Incentive Compatible Mode Selection and Spectrum Partitioning in Overlay D2D-Enabled Network

Yi Zhang
Graduate Institute of
Communication Engineering
National Taiwan University, Taiwan
Email: yzhang.cn@outlook.com

Chih-Yu Wang
Research Center for
Information Technology Innovation
Academia Sinica, Taiwan
Email: cywang@citi.sinica.edu.tw

Hung-Yu Wei
Graduate Institute of
Communication Engineering
National Taiwan University, Taiwan
Email: hywei@cc.ee.ntu.edu.tw

***Abstract*—With the large expected demand of wireless network communication, Device-to-Device (D2D) communication has been proposed as a promising technology to enhance network performance. The selfish nature of potential D2D users, may impale the performance of D2D-enabled network. In this paper, we consider a D2D-enabled cellular network framework, which supports both divided and shared D2D modes, under overlay D2D communication. The framework provides a pricing-based Stackelberg game for optimal mode selection and spectrum partitioning. We propose the incentive compatible pricing strategy to provide proper incentive for these selfish potential D2D pairs to make optimal choices in mode selection. Our results show that the pricing and spectrum partition strategy effectively prevents selfish potential D2D users from harming the system performance while fully exploits the potential of D2D communication.**

I. Introduction

Device-to-Device (D2D) communication is a promising solution [1] to help next generation cellular communication system meet the challenging requirements in 5G standard such as Gbs-scale throughput and millions-scale device number [2]. It can improve the spectrum utilization efficiency, energy efficiency, and offloading from base station.

One of the most challenging issues in integrating D2D communication into conventional cellular system is the spectrum assignment on both D2D links and cellular links. Two main approaches, the *underlay* and the *overlay* spectrum access, are proposed in the literature [3]. Comparing with underlay approach, which is that D2D users reuse the same spectrum / carriers as the conventional cellular spectrum subject to tolerable interference to the cellular users [4], the D2D users utilize a dedicated spectrum reserved for D2D communications in overlay spectrum access. The interference to existing cellular users is not a threat here. Under overlay D2D communication, there are two D2D modes considered: *divided D2D mode* and *shared D2D mode*. In divided D2D mode, the dedicated D2D spectrum is split into multiple orthogonal resource units, which are then allocated to each D2D user. For shared D2D mode, on the other hand, all D2D users share the whole dedicated D2D spectrum. In brief, divided D2D mode may guarantee the transmission quality when more users are accessing, while shared D2D mode may provide higher spectrum utilization efficiency.

D2D users in D2D-enabled networks usually are assumed to have the freedom to choose between D2D mode and cellular mode, called *mode selection*. Thus, the choices of rational D2D users are more likely to be based on their own self-interests instead of overall performance, such as higher transmission quality, lower service price, or both. In such a case, their selfish choices may be not favored by the BS and also degrade the system performance. Mode selection in D2D communication has been studied in the literature with different game-theoretic approaches. Most previous works study D2D mode selection in underlay spectrum access [5][6]. In overlay spectrum access, on the other hand, divided D2D mode has been widely discussed. Nevertheless, the proposed algorithm in [7] handles the users one at a time, while our approach can handle multiple users at once. In [8], the selfish nature of potential D2D pairs in mode selection is not discussed. Stochastic geometry is adopted in [9] to estimate average spectrum efficiency in different modes, but the user distribution has to be known in advance. The truth telling issue is also not considered in [9]. Besides, the shared D2D mode is not discussed in most existing works such as [7][8][9]. We will show that the shared D2D mode can greatly improve the overall system performance comparing to divided D2D mode due to higher spectrum utilization efficiency.

Additionally, the spectrum utilization efficiency is another challenge in overlay approach. The service provider or base station should reserve a dedicated spectrum for all D2D communication, which we refer to as *spectrum partitioning* [8]. The partition strategy should be aware of the loading and requirements from both potential D2D users and conventional cellular users. In [8], it is lack of adaptability and robustness that the optimal spectrum partitioning depends on fixed D2D mode selection threshold, which is purely due to the density of BS. The authors in [9] suggest that the control of spectrum partitioning need to be dynamically adjusted by considering D2D mode selection behaviors responded by users. We share a similar concept but our framework utilizes the dynamic pricing strategy as an additional tool to regulate the selfish behaviors of users in D2D mode selection.

In this paper, we propose a pricing-based mode selection and spectrum partitioning framework for integrating overlay D2D communication into existing conventional cellular networks. The framework supports both divided and shared D2D modes, while the differences between these two modes are modeled theoretically and evaluated through simulations. Our goal is to maximize the overall system utility of D2D-enabled network, with service quality of existing conventional cellular users and incentive for selfish D2D users in mode selection in mind. We will show that the proposed primal-dual pricing strategy satisfies the incentive compatibility of potential D2D users in mode selection. Besides, the dynamic spectrum partition strategy guarantees the service quality of existing cellular users in conjunction with the pricing strategy.

II. SYSTEM MODEL

We consider a D2D-enabled cellular system with one cell and multiple UEs. All UEs may communicate through conventional cellular communications, while some of them, denoted as potential D2D UEs, are D2D enabled. These UEs have formed transmitter-receiver pairs in advance. A part of UE pairs, of which both transmitter and receiver are potential D2D UEs, are denoted as potential D2D pairs. Other pairs, which can only communicate through BS in conventional way, are denoted as cellular pairs.

Formally speaking, we have a set of UE pairs $\mathcal{U}$ with total number of pairs $N = |\mathcal{U}|$, with a subset of cellular pairs $\mathcal{U}_c$ and potential D2D pairs $\mathcal{U}_d$, respectively. For potential D2D pair $i \in \mathcal{U}_d$, its decision $x_i \in \{0, 1\}$ denotes whether or not pair i choose D2D mode. Here we let $\mathbf{X} = [x_i]$ denotes the mode selection vector.

A. Link Quality

If pair i chooses D2D mode, which means $x_i = 1$, we let $\text{SINR}_{i,d}$ denote the signal-to-noise-ratio (SINR) under D2D mode. We let $r_{i,d}$ denote the network utility under D2D mode, in which a logarithmic function to achievable rate under certain SINR is considered.

$$r_{i,d} = \log(w_d \log(1 + \frac{\text{SINR}_{i,d}}{\Gamma})) \quad (1)$$

where w_d is the bandwidth allocated to pair i, Γ is the SINR gap according to applied modulation and coding schemes. Notice that the network utility strictly increases with the achievable rate of certain mode.

In contrast, if pair i chooses cellular mode, which means $x_i = 0$, we let $\text{SINR}_{i,up}$ be the uplink SINR value from transmitter i to BS, and $\text{SINR}_{i,down}$ be the downlink SINR value from BS to receiver i. Similarly, we denote by $r_{i,c}$ the network utility under cellular mode as follows:

$$\begin{aligned} r_{i,c} &= \log(w_c \log(1 + \frac{\text{SINR}_{i,c}}{\Gamma})) \\ &= \log(w_c \log(1 + \frac{\min\{\text{SINR}_{i,up}, \text{SINR}_{i,down}\}}{\Gamma})) \quad (2) \end{aligned}$$

where w_c is the bandwidth allocated to pair i. We select minimum between uplink SINR and downlink SINR as cellular connection SINR [5][6]. Notice that the same pair may achieve different network utilities under D2D and cellular mode due to differences in SINR and/or allocated bandwidth.

B. D2D Bandwidth Allocation Modes

In the proposed system, all D2D connections are established on a dedicated spectrum without interference to/from the cellular connections. In such a case, the BS should partition the spectrum for D2D and cellular connections following some partition strategy. We let W be the total available bandwidth of the spectrum and p denote the proportion of total bandwidth reserved for D2D communication, that is, Wp bandwidth for D2D communication and $W(1-p)$ for cellular communication. We further denote the number of potential D2D pairs selecting D2D mode by m. It can be seen that $m = \sum_{i \in \mathcal{U}_d} x_i$, which indicates the loading of D2D communication in the dedicated spectrum. We consider two D2D modes under the overlay spectrum access, **divided D2D mode** and **shared D2D mode**, which have been described before. The proposed system only adopts one of the D2D modes, while the proper choice of D2D mode depends on the loading, spectrum availability, and objective of the service provider as we will explain later.

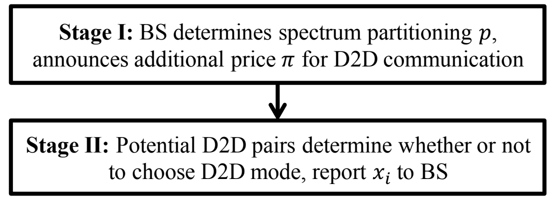


Fig. 1. A Two-Stage Stackelberg Game

There exists a complex and interactive relationship between spectrum partition strategy for the BS and mode selection strategy for potential D2D pairs. The spectrum partition strategy should be aware of the D2D mode requests, which is reflected by m and mode selection vector $\mathbf{X}$. Nevertheless, the spectrum partition strategy also has a significant impact on the quality of D2D connections due to its influence on the allocated bandwidth to each connection, and therefore has an impact on the mode selection of each potential D2D pair. Additionally, due to the characteristic of D2D communications, selfish potential D2D pairs may be unwilling to select D2D mode when the network utility under the achievable rate is undesired, even if it is better regarding the overall system performance and load balancing. We therefore propose to use game theory to analyze the proposed system.

C. Stackelberg Game Model

Based on the system model, we consider a two-stage Stackelberg game in which the BS and potential D2D pairs act as the leader and followers as shown in Fig. 1. We consider an one-shot game, that is, each pair starts to communicate after playing the Stackelberg game. All UEs have prepaid a fixed entrance fee to access the network, thus the price π here is additional payment for D2D communication. Specifically, the price π is served as a tool to balance the loading between D2D and cellular modes while maintaining the incentive compatibility of potential D2D pairs in mode selection.

The objective of the BS is to maximize the overall network utility of all cellular and D2D pairs, while each potential D2D pair's objective is to maximize their own utility. We define the utility of each potential D2D pair as its network utility under selected mode minus the additional D2D payment (if exists), that is,

$$u_i = \begin{cases} r_{i,d} - \pi, & x_i = 1. \\ r_{i,c}, & \text{else.} \end{cases} \quad (3)$$

Here notice that the D2D price is relatively simple as it is not related to interference or SINR. Although a more complex price can be considered, we will show that this simple pricing scheme is sufficient to achieve optimal performance in the proposed system.

III. Divided D2D Mode

We first analyze the Stackelberg game in divided D2D mode setting. Following the standard backward induction process, we first check the incentive compatible conditions for potential D2D pairs when the partition proportion p, target D2D loading m^*, and D2D price π are given.

For divided D2D mode, the bandwidth allocated for D2D communication is equally divided into $m = \sum_{i \in \mathcal{U}_d} x_i$ slices. The BS allocates exactly one slice to each potential D2D pair in D2D mode ($x_i = 1$), that is,

$$w_d = \frac{Wp}{m} \tag{4}$$

Notice that the real D2D loading m is not necessary equal to the target D2D loading m^* defined by the BS. The realized loading depends on the selections of potential D2D pairs, which follow their own rationality.

Each cellular pair or each potential D2D pair in cellular mode needs some bandwidth for both uplink and downlink communication. The bandwidth w_c allocated to each pair for either downlink or uplink is

$$w_c = \frac{W(1-p)}{2(N-m)} \tag{5}$$

A. Mode Selection in Stage II

Each potential D2D pair is a follower in the Stackelberg game. For potential D2D pair i, its utility described in (3) depends on whether it chooses cellular or D2D mode. A rational potential D2D pair will select the mode that maximizes its utility. Thus, potential D2D pair i will select D2D mode when D2D link utility is larger than cellular link utility, which can be expressed as

$$x_i = 1 \text{ if and only if } r_{i,d} - r_{i,c} - \pi > 0 \tag{6}$$

where $r_{i,d} - r_{i,c} - \pi = \log(\frac{Wp}{m}\log(1 + \frac{\text{SINR}_{i,d}}{\Gamma})) - \log(\frac{W(1-p)}{2(N-m)}\log(1 + \frac{\text{SINR}_{i,c}}{\Gamma})) - \pi$, according to equation (1)(2)(4)(5). To simplify the notations, we introduce parameters $a_{i,d} = \log(W\log(1 + \frac{\text{SINR}_{i,d}}{\Gamma}))$ and $a_{i,c} = \log(W\log(1 + \frac{\text{SINR}_{i,c}}{\Gamma}))$. Substituting $a_{i,d}$ and $a_{i,c}$ back into (6), we have

$$x_i^* = \begin{cases} 1, & \text{if } a_{i,d} - a_{i,c} - [\pi - \log\frac{2p(N-m)}{m(1-p)}] > 0. \\ 0, & \text{otherwise.} \end{cases} \tag{7}$$

The (7) are regarded as the incentive compatible conditions for potential D2D pairs to follow the specific mode selection strategy.

B. Spectrum Allocation and Pricing Strategy in Stage I

The goal of the BS, who is the leader of the Stackelberg game, is to maximize total network utility of network. We first assume that the partition proportion p is fixed. In such a case, the BS should deal with spectrum allocation and pricing problems. The network utility of all cellular pairs in the system is given as

$$\begin{aligned}\Pi_c &= \sum_{i \in \mathcal{U}_c} r_i = \sum_{i \in \mathcal{U}_c} w_c \log(1 + \frac{\text{SINR}_i}{\Gamma}) \\ &= \sum_{i \in \mathcal{U}_c} [a_i + \log\frac{(1-p)}{2(N-m)}]\end{aligned} \tag{8}$$

where $a_i = \log(W\log(1 + \frac{\text{SINR}_i}{\Gamma}))$. For cellular pair i, r_i is the network utility and SINR_i is the minimum between uplink SINR and downlink SINR.

Similarly, the network utility of all potential D2D pairs is

$$\begin{aligned}\Pi_d &= \sum_{i \in \mathcal{U}_d} x_i r_{i,d} + \sum_{i \in \mathcal{U}_d} (1-x_i) r_{i,c} \\ &= \sum_{i \in \mathcal{U}_d} r_{i,c} + \sum_{i \in \mathcal{U}_d} x_i (r_{i,d} - r_{i,c})\end{aligned} \tag{9}$$

Then, the utility of the BS is given as $\max_{X,m}\{\Pi = \Pi_c + \Pi_d\}$. According to equations (1)(2)(4)(5)(8)(9) and the definitions of $a_{i,d}$ and $a_{i,c}$, we simplify the utility function as

$$\begin{aligned}\Pi = &\sum_{i \in \mathcal{U}_c} [a_i + \log\frac{(1-p)}{2(N-m)}] + \sum_{i \in \mathcal{U}_d} [a_{i,c} + \log\frac{(1-p)}{2(N-m)}] \\ &+ \sum_{i \in \mathcal{U}_d} x_i [a_{i,d} + \log\frac{p}{m} - a_{i,c} - \log\frac{(1-p)}{2(N-m)}]\end{aligned} \tag{10}$$

The goal of the BS is to solve the optimization problem in (10) under the incentive compatible constraint (7).

C. Primal-Dual Pricing Update Method

The incentive compatible constraints from potential D2D pairs in (7) make the optimization problem hard to be handled. Nevertheless, we observe that (7) can be integrated into the optimization problem through primal-dual method [10] [12]. The primal formulation in (10) can be expressed in an equivalent form by introducing a set of three new variables as load metrics: $N_c = |\mathcal{U}_c|$, $N_d = |\mathcal{U}_d|$ and $m = \sum_{i \in \mathcal{U}_d} x_i$.

$$\begin{aligned}\Pi = &\sum_{i \in \mathcal{U}_d} x_i (a_{i,d} - a_{i,c}) + \sum_{i \in \mathcal{U}_c} a_i + \sum_{i \in \mathcal{U}_d} a_{i,c} \\ &+ m\log\frac{p}{m} + (N-m)\log\frac{(1-p)}{2(N-m)}\end{aligned} \tag{11}$$

The coupling constraint $m = \sum_{i \in \mathcal{U}_d} x_i$ motivates us to turn to the Lagrangian dual decomposition method whereby a dual variable μ introduced for our utility function Π. The dual problem is

$$\begin{aligned}D(\mu) = &\sum_{i \in \mathcal{U}_d} x_i (a_{i,d} - a_{i,c}) + \sum_{i \in \mathcal{U}_c} a_i + \sum_{i \in \mathcal{U}_d} a_{i,c} + m\log\frac{p}{m} \\ &+ (N-m)\log\frac{(1-p)}{2(N-m)} + \mu(m - \sum_{i \in \mathcal{U}_d} x_i)\end{aligned} \tag{12}$$

To solve the dual optimization problem of (12), we decouple it into two sub-problems

$$\mathbf{D} : \min_u D(\mu) = f_{\mathbf{X}}(\mu) + g_m(\mu) \tag{13}$$

where $$f(\mu) = \max_{\mathbf{X}}\{\sum_{i\in\mathcal{U}_d} x_i(a_{i,d} - a_{i,c} - \mu)\},\ \mathbf{X} = [x_i] \quad (14)$$

$$g(\mu) = \max_{m}\{\sum_{i\in\mathcal{U}_c} a_i + \sum_{i\in\mathcal{U}_d} a_{i,c} + m\log\frac{p}{m} + (N-m)\log\frac{(1-p)}{2(N-m)} + m\mu\} \quad (15)$$

When μ is fixed, from (14) we have

$$x_i^* = \begin{cases} 1, & \text{if } a_{i,d} - a_{i,c} - \mu > 0. \\ 0, & \text{otherwise.} \end{cases} \quad (16)$$

We observe that (16) closely (but not exactly) resembles the incentive compatible constraint in (7). The μ can be considered as **virtual price** in (16). We may ignore the value of $\sum_{i\in\mathcal{U}_c} a_i + \sum_{i\in\mathcal{U}_d} a_{i,c}$, which is only affected by background noise, from the optimization problem (15). Thus, the optimal solution m^* can be solved by linear integer search algorithm given μ is fixed.

$$m^* = \arg\max_{m} g(u), \quad m \in [0, N_d] \quad (17)$$

According to subgradient method, μ is updated by

$$\mu_{t+1} = \mu_t - \delta_t(m - \sum_{i\in\mathcal{U}_d} x_i) \quad (18)$$

where $\delta_t > 0$ is a dynamically chosen step size sequence. t is the times of playing this Stackelberg game.

Recall the mode selection of potential D2D pair i by (7), the virtual price μ can be transformed into the real price π announced by the BS with the following pricing strategy:

$$\pi = \mu + \log\frac{2p(N-m)}{m(1-p)} \quad (19)$$

When the BS adopts the pricing strategy by (19), the actions of all potential D2D pairs will be absolutely governed by the BS, that is, the incentive compatible conditions in (7) are satisfied.

D. Dynamic Spectrum Partition Strategy

Here we relax the assumption that p is given in Stage I. An efficient spectrum partition strategy should address the requirements from both cellular and D2D pairs and the loading of both modes in the system. Recall that the original dual optimization function (12) is a differentiable concave function of p given m and $\mathbf{X}$ are fixed. Thus, the optimal p^* can be found by checking the first order differentiation of (12) as

$$\frac{m}{p^*} - \frac{N-m}{1-p^*} = 0 \quad \Longrightarrow \quad p^* = \frac{m}{N} \quad (20)$$

In proposed system, we propose a dynamic spectrum partition strategy by applying (20) in the proposed primal-dual pricing strategy. It should be noted that m is the number of potential D2D pairs who select D2D mode. For these potential D2D pairs, the total bandwidth $W\frac{m}{N}$ will be allocated to them regardless of any mode selections they made. In such a case, the bandwidth allocated to existing cellular users will remain unaffected regardless of the choices of potential D2D pairs. Therefore, the service quality of cellular users and potential D2D pairs who stay in cellular mode will not be affected under the proposed dynamic spectrum partition strategy when we introduce D2D mode into conventional cellular system.

Algorithm 1 Primal-Dual Algorithm for Divided D2D Mode

```
Initialization: Set m = randi([0, N_d]). Set p = m/N. Set
  X = [x_i] = 0. Set μ_0 = 0 − δ_0(m − Σ_{i∈U_d} x_i).
repeat
  The BS updates m according to (17).
  The BS updates p according to (20).
  The BS updates μ according to (18).
  The BS computes π according to (19).
  for each i ∈ U_d do
    Potential D2D pair i determines x_i according to (7),
    and then reports its mode selection to the BS.
  end for
until m = Σ_{i∈U_d} x_i.
```

The complete primal-dual pricing and partitioning update algorithm is described in Algorithm 1. The convergence of the proposed algorithm is basically guaranteed [10]. Nevertheless, the detailed proof is not provided here due to page limitation. In short, to reach the optimal solution, we adopt the dynamic step size rule (6.61) with the adjustment procedures (6.62)-(6.63) in [11]. Proposition 6.3.6 in [11] shows the convergence of the proposed algorithm therefore can be guaranteed.

IV. Shared D2D Mode

The shared D2D mode system has a similar structure to the divided D2D mode except that the D2D bandwidth Wp partitioned by the BS is shared by all potential D2D pairs in D2D mode, that is,

$$w_d = Wp \quad (21)$$

The main difference of shared D2D mode from divided D2D mode is that potential D2D pairs in shared D2D mode will interfere each other. When the D2D loading m increases, the SINR of all potential D2D pairs in D2D mode will generally decrease due to interference from other pairs. Again, a rational potential D2D pair will select D2D mode if and only if the network utility minus the price in D2D mode maximizes its utility. Additionally, the SINR in D2D mode should be higher than a minimum threshold under the interference so that the link can be established. Thus, we impose a minimum SINR constraint in shared D2D mode: $\text{SINR}_{i,d} \geq K$, where K is a threshold determined by the communication system. Accordingly, the original binary predicate (16) will be modified as follows:

$$x_i^* = \begin{cases} 1, & \text{if } \text{SINR}_{i,d} \geq K \text{ and } (a_{i,d} - a_{i,c} - \mu) > 0. \\ 0, & \text{else.} \end{cases} \quad (22)$$

In shared D2D mode system, each potential D2D pair i can adopt the mode selection strategy by (22). Theoretically, the total number of user pairs in D2D mode will be under a certain threshold.

V. Simulation Results

We evaluate the performance of proposed algorithms under divided and shared D2D modes through simulations. We consider an urban macro hexagonal cell with a transmission range of 500 m. The carrier frequency is 2 GHz and the total system bandwidth W is 20 MHz. All simulation settings, if not mentioned, follow the suggested values in 3GPP TR36.843 [13]. There are N UE pairs, including N_d potential D2D

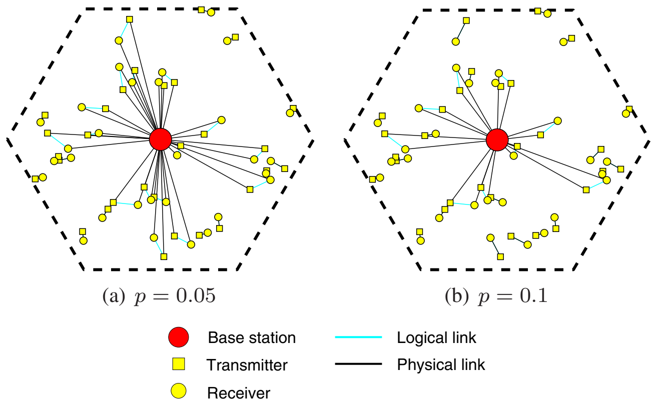


Fig. 2. Behaviors performed by potential D2D pairs: $N = 100$; $N_d = 30$; $N_c = 70$; adopt the Stackelberg game for divided D2D mode with different partition p. (a) $p = 0.05$; (b) $p = 0.1$.

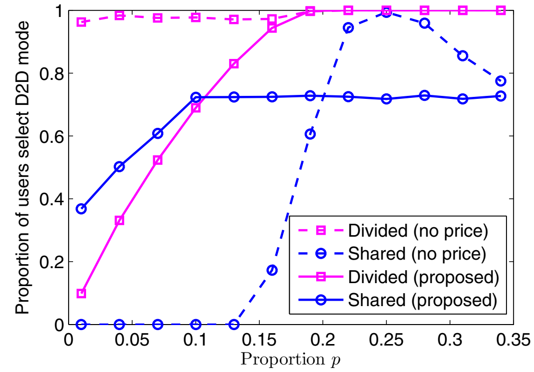
pairs and N_c cellular pairs, randomly and uniformly distributed within the cell. For each potential D2D pair, the receiver will be randomly located within 50 m of corresponding transmitter. According to the guideline [13], the minimum distance between UE and BS is 35 m and the minimum distance between any two transmitters of potential D2D UEs is 3 m. The transmit power of base station and each UE is 46 dBm and 23 dBm, respectively. All channel links follow the outdoor-to-outdoor channel model. The details about path loss, LOS probability, shadowing and fading strictly follow the description of 3GPP TR36.843 [13].

A. Effect of D2D Spectrum Partition Proportion

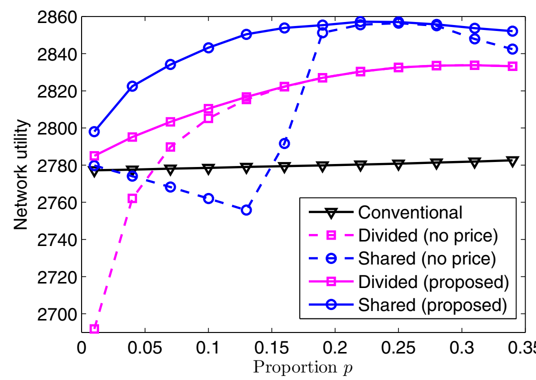
We first simulate the proposed algorithm under a fixed partition proportion p to understand the influence of D2D bandwidth to different D2D modes. Fig. 2 shows the physical connection of potential D2D pairs in divide D2D mode under the proposed algorithm. A potential D2D pair consists of a transmitter, a receiver and a logical link between them. The actual physical link depends on the mode it selects. We observe that some potential D2D pairs change their decisions from cellular mode to D2D mode with increasing p. The increase of p means more bandwidth reserved for D2D communication and less for conventional cellular communication. Thus, potential D2D pairs are more likely to receive higher utility from D2D mode and thus choose D2D mode.

Next, we would like to compare the performance among the conventional cellular system, the D2D-enabled system with no price and the proposed system, as shown in Fig. 3. In conventional cellular system, all UEs, either conventional or potential D2D pairs, can only transmit in cellular mode. Under D2D-enabled system, no price represents the case that each potential D2D pair selects the mode selfishly without any additional D2D payment for regulation. The proposed system, on the other hand, includes the optimal price we derived in Section III and IV.

Fig. 3(a) shows the average proportion of potential D2D pairs who will select D2D mode with the increase of D2D bandwidth proportion p. For the proposed system, we observe that shared D2D mode attracts more potential D2D pairs than divided D2D mode when p is low. However, the proportion



(a) The proportion of potential D2D pairs which select in D2D mode with increasing p

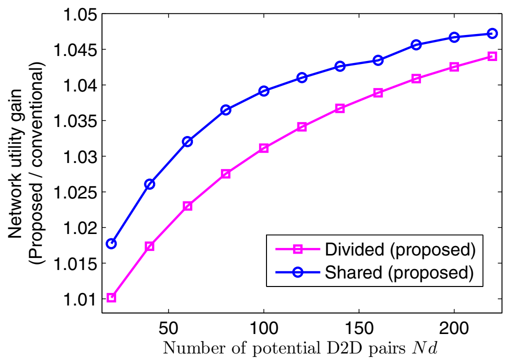


(b) The network utility in each communication networks

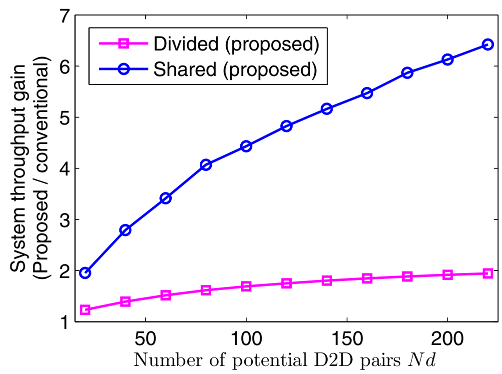
Fig. 3. Comparison of different communication network: $N = 200$; $N_d = 60$; $N_c = 140$; $K = 6$ dB.

of D2D pairs saturates to around 0.72 in shared D2D mode when p increases to 0.1. This is due to the fact that the inter-pair interference significantly increases with the proportion of D2D pairs in shared D2D mode. The interference reduces the incentive of potential D2D pairs to choose D2D mode, even with the benefit from the increasing bandwidth allocated to each potential D2D pair. On the contrary for divide D2D mode, the number of D2D pairs m grows steadily with the increase of p since no inter-pair interference exists in D2D communication. For the D2D-enabled system with no price, the network is not regulated by base station and thus pairs will select the mode purely based on the transmission quality. It can be seen that potential D2D pairs shows more interests to D2D transmission under divided D2D mode while much less interests when under shared D2D mode. These unregulated selections will degrade the overall system performance, as we will illustrate in Fig. 3(b).

The network utility is shown in Fig. 3(b). The overall system achieves a better performance with the increase of bandwidth reserved for D2D communication under both modes when the proposed pricing strategy is applied. Specifically, the shared D2D mode performs significant better due to higher spectrum utilization efficiency from shared spectrum. For the D2D-enabled system with no price applied, on the other hand, the system performance may be worse than the conventional cellular system. For divided D2D mode, the network utility is worse than conventional cellular system when p is low. Nevertheless, it obtains the same overall utility as the one



(a) Network utility gain



(b) System throughput gain

Fig. 4. Adopting dynamic spectrum partition strategy with the increase of potential D2D pairs N_d: $N_c = 100$; $K = 6$ dB.

under the proposed pricing strategy when p is larger than 0.19, since the optimal choices (in terms of overall system performance) for all potential D2D pairs are D2D mode, which is exactly the same as the selfish choice of these D2D pairs even when no price is applied. Additionally, the performance of shared D2D mode without price is strictly lower than the one under the proposed pricing strategy. Specifically, the allocated D2D bandwidth is under-utilized with significantly lower number of pairs choosing D2D mode. In general, the proposed pricing strategy system impresses a performance gain by fully exploiting the advantage of D2D system while avoiding undesired selfish selection by a proper pricing regulation.

B. Dynamic Spectrum Partition Strategy

Next, we adopt the proposed spectrum partition strategy to the proposed algorithm. In this simulation, we increase the number of potential D2D pairs N_d with fixed N_c to check the effect of loading to the performance in different D2D modes. Fig. 4 shows the network utility gain and system throughput gain in different D2D modes. We define network utility gain as the ratio of total network utility of proposed D2D-enabled system over conventional one. Similarly, system throughput gain is the ratio of total system throughput of proposed D2D-enabled system over conventional one. In general, the overall system achieves better network utility gain with the increased number of potential D2D pairs, as shown in Fig. 4(a). Besides, the performance of shared D2D mode is better than the divided D2D mode because of higher spectrum utilization efficiency. In Fig. 4(b), the system throughput of divided D2D mode draws near twice over conventional one with the increase number of potential D2D pairs. Additionally, shared D2D mode achieves up to six times system throughput improvement when around 180 potential D2D pairs exist in the cell.

VI. Conclusion

We presented a pricing-based Stackelberg game for optimal mode selection and spectrum partitioning for D2D communication. The proposed pricing-based algorithm displays a significant performance improvement over conventional system and D2D-enabled system with no price applied. The results showed that the BS can manage D2D-enabled network through the simple price design. Besides, both shared and divided D2D modes own their superiority in different environments.

Acknowledgment

This work was supported by Ministry of Science and Technology under Grants MOST 103-2221-E-002-086-MY3 and 103-2218-E-001-002-MY2. The authors would like to thank the anonymous reviewers for their helpful suggestions.

References

[1] X. Lin, J. Andrews, A. Ghosh, R. Ratasuk, "An overview of 3GPP device-to-device proximity services," *IEEE commun. Mag.*, vol. 52, no. 4, pp. 40-48, April 2014.

[2] A. Osseiran *et al.*, "Scenarios for 5G mobile and wireless communications: the vision of the METIS project," *IEEE commun. Mag.*, vol. 52, no. 5, pp. 26-35, May 2014.

[3] A. Asadi, Q. Wang, V. Mancuso, "A Survey on Device-to-Device Communication in Cellular Networks," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 4, pp. 1801-1819, Fourthquarter 2014.

[4] J. Liu, N. Kato, J. Ma, N. Kadowaki, "Device-to-Device Communication in LTE-Advanced Networks: A Survey," *IEEE Commun. Surveys Tuts.*, vol. PP, no. 99, pp. 1-1, 2014.

[5] C.G. Diaz, W. Saad, B. Maham, D. Niyato, A.S. Madhukumar, "Strategic device-to-device communications in backhaul-constrained wireless small cell networks," *2014 IEEE Wireless Commun. Netw. Conf. (WCNC)*, pp. 1661-1666, April 2014.

[6] H. Chen, D. Wu, Y. Cai, "Coalition Formation Game for Green Resource Management in D2D Communications," *IEEE Commun. Lett.*, vol. 18, no. 8, pp. 1395-1398, Aug 2014.

[7] B.Y. Huang, S.T. Su, C.Y. Wang, C.W. Yeh, H.Y. Wei, "Resource allocation in D2D communication - A game theoretic approach," *2014 IEEE Int. Conf. Commun. Workshops (ICC)*, pp. 483-488, June 2014.

[8] X Lin, J.G. Andrews, "Optimal spectrum partition and mode selection in device-to-device overlaid cellular networks," *2013 IEEE Global Commun. Conf. (GLOBECOM)*, pp. 1837-1842, Dec 2013.

[9] K. Zhu, E. Hossain, "Joint Mode Selection and Spectrum Partitioning for Device-to-Device Communication: A Dynamic Stackelberg Game," *IEEE Trans. Wireless Commun.*, vol. 14, no. 3, pp. 1406-1420, March 2015.

[10] Q. Ye, B. Rong, Y. Chen, M. Al-Shalash, C. Caramanis, J.G. Andrews, "User Association for Load Balancing in Heterogeneous Cellular Networks," *IEEE Trans. Wireless Commun.*, vol. 12, no. 6, pp. 2706-2716, June 2013.

[11] D. Bertsekas, *Convex Optimization Theory.* Athena Scientific, 2009.

[12] K. Shen, W. Yu, "Distributed Pricing-Based User Association for Downlink Heterogeneous Cellular Networks," *IEEE J. on Select. Areas in Commun.*, vol. 32, no. 6, pp. 1100-1113, June 2014.

[13] "Study on LTE Device to Device Proximity Services; Radio Aspects," 3GPP TR 36.843 v12.0.1, March 2014.