_1^3 = B_1 \cdot \log_2 \left(1 + \frac{G_{BS_1 1} p_{BS_1}}{N_0}\right), \tag{5}$$

$$R_2^3 = B_2 \cdot \log_2 \left(1 + \frac{G_{BS_2 2} p_{BS_2}}{N_0}\right). \tag{6}$$

The sum rates of both BSs allow us to obtain their payoffs collected from cellular communications. Note that the interference incurred by the D2D link has been taken into the sum rate account, which is a key parameter impacting the total payoff of the BS. Essentially the more resources, for example bandwidth (or physical resource block in LTE-A), allocated to the D2D, the lower interference it generates. Hence resource should be carefully allocated to D2D. In the following, we apply game theory to determine the amount of resources that should be allocated to D2D transmitter by each BS. We assume that the channel state information (CSI) of all involved links in each cell is available to the corresponding BS so that both BSs are capable of coordinating the radio resources.

4 Repeated Game Theoretic Resource Allocation

As a D2D link reuses the common resources across two cells, each operator can charge the D2D UE fees, and thus operators have incentive to allocate resources to D2D users for maximizing their payoffs. The competition among both operators for resource allocation can be formulated as a non-cooperative game, in which BSs are modeled as players. In this section, we first present a static game model with an assumption that each BS can completely observe the strategies and payoffs of the other BS, and then we extend this model to a repeated version. Note that the game repetition times are set finite so that the D2D pair can obtain the resource for data transmission immediately.

4.1 Static Resource Allocation Game

We define the utility of a player as the monetary revenue that consists of two parts. The first part comes from the fees collected from cellular users, and the second part is the fees charged from D2D communications. The utility function of players are defined as

$$U_1^n = \alpha \cdot R_1^n + \beta \cdot B_3^\delta - \gamma \cdot B_3^\delta, \tag{7}$$

$$U_2^n = \alpha \cdot R_2^n + \beta \cdot B_3^\theta - \gamma \cdot B_3^\theta, \tag{8}$$

where α and β are constants denoting the charging price of unite data rate and resource, respectively. γ is the cost function of resource, B_3^δ and B_3^θ are the allocated bandwidth (resources) from BS1 and BS2.

With respect to γ, a pricing function from [19] is employed, thus it can be expressed as

$$\gamma = x + y(B_3^\delta + B_3^\theta)^\tau, \tag{9}$$

where x, y, τ are non-negative constants, and $\tau \geq 1$ guarantees that the cost function is convex.

Eq. (9) implies that the cost of both BSs are essentially relevant to the resources obtained by D2D. When a BS, say BS2, unilaterally increases the allocations to maximize its utility, the cost of both BSs would be raised accordingly. This would further lead to the decrease of BS1's utility, and thus BS1 has incentive to allocate more resources competing with BS2.

Since there is a trade-off between power and bandwidth [34], we have

$$p_3 \propto \frac{1}{B_3^\delta + B_3^\theta}, \tag{13}$$

$$\begin{cases} \frac{\partial U_1^1(B_3^\delta,B_3^\theta)}{\partial B_3^\delta} = \alpha \cdot B_1 \cdot \frac{G_{1BS_1}p_1}{(z_1+G_{1BS_1}p_1 \cdot B_3^\delta)\ln 2} + \beta - [x+y(B_3^\delta+B_3^\theta)^\tau] - B_3^\delta[y\cdot\tau(B_3^\delta+B_3^\theta)^{\tau-1}] = 0 \\ \frac{\partial U_2^1(B_3^\delta,B_3^\theta)}{\partial B_3^\theta} = \alpha \cdot B_2 \cdot \frac{G_{2BS_2}p_2}{(z_2+G_{2BS_2}p_2 \cdot B_3^\theta)\ln 2} + \beta - [x+y(B_3^\delta+B_3^\theta)^\tau] - B_3^\theta[y\cdot\tau(B_3^\delta+B_3^\theta)^{\tau-1}] = 0 \\ 0 \le B_3^\delta \le B_1 \\ 0 \le B_3^\theta \le B_2 \\ B_{\min} \le B_3^\delta + B_3^\theta \le B_{\max} \end{cases}. \tag{10}$$

$$\begin{cases} \frac{\partial U_1^1(B_3^\delta,B_3^\theta)}{\partial B_3^\delta} = \beta - [x+y(B_3^\delta+B_3^\theta)^\tau] - B_3^\delta[y\cdot\tau(B_3^\delta+B_3^\theta)^{\tau-1}] = 0 \\ \frac{\partial U_2^1(B_3^\delta,B_3^\theta)}{\partial B_3^\theta} = \alpha \cdot B_2 \cdot \frac{G_{2BS_2}p_2}{(z_2+G_{2BS_2}p_2 \cdot B_3^\theta)\ln 2} + \beta - [x+y(B_3^\delta+B_3^\theta)^\tau] - B_3^\theta[y\cdot\tau(B_3^\delta+B_3^\theta)^{\tau-1}] = 0 \\ 0 \le B_3^\delta \le B_1 \\ 0 \le B_3^\theta \le B_2 \\ B_{\min} \le B_3^\delta + B_3^\theta \le B_{\max} \end{cases}. \tag{11}$$

$$\begin{cases} \frac{\partial U_1^1(B_3^\delta,B_3^\theta)}{\partial B_3^\delta} = \beta - [x+y(B_3^\delta+B_3^\theta)^\tau] - B_3^\delta[y\cdot\tau(B_3^\delta+B_3^\theta)^{\tau-1}] = 0 \\ \frac{\partial U_2^1(B_3^\delta,B_3^\theta)}{\partial B_3^\theta} = \beta - [x+y(B_3^\delta+B_3^\theta)^\tau] - B_3^\theta[y\cdot\tau(B_3^\delta+B_3^\theta)^{\tau-1}] = 0 \\ 0 \le B_3^\delta \le B_1 \\ 0 \le B_3^\theta \le B_2 \\ B_{\min} \le B_3^\delta + B_3^\theta \le B_{\max} \end{cases}. \tag{12}$$

without loss of generality, we assume

$$\begin{aligned} [N_0 + G_{3BS_1}p_3] &= \frac{z_1}{B_3^\delta}, \\ [N_0 + G_{3BS_2}p_3] &= \frac{z_2}{B_3^\theta}, \end{aligned} \tag{14}$$

where z_1 and z_2 are non-negative constants, then

$$U_1^n = \alpha \cdot R_1^n + \beta \cdot B_3^\delta - [x + y(B_3^\delta + B_3^\theta)^\tau] \cdot B_3^\delta, \tag{15}$$

$$U_2^n = \alpha \cdot R_2^n + \beta \cdot B_3^\theta - [x + y(B_3^\delta + B_3^\theta)^\tau] \cdot B_3^\theta. \tag{16}$$

The optimization problem of resource allocation for intercell D2D communication can be formulated as

$$\begin{aligned} \max \quad & U_m^n(B_3^\delta, B_3^\theta) \\ \text{s.t.} \quad & B_{\min} \le B_3^\delta + B_3^\theta \le B_{\max}, \\ & 0 \le B_3^\delta \le B_1, \\ & 0 \le B_3^\theta \le B_2, \\ & \alpha, \beta, x, y > 0, \\ & z_1, z_2 \ge 0, \\ & \tau \ge 1. \end{aligned} \tag{17}$$

where $B_{\min}$ and $B_{\max}$ are the minimum and maximum resource demand of D2D pair.

Note that $B_{\min}$ is used to implicitly restrict the D2D's transmission power that does not cause harmful interferences to both BSs and cellular users. On the other hand, since the D2D link reuses the common resources of two cells, the bandwidth allocated to D2D by each BS should not exceed to the bandwidth allocated to the corresponding cellular user in each cell, therefore, we have $0 \le B_3^\delta \le B_1$ and $0 \le B_3^\theta \le B_2$.

According to the definition of NE, it can be obtained by solving the best response function of each player, that is

$$\begin{aligned} (\hat{B}_3^\delta, \hat{B}_3^\theta) = \arg\max & \, U_m^n(B_3^\delta, B_3^\theta) \\ \text{s.t.} \quad B_{\min} \le B_3^\delta & + B_3^\theta \le B_{\max}, \\ 0 \le & B_3^\delta \le B_1, \\ 0 \le & B_3^\theta \le B_2, \\ & \alpha, \beta, x, y > 0, \\ & z_1, z_2 \ge 0, \\ & \tau \ge 1. \end{aligned} \tag{18}$$

To obtain the NE of the above static game, we differentiate U_m^n with respect to B_3^δ and B_3^θ, respectively. Therefore

$$\begin{cases} \frac{\partial U_1^n(B_3^\delta,B_3^\theta)}{\partial B_3^\delta} = 0 \\ \frac{\partial U_2^n(B_3^\delta,B_3^\theta)}{\partial B_3^\theta} = 0 \\ 0 \le B_3^\delta \le B_1 \\ 0 \le B_3^\theta \le B_2 \\ B_{\min} \le B_3^\delta + B_3^\theta \le B_{\max} \end{cases}. \tag{19}$$

For each communication case, the NE can be obtained through solving (10), (11), and (12), respectively.

4.2 Repeated Resource Allocation Game

Prior to delving into the design of repeated resource allocation game, let us analyze the NE property for both players in above static game first. Fig. 2 describes the illustrative NE properties of static game, where the red and blue line represent the best response function of BS1 and BS2, the black lines are the D2D resource demand constraints, and the gray area, formed by black lines and coordinate axes, is the feasible strategy space of players. Fig. 2(a), Fig. 2(b), and Fig. 2(c) show the intersections

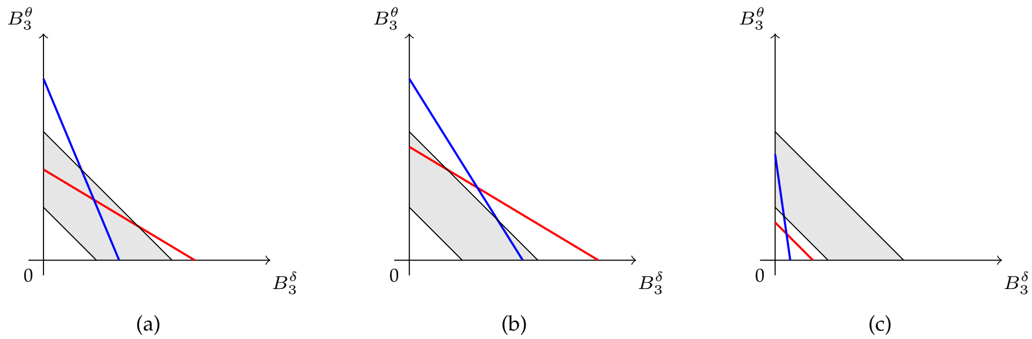


Fig. 2. NE analysis for static resource allocation game.

of blue and red lines locate inside and outside of gray area, which correspond to the cases that the NE exists (Fig. 2(a)) and does not exist (Fig. 2(b), (c)), respectively. It is obvious to observe from Fig. 2(a) that the solution of the static game, i.e., the intersection of blue and red lines, could be improved by increasing both B_3^δ and B_3^θ iteratively while keeping the NE within the gray area. In an extreme case, the solution is able to be refined intersecting at the boundary of gray area, namely the upper black line. Moreover, as Fig. 2(c) indicated, one can expect that the game repetition may enable the NE feasible. Inspired by these observations, we develop a repeated resource allocation game model in the following.

Since the BSs are rational players, they can adjust the resource allocations to maximize their payoffs. The adjustment of each player can be expressed as

$$B_3^\delta(t+1) = (1 + t \cdot a_1) \cdot B_3^\delta(t), \tag{20}$$

$$B_3^\theta(t+1) = (1 + t \cdot a_2) \cdot B_3^\theta(t). \tag{21}$$

where $B_3^\delta(t+1)$ and $B_3^\theta(t+1)$ are the allocated resources at $(t+1)$-th round, a_1 and a_2 are the adjustment parameters of BS1 and BS2.

With above equations, the repeated game for resource allocation can be modeled as

$$\begin{aligned} \max \quad & U_m^n(B_3^\delta(t), B_3^\theta(t)) \\ \text{s.t.} \quad & B_{\min} \le B_3^\delta(t) + B_3^\theta(t) \le B_{\max}, \\ & 0 \le B_3^\delta(t) \le B_1, \\ & 0 \le B_3^\theta(t) \le B_2, \\ & \alpha, \beta, t, x, y > 0, \\ & z_1, z_2 \ge 0, \\ & \tau \ge 1. \end{aligned} \tag{22}$$

Note that the iterations of game are limited. This is due to the fact that a D2D pair in practical cellular networks has to obtain the resource for communication immediately. To a finite repeated game, the NE can be obtained as long as it exists.

4.3 Resource Allocation Protocol

A resource allocation protocol is designed based on the resource allocation algorithm, which is shown in Algorithm 1. In this algorithm, the communication scenario in line 1 refers to three cases that we defined in Fig. 1. After the scenario is determined, the algorithm steps into the game: the while-loop as indicated from line 3 to line 28. The game will be played repeatedly by updating $B_3^\delta(t)$ and $B_3^\theta(t)$ (line 24, 25) in the case that any

Algorithm 1: Resource Allocation Algorithm

Input: $N_0, G_{ij}, x, y, z_1, z_2, \tau, \alpha, \beta, B_{\max}, t_{\max}, a_1, a_2$.
Output: $\hat{B}_3^\delta, \hat{B}_3^\theta$.

1 Determine the communication scenario and initialize the corresponding R_1^n and R_2^n where $n \in \{1, 2, 3\}$;
2 $t \leftarrow 1$;
3 **while** $t \le t_{\max}$ **do**
4   Calculate $U_1^n(B_3^\delta(t), B_3^\theta(t))$ and $U_2^n(B_3^\delta(t), B_3^\theta(t))$ in terms of (11) and (12);
5   Calculate $B_3^\delta(t), B_3^\theta(t)$ by solving one of (16), (17), and (18);
6   **if** $B_3^\delta(t) + B_3^\theta(t) > B_{\max}$ **then**
7   **if** $t = 1$ **then**
8       $\hat{B}_3^\delta \leftarrow \frac{B_{\max}}{2}$, $\hat{B}_3^\theta \leftarrow \frac{B_{\max}}{2}$;
9   **return** $\hat{B}_3^\delta, \hat{B}_3^\theta$;
10   **else**
11       $\hat{B}_3^\delta \leftarrow B_3^\delta(t-1)$, $\hat{B}_3^\theta \leftarrow B_3^\theta(t-1)$;
12   **return** $\hat{B}_3^\delta, \hat{B}_3^\theta$;
13   **end**
14   **end**
15   **if** $t = t_{\max}$ **then**
16   **if** $B_3^\delta(t) + B_3^\theta(t) < B_{\min}$ **then**
17       $\hat{B}_3^\delta \leftarrow \frac{B_{\min}}{2}$, $\hat{B}_3^\theta \leftarrow \frac{B_{\min}}{2}$;
18   **return** $\hat{B}_3^\delta, \hat{B}_3^\theta$;
19   **else**
20       $\hat{B}_3^\delta \leftarrow B_3^\delta(t)$, $\hat{B}_3^\theta \leftarrow B_3^\theta(t)$;
21   **return** $\hat{B}_3^\delta, \hat{B}_3^\theta$;
22   **end**
23   **else**
24     $B_3^\delta(t+1) = (1 + t \cdot a_1) \cdot B_3^\delta(t)$;
25     $B_3^\theta(t+1) = (1 + t \cdot a_2) \cdot B_3^\theta(t)$;
26     $t \leftarrow t + 1$;
27   **end**
28 **end**

termination condition is not satisfied. More specifically, if $B_3^\delta(1) + B_3^\theta(1) > B_{\max}$ in the first stage, the NE does not exist, that is, the case illustrated in Fig. 2(b), the algorithm exits with $\hat{B}_3^\delta = \hat{B}_3^\theta = \frac{B_{\max}}{2}$ as indicated from line 7 to line 9. If $B_3^\delta(t) + B_3^\theta(t) > B_{\max}$ during the game repeating, the game is terminated immediately with $\hat{B}_3^\delta = B_3^\delta(t-1)$ and $\hat{B}_3^\theta = B_3^\theta(t-1)$ as described from line 10 to line 12. Also, if $t = t_{\max}$ and $B_3^\delta(t) + B_3^\theta(t) < B_{\min}$, the NE does not exist, that is, the case illustrated in Fig. 2(c), the algorithm exits with $\hat{B}_3^\delta = \hat{B}_3^\theta = \frac{B_{\min}}{2}$ as indicated from line 16 to line 18. If $t = t_{\max}$ and $B_{\min} \le B_3^\delta(t) + B_3^\theta(t) \le B_{\max}$ the game is stopped with $\hat{B}_3^\delta = B_3^\delta(t)$ and $\hat{B}_3^\theta = B_3^\theta(t)$ as described from line 19 to 21.

Note that the resource allocations are unpredictable when NE does not exist. In response, the proposed resource allocation quotas from both BSs are all set to be $\frac{B_{\max}}{2}$ or $\frac{B_{\min}}{2}$; thus ensuring the *fairness* of the stations. The term fairness here refers to the amount of resources obtained by D2D from each BS is identical. Based on Algorithm 1, we present a resource allocation protocol, which gives the details how BSs and D2D pair should respond to each case.

In the protocol, the actions of BS consist of three major steps. First, each BS exchanges the parameter information (including all of input parameters in Algorithm 1) with another BS as well as D2D pair through a messaging mechanism at the beginning of resource allocation [35]. That is, the messaging mechanism makes all the information publicly available, and thus the utility functions of all players are the common knowledge. Second, the BSs cooperate to determine the communication scenario, from which the BSs initialize the corresponding sum rate R_1^n, R_2^n, and t. Since each BS knows the utility function of another, it can predict the strategy of its opponent play. Therefore, both BSs simultaneously submit their resource assignment proposals, i.e., $B_3^\delta(t)$ and $B_3^\theta(t)$, to D2D.

After receiving the resource assignment proposals, D2D pair would examine whether the game is terminated or not. In the first round, if the sum of resource assignment proposals from both BSs does not exceed the maximum constraint ($B_{\max}$), BSs continue to play the game by updating $B_3^\delta(t)$ and $B_3^\theta(t)$; otherwise D2D pair notifies both BSs with requested resources $\frac{B_{\max}}{2}$, and D2D eventually obtains $B_{\max}$ resources in total for transmission. During the game repetition, if the sum of current proposals, i.e. $B_3^\delta(t) + B_3^\theta(t)$ is beyond the constraint, D2D would send a message to both BSs that the game is terminated and inform them the requested resources are the submitted proposals of previous stage, i.e., $B_3^\delta(t-1)$ and $B_3^\theta(t-1)$. If the above two cases did not occur, D2D pair would check if the current proposals are satisfied the minimum constraint, i.e., $B_3^\delta(t) + B_3^\theta(t) \ge B_{\min}$. If so, the game is completely terminated, and the D2D acknowledges BSs with current proposals, otherwise, D2D pair notifies both BSs with requested resources $\frac{B_{\min}}{2}$.

TABLE 1
Parameter settings.

Parameter	Value
Cell radius	1000m
Max D2D communication range	50m
Cellular UE Tx power	25dBm
D2D UE Tx power	0dBm – 25dBm
Channel gain	$N(0,1)$
B_1, B_2	20MHz
$B_{\min}$	10MHz, 15MHz
$B_{\max}$	15MHz, 20MHz
$N_0, x, y, z_1, z_2, \tau$	1
α, β	20
$t_{\max}$	3
a_1, a_2	0.02, 0.05, 0.08

5 Numerical Results

In this section, the NE of developed game and the system performance are evaluated through numerical simulations. The results will show that the sum rate as well as the sum rate gain of both BSs are improved. Parameter settings for simulations are listed in Table 1. For simulations, all of the data presented are calculated by averaging the results from 100 runs, which makes the evaluations more representative and not heavily affected by stochastic factors.

5.1 NE Evaluation and Discussion

In the first set of experiments, we evaluate NE for three communication scenarios with different a_1 and a_2. Fig. 3, Fig. 4 and Fig. 5 display the NE evaluations with the same constraints $10 \le B_3^\delta + B_3^\theta \le 20$, but $a_1 = a_2 = 0.02$, $a_1 = a_2 = 0.05$, and $a_1 = a_2 = 0.08$, respectively. Fig. 6 and Fig. 7 shows the NE evaluation with tighter constraints, i.e., $10 \le B_3^\delta + B_3^\theta \le 15$ and $15 \le B_3^\delta + B_3^\theta \le 20$, when $a_1 = a_2 = 0.08$. In these figures, the subfigures correspond to the communication scenarios, which are shown in Fig. 1. For instance, Fig. 3(a), Fig. 3(b), and Fig. 3(c) are the NE evaluations for Case 1 (Fig. 1(a)), Case 2 (Fig. 1(b)), and Case 3 (Fig. 1(c)), respectively. The func1 and func2 represent the best response function of BS1 and BS2, and t is the game repetition times.

As indicated in Fig. 3, all intersections of best response function of BS1 and BS2 in Fig. 3(a), Fig. 3(b), and Fig. 3(c) meet the constraints $10 \le B_3^\delta + B_3^\theta \le 20$, that is, the intersections fall into the region of $10 \le B_3^\delta + B_3^\theta \le 20$. This indicates that the NE exists in three scenarios. With the game repeating, BSs eventually allocate $B_3^\delta(t_{\max})$ and $B_3^\theta(t_{\max})$ where $t_{\max} = 3$, to D2D according to the resource allocation protocol. Thus D2D pair obtains the maximum resources $B_3^\delta(t_{\max}) + B_3^\theta(t_{\max})$ for data transmission in three communication scenarios.

Fig. 4 plots the NE evaluations with larger a_1 and a_2, i.e., $a_1 = a_2 = 0.05$. Fig. 4(b) and Fig. 4(c) provide the same insights with Fig. 3(b) and Fig. 3(c), therefore D2D link obtains $B_3^\delta(t_{\max}) + B_3^\theta(t_{\max})$ resources in these two cases. In the contrary, Fig. 4(a) shows that the NE of the game at the last stage repetition does not exist as the

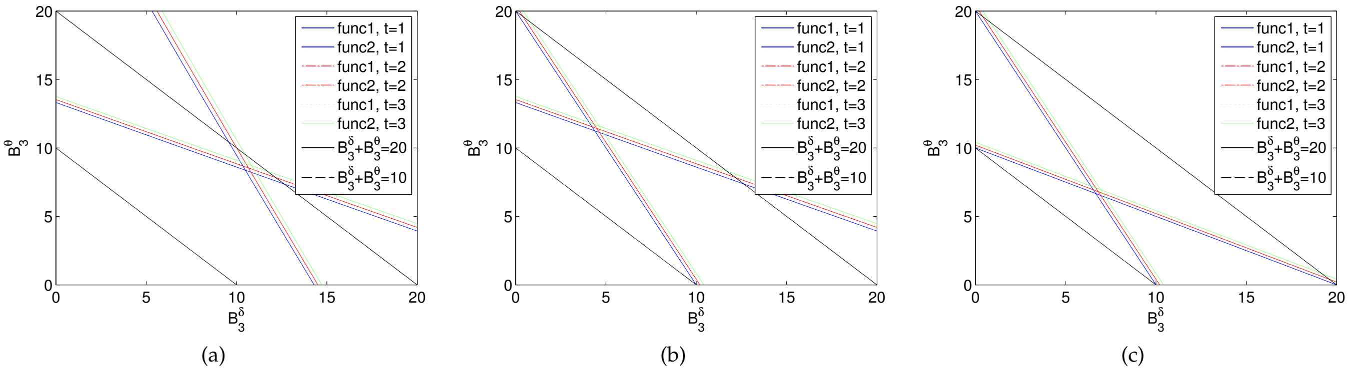


Fig. 3. NE evaluations with $a_1 = a_2 = 0.02$.

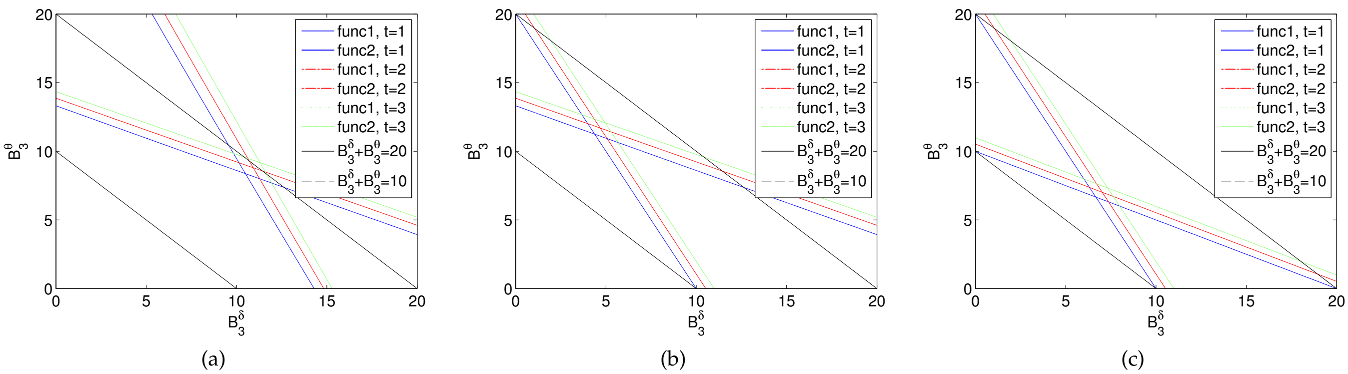


Fig. 4. NE evaluations with $a_1 = a_2 = 0.05$.

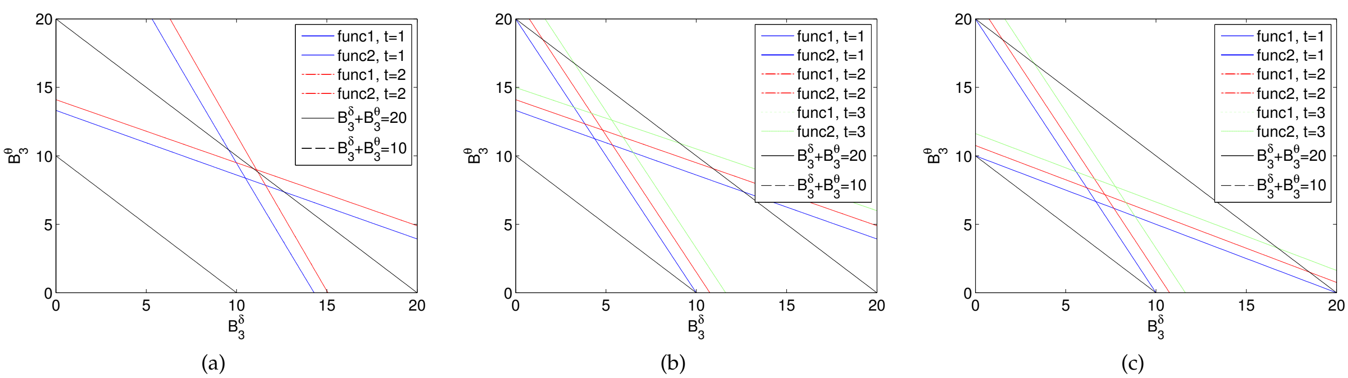


Fig. 5. NE evaluations with $a_1 = a_2 = 0.08$.

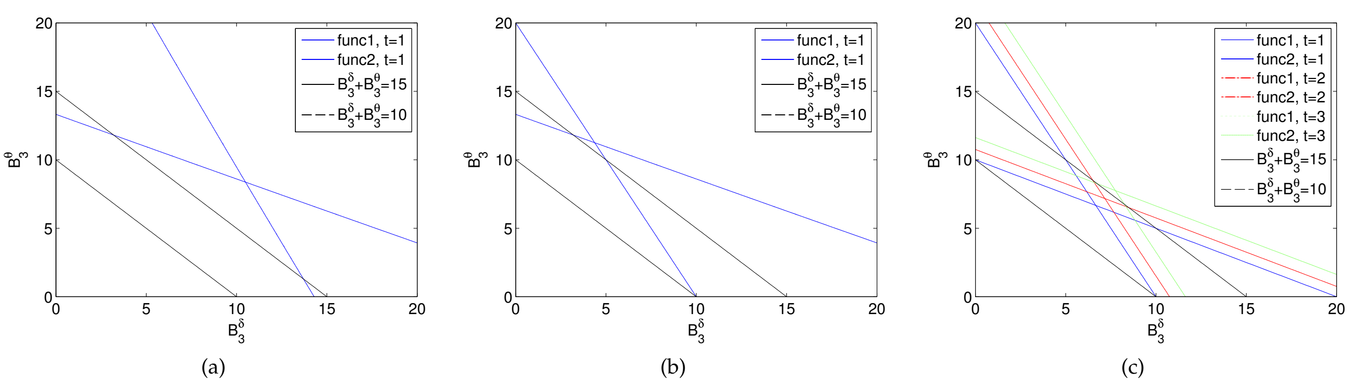
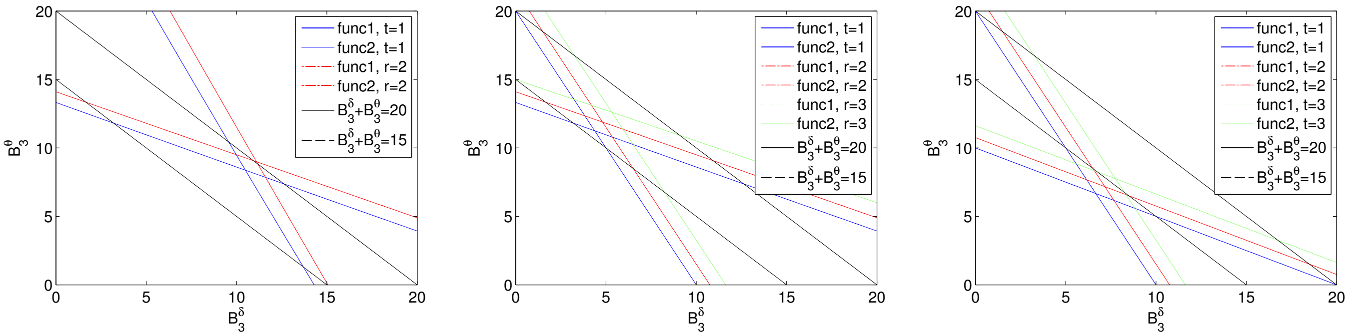


Fig. 6. NE evaluations with $10 \leq B_3^\delta + B_3^\theta \leq 15$ when $a_1 = a_2 = 0.08$.



(a) (b) (c)

Fig. 7. NE evaluations with $15 \leq B_3^\delta + B_3^\theta \leq 20$ when $a_1 = a_2 = 0.08$.

intersection of best response function of BS1 and BS2 in the third round is located out of the feasible strategy space, which means that the NE generated by the game may not exist during the game repetition with a larger adjustment parameter. This matches the design principle of our game. Thus D2D pair would ultimately receive $B_3^\delta(2) + B_3^\theta(2)$ resources for communication.

Fig. 5 draws the NE evaluation with the largest a_1 and a_2, i.e., $a_1 = a_2 = 0.08$. Fig. 5(b) and Fig. 5(c) provide the same observations compared with Fig. 4(b) and Fig. 4(c), that is, D2D pair obtain the maximum resources $B_3^\delta(t_{\max}) + B_3^\theta(t_{\max})$ in these two cases. It is interesting to notice that Fig. 5(a) only presents the NE data by first two repetitions of the game. This is because both BSs will no longer play the game if the NE does not exist in the second stage, and thus the D2D pair would finally receive $B_3^\delta(1) + B_3^\theta(1)$ resources.

Next we examine the sensitivity of NE to the constraint as shown in Fig. 6 and Fig. 7, which depict the properties of NE with tighter constraints $10 \leq B_3^\delta + B_3^\theta \leq 15$ and $15 \leq B_3^\delta + B_3^\theta \leq 20$, respectively, when $a_1 = a_2 = 0.08$. From Fig. 6 we can observe that the NE of the developed game is sensitive to the constraint. To the first two scenarios (Fig. 1(a) and Fig. 1(b)), NE does not exist, and thus each BS would allocate $\frac{B_{\max}}{2} = 7.5$ unit resources to the D2D pair by protocol. Whereas to the third scenario (Fig. 1(c)), D2D pair receives $B_3^\delta(2)+B_3^\theta(2)$ resources. In Fig. 7, Fig. 7(a) and Fig. 7(b) present the same insight with Fig. 5(a) and Fig. 5(b), but Fig. 7(c) shows that the repetition of game can facilitate the NE to be feasible, which is consistent with our previous NE analysis as expected.

Based upon above results, we claim that, given the reaction functions of both BSs, the NE is sensitive to the adjusting parameters of the game and the system constraint. In practical scenarios, one possible way for choosing such parameters is to set a small value and to increase them progressively if the NE exists. Likewise, for the parameters in the reaction functions such as x, y, τ, z_1, z_2, which also impact the performance of proposed approach, they can be configured empirically according to the scenarios or statistically by history communication profile.

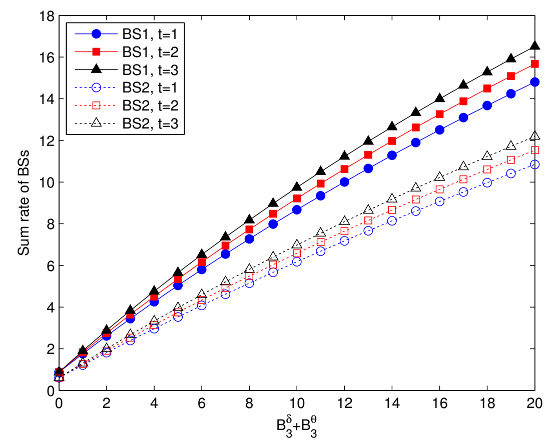


Fig. 8. Sum rate comparison for BSs.

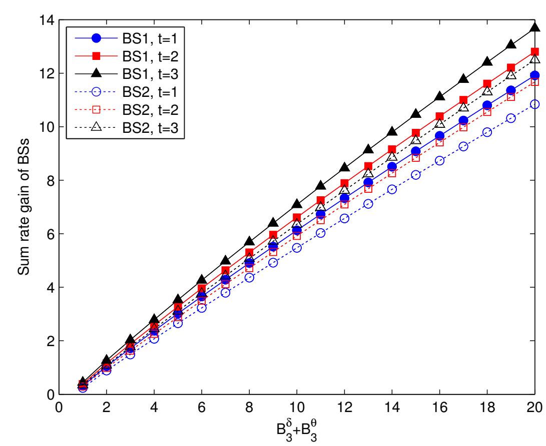


Fig. 9. Sum rate gain comparison of BSs.

5.2 System Performance Evaluation

In order to further validate the solutions generated by the developed game, system performance including sum rate and sum rate gain of BSs are evaluated in the second set of experiments. The sum rate of BSs for each scenario are specified by equations from (1) to (6), while the sum rate gain is defined as

$$sum\ rate\ gain = \frac{R_m^n + R_{D2D}}{R_{cellular}},$$

where R_m^n is defined by equations from (1) to (6), R_{D2D} is the sum rate of D2D communications, and $R_{cellular}$ is the sum rate of cellular communications in the absence of D2D ones.

We consider the above two performance metrics for the first communication scenario (Fig. 1(a)) under the condition of $a_1 = a_2 = 0.02$ and $B_3^{\delta}(t) + B_3^{\theta}(t) \leq 20$. The comparison results of sum rate and sum rate gain are presented in Fig. 8 and Fig. 9, respectively. As can be seen in these two figures, both of the sum rate and sum rate gain increase with game iterating, which implies that both BSs have incentive to allocate more resources to the D2D pair for revenue improvement as long as the sum of their allocations meet the constraint. With regard to other communication scenarios, i.e., Fig. 1(b) and Fig. 1(c), we can make similar observations with Fig. 8 and Fig. 9 if the NE exists in the game. Those results are skipped due to the space limitation. In summary, the performance simulations verify that the design of the repeated game is reasonable, thus enhancing the system performance significantly.

6 Conclusion

In this paper, we have considered the resource allocation problem for intercell D2D communications underlaying cellular network where D2D link is located in the common area of two neighboring cells. We have presented three intercell scenarios regarding the resource allocation problem. A repeated game model under these scenarios has been developed to address this problem. In the developed game, the BSs have been characterized as players competing for resource allocation quota from the D2D demand, and the utility of each player has been formulated as payoff from both cellular and D2D communications using resources. Through the NE derivation and analysis, we have proposed a resource allocation algorithm, based on which a resource allocation protocol for BSs has been presented. Numerical results have verified that the model developed significantly enhances the system performance and further provides a global insight into resource allocation for intercell D2D communication scenarios.

Since our approach is developed under the assumption that each BS has complete information of another BS, that is, each BS (player) is assumed to be willing to fully exhibit its private communication parameters to its competitor and D2D pair, we plan to, in our future work, extend our model to support the *incomplete information*, i.e., each BS only knows the part of the strategies and payoff parameters of the other BS.

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