A Cascaded Channel-Power Allocation for D2D Underlaid Cellular Networks Using Matching Theory

Yiling Yuan*, Tao Yang*, Yuedong Xu*, Hui Feng* and Bo Hu†

* Research Center of Smart Networks and Systems, School of Information Science and Engineering
† Key Laboratory of EMW Information (MoE)
Fudan University, Shanghai, China, 200433
Emails: {yilingyuan13, taoyang, ydxu, hfeng, bohu}@fudan.edu.cn

Abstract—We consider a device-to-device (D2D) underlaid cellular network, where each cellular channel can be shared by several D2D pairs and only one channel can be allocated to each D2D pair. We try to maximize the sum rate of D2D pairs while limiting the interference to cellular links. Due to the lack of global information in large scale networks, resource allocation is hard to be implemented in a centralized way. Therefore, we design a novel distributed resource allocation scheme which is based on local information and requires little coordination and communication between D2D pairs. Specifically, we decompose the original problem into two cascaded subproblems, namely channel allocation and power control. The cascaded structure of our scheme enables us to cope with them respectively. Then a two-stage algorithm is proposed. In the first stage, we model the channel allocation problem as a many-to-one matching with externalities and try to find a strongly swap-stable matching. In the second stage, we adopt a pricing mechanism and develop an iterative two-step algorithm to solve the power control problem.

I. INTRODUCTION

Device-to-device (D2D) communication as an underlay to cellular networks is one of the key technologies to meet the dramatically increasing traffic demand and provide better user experience in future cellular networks [1]. The basic idea is to allow nearby mobile devices to reuse cellular spectrum by establishing direct communication links without interacting with base station (BS).

One big challenge for implementing underlaid D2D communication is how to allocate spectrum resource efficiently. To date, numerous resource allocation schemes have been proposed [2]–[4]. In [2], an efficient scheme was developed to jointly optimize the channel allocation and power control. Nevertheless, only one D2D pair was allowed to use one cellular channel, which may limit the system throughput. The spectrum efficiency of the cellular system can be improved further if multiple D2D pairs are allowed to share the same channels [3], [4].

Most of existing resource allocation schemes worked in centralized way. These schemes are developed under the assumption that the channel state information (CSI) between every transmitter and receiver is available to a central controller (e.g., the BS), which incurs heavy overhead. Therefore, it is more preferable to design a distributed resource allocation scheme with limited local channel information [5]–[9]. In [5], authors studied the system that allowed the channels to be shared by several D2D pairs. Nonetheless, the proposed algorithm lacked an efficient distributed power control approach to guarantee the service level of cellular user (CU). In [6]–[9], authors investigated the system where D2D pairs could reuse all the channels. However, the D2D pairs in close proximity will suffer from severe mutual interference, which may make the interference management complicated.

In this paper, we consider the system where each channel can be shared by multiple D2D pairs and each D2D pair can reuse at most one channel at each slot. The distributed resource allocation schemes for such system are less explored in the literature. Unlike [5], we try to maximize the sum rate of D2D pairs while guaranteeing the service level of CUs. We decompose the original problem into two cascaded subproblems: channel allocation and power control, and then a two-stage distributed algorithm is proposed.

Specifically, in the first stage, the channel allocation problem is modelled as many-to-one matching, which is suitable for assignment problem between two disjoint sets of players with local information. Unlike many existing works for resource allocation, the proposed matching game has externalities, which are resulted from the mutual interference among D2D pairs sharing the same channel. A distributed algorithm is proposed to find a strongly swap-stable matching as solution. Moreover, the existence of strongly swap-stable matching is proved. In the second stage, a pricing mechanism is adopted and an iterative two-step algorithm is presented to solve the power control problem. At the beginning, a virtual price factor based on the received interference is broadcast. Then, each D2D pair independently maximizes its utility according to the virtual price factor. The virtual price factor acts as control signal to limit the interference. Our contribution is that the proposed scheme can be implemented via distributed decision at each device based on local information. Moreover, the cascaded structure can reduce the exchange of control signal in need. The numerical simulations show the proposed algorithm with limited CSI is efficient and the throughput loss compared to brute-force method is small in our setup.

The rest of this paper is organized as follows. In Section II, the system model and problem formulation are established. In Section III, a two-stage algorithm is proposed to solve the two subproblems respectively. The Section IV gives the numerical results. Finally Section V concludes this paper.
II. SYSTEM MODEL AND PROBLEM FORMULATION

A. System Model

We study a D2D underlay cellular network comprised of a BS, C CUs and D D2D pairs. The scenario where D2D pairs reuse uplink resource is considered in this paper. The set of CUs and D2D pairs are denoted by \( C = \{1, \ldots , C\} \) and \( D = \{1, \ldots , D\} \) respectively. All devices are equipped with one antenna. The network is provided with a set \( K \) of \( K \) orthogonal frequency channels. We assume a fully loaded cellular network, i.e., \( K = C \). Each channel has been already allocated to one cellular user. For simplicity, CU \( k \in K \) is referred to the CU assigned to channel \( k \) in our discussion. Multiple D2D pairs can share the same cellular channels and each D2D pair is allowed to access at most one cellular channel. The set of D2D pairs sharing the channel \( k \) is denoted by \( D_k \subseteq D \), and \( D_k \cap D_{k'} = \emptyset \) when \( k \neq k' \).

Then, the SINR of D2D pair \( i \) on channel \( k \) is given by:

\[
\gamma_{ik}^D = \frac{p_d g_{id}^k}{n_0 + q_i g_{id}^k + \sum_{i \in D_k \setminus \{i\}} p_i g_{id}^k},
\]

where \( q_i \) and \( p_d \) are the transmit powers of cellular link and D2D pair \( d \), respectively. \( g_{id}^k \) denotes the channel gain from D2D transmitter \( i \) to D2D receiver \( d \) on channel \( k \). \( g_{id}^k \) is the channel gain from CU \( k \) to D2D receiver \( i \) on channel \( k \), and \( n_0 \) is the noise power.

B. Problem Formulation

In this paper, we aim to maximize the sum rate of D2D pairs while guaranteeing the maximum interference to cellular users. Mathematically, the problem can be formulated as

\[
\max_{p, D} \sum_{k \in K} \sum_{d \in D_k} \ln(1 + \gamma_{ik}^D) \quad (2a)
\]

s.t. \( 0 \leq p_d \leq P_m, \forall d \in D, \) \( (2b) \)
\[\sum_{d \in D_k} p_d h_{ik}^k \leq Q_k, \forall k \in K, \quad (2c)\]
\[D_k \cap D_{k'} = \emptyset, \forall k, k' \in K, k \neq k', \quad (2d)\]

where \( p = (p_1, p_2, \ldots , p_D) \), \( D = \{D_1, D_2, \ldots , D_K\} \), \( P_m \) is the maximum transmit power and \( h_{ik}^k \) denotes the channel gain from D2D transmitter \( d \) to cellular link on channel \( k \). The constraint \( 2c \), referred to as interference constraint, is for protection of cellular links, where \( Q_k \) is the interference tolerance level which depends on the requirements and channel gain of cellular link on device \( k \). Moreover, we assume only local information is available at each device. Explicitly, D2D pair \( d \) only knows the channel gain \( h_{id}^k, g_{id}^k, g_{id}^k \) and \( g_{di}^k \), and the BS only knows \( h_{id}^k \).

1We assume the system works in TDD mode. Hence, due to channel reciprocity, these CSI can be easily obtained by listening to the pilot transmitted by CU or other devices.

III. CHANNEL ALLOCATION AND POWER CONTROL

Problem [3] is a mixed integer non-linear programming problem, which is usually intractable. Moreover, only local information is available, which makes the problem more difficult to solve. Therefore, our goal is to develop an efficient distributed approach. For this purpose, we decompose the problem into two cascaded subproblems, namely channel allocation and power control. The former one is solved by matching theory and a pricing mechanism is adopted for the latter one. The entire framework is depicted in Fig. 1.

A. Channel Allocation Stage

We consider the optimization problem of the channel allocation solution given the transmit power \( p \) by solving the following optimization problem:

\[
\max_{D} \sum_{k \in K} \sum_{d \in D_k} \ln(1 + \gamma_{ik}^D) \quad (3a)
\]

s.t. \( D_k \cap D_{k'} = \emptyset, \forall k, k' \in K, k \neq k', \) \( (3b) \)
\[p_d = P_m, \forall d \in D. \quad (3c)\]

In problem [3], the interference constraint \( 2c \) will be considered in power control stage. In order to estimate the contribution of each D2D pair to the overall throughput, D2D transmitters are requested to transmit at power \( P_m \), as represented in constraint \( 3c \).

To solve problem [3], which is a combinatorial optimization problem, we model it as many-to-one matching game. Originally stemming from economics [10], matching theory provides a mathematical framework to cope with the problem of matching players in two distinct sets, based on each player’s individual preference and local information. It has been used for many resource allocation problems in communication networks [11]. In our context, one side is D2D pairs and the other side is the cellular channels. In the implementation, the BS will make decisions on behalf of channel \( k \).

Definition 1. A many-to-one matching \( \mu \) is a subset of \( D \times K \) such that \( |\mu(d)| = 1, |\mu(k)| = n_k, \forall d \in D, \forall k \in K \), where \( n_k \) is the quota of CU \( k \), \( \mu(d) = \{k \in K : (d, k) \in \mu\} \) and \( \mu(k) = \{d \in D : (d, k) \in \mu\} \).

If the number of D2D pair in \( \mu(k) \), say \( r \), is less than \( n_k \), then \( \mu(k) \) has \( n_k - r \) “holes” represented as D2D pairs with no preference over matchings. In this paper, we assume \( n_k = D \) for simplicity. We will also use \( \mu(d) \) to denote the channel reused by D2D pair \( d \). Utility function is adopted to describe

![Fig. 1: Framework for resource allocation](image-url)
the preferences of agents over matchings. Given matching \( \mu \), the utility of D2D pair \( d \) is defined as follows:

\[
U_d(\mu) = \xi_1 \phi_d(\mu) - \theta,
\]

where \( \phi_d(\mu) \) is the gain obtained from accessing channel \( \mu(d) \), \( \xi_1 \) is the equivalent revenue with respective to gain \( \phi_d(\mu) \), and \( \theta \) is the price for using cellular channel. We set \( U_d(\mu) = -\infty \) when D2D pair \( d \) is not matched with any channel. Specifically, the gain is represented as follows:

\[
\phi_d(\mu) = \ln\left(\frac{P_m g^{\mu(d)}_{dd}}{n_0} \right) - w q_d g^{\mu(d)}_d - \sum_{i \in \mu^2(d), i \neq d} \frac{w}{2} P_m (g^{\mu(d)}_{di} + g^{\mu(d)}_{id}),
\]

where \( w \) is tradeoff coefficient and \( \mu^2(d) \) denotes the set of D2D pairs reusing channel \( \mu(d) \). The difference between the first two terms of (5) can be regarded as the benefit from channel, which takes into consideration both the channel gain and interference from cellular, and only depends on the matched channel itself. The last term is the loss resulted from the mutual interference between D2D pairs. The following lemma implies that \( \sum_{d \in D} \phi_d(\mu) \) can be regarded as a lower bound of the aggregated throughput of D2D pairs.

**Lemma 1.** Suppose that each D2D pair is matched with one channel. Then, given \( p_d = P_m, \forall d \in D \), for any matching \( \mu \),

\[
\sum_{d \in D} \phi_d(\mu) + \text{const.} < \sum_{k \in K} \sum_{d \in \mu(k)} \ln(1 + \gamma_{dk}).
\]

**Proof:**

\[
\begin{align*}
&> \sum_{k \in K} \sum_{d \in \mu(k)} \ln\left(\frac{P_m g^{k}_{dd}}{n_0 + q_d g^k_d} + \sum_{i \in \mu(k) \setminus \{d\}} P_m g^{k}_{id}\right) \\
&= \sum_{k \in K} \sum_{d \in \mu(k)} \left\{\ln(w P_m g^{k}_{dd}) - \ln \left[\frac{w}{n_0 + q_d g^k_d} + \sum_{i \in \mu(k) \setminus \{d\}} P_m g^{k}_{id}\right]\right\} \\
&\geq \sum_{d \in D} \sum_{d \in \mu(k)} \left\{\ln\left(\frac{P_m g^{k}_{dd}}{n_0}\right) - w(q_d g^k_d + \sum_{i \in \mu(k) \setminus \{d\}} P_m g^{k}_{id})\right\} + \text{const.} \\
&= \sum_{d \in D} \phi_d(\mu) + \text{const.},
\end{align*}
\]

where the inequality (a) follows from the standard logarithm inequality, \( \ln x < x - 1, \forall x > 0 \).

In addition, the utility of channel \( k \) is defined as follows:

\[
U_k(\mu) = \theta |\mu(k)| - \xi_2 C(\sum_{d \in \mu(k)} \frac{P_m h^k_d}{Q_k} - 1),
\]

where \( C(x) = \max(0, x) \) quantifies the degree of violation of the constraint (2c) and \( \xi_2 \) is the cost coefficient. Note that (4) and (5) can be calculated locally at each device.

Because of the interference between D2D pairs, the utility of D2D pair \( d \) will be affected by the choice of other D2D pairs. Thus, the proposed matching has externalities and is called many-to-one matching with externalities [10]. Due to

**Algorithm 1** Stage 1: Channel Allocation for D2D Pairs

**GS-algorithm-based initialization:**

1. D2D pairs and channels construct their preference lists based on estimated SINR \( \gamma^d_k = \frac{P_m g^k_{dd}}{n_0 + q_d g^k_d} \) and interference channel gain \( h^k_d \), respectively.
2. Each D2D pair proposes to its most preferred channel that has not rejected it before.
3. Each channel keeps the most preferred \( n_k \) D2D pairs and rejects the others.
4. Repeat step 2 and 3 until each D2D pair is accepted by a channel.

**Swap operation:**

5. Each D2D pair \( s \) searches for swap-matching \( \mu^s_t \) “approved” by the players involved in the swap. Then, \( \mu = \mu^s_t \).
6. If \( \mu \) is changed, repeat step 5.

Note that the above swap-stability is stronger than that defined in [12]. The rationality of our stability notion comes from the observation that the BS aims to maximize the total utility of CUs and can permit monetary transfer among CUs. Algorithm [11] is proposed to find a strongly swap-stable matching. The initialization step is based on Gale-Shapely (GS) algorithm. Each D2D pair \( d \) ranks channels based on the descending order of estimated SINR. Meanwhile, each channel \( k \) ranks the D2D pair according to the ascending order of interference channel gain \( h^k_d \). Then, each D2D pair proposes to its most preferred channel, and each channel accepts the most preferred \( n_k \) D2D pair and rejects the others. Initialization step terminates when each D2D pair is accepted by a channel, which can be guaranteed by the assumption \( n_k = D \). Next, the algorithm seeks “approved” swap-matching until no such swap-matching exists.

To prove the convergence of Algorithm [11] we introduce a potential function for the proposed game:

\[
\Phi(\mu) = \sum_{k \in K} \sum_{d \in \mu(k)} \xi_1 \left\{\ln \left(\frac{P_m g^k_{dd}}{n_0}\right) - w(q_d g^k_d + \sum_{i \in \mu(k) \setminus \{d\}} \frac{P_m g^k_{id}}{2})\right\}
- \sum_{k \in K} \xi_2 C(\sum_{d \in \mu(k)} \frac{P_m h^k_d}{Q_k} - 1).
\]
Theorem 1. Algorithm [1] always converges to a strongly swap-stable matching.

Proof: The proof is based on the fact that the potential function is improved after each swap operation in Algorithm 1, which is proved as follows.

Note that each D2D pair is matched with one channel after initialization. Assume the “approved” swap-matching is \( \mu_s \). For convenience, let \( W_{\mu}(\mu) = \xi_1 \ln \left( \frac{P_{\mu}}{m_{\mu}(\mu)} \right) - \xi_1 w_{l,\mu,\mu}(\theta) \). For \( i, j \in D, k \in K \), \( I_k(i, i) = 0 \) and \( I_k(i, j) = \xi_2 w_{l,\mu,\mu}(g_{k,i} + g_{k,j})/2 \). Moreover, we assume \( \mu(s) = m, \mu(t) = n \). Thus

\[
\Phi(\mu) - \Phi(\mu') = \sum_{k \in K} U_k(\mu) + \sum_{d \in D} W_d(\mu) - \frac{1}{2} \sum_{k \in K} \sum_{i \in \mu(k)} I_k(i, i) \cdot \sum_{k \in K} U_k(\mu') + \sum_{d \in D} W_d(\mu') - \frac{1}{2} \sum_{k \in K} \sum_{i \in \mu(k)} I_k(i, i).
\]

Expanding and canceling the like terms, and using the symmetric property of \( I(i, j) \), we obtain

\[
\Phi(\mu) - \Phi(\mu') = U_m(\mu) + U_n(\mu) + U_s(\mu) + U_i(\mu) - \frac{1}{2} \sum_{i \in \mu(m)} I^m(i, s) - \sum_{i \in \mu(m)} I^m(i, t) - \frac{1}{2} \sum_{i \in \mu(s)} I^s(i, s) + I^s(i, t).
\]

Considering the utilities of players involved in the swap, we can find out that

\[
\Phi(\mu) - \Phi(\mu') = U_m(\mu) + U_n(\mu) + U_s(\mu) + U_i(\mu) - \frac{1}{2} \sum_{i \in \mu(m)} I^m(i, s) - \sum_{i \in \mu(m)} I^m(i, t) - \frac{1}{2} \sum_{i \in \mu(s)} I^s(i, s) + I^s(i, t).
\]

Thus we can conclude that the potential function is improved after a swap. The proof is similar when one of D2D pairs is a “hole”.

Furthermore, no number of possible matching between D2D pairs and channels is limited. Algorithm 1 will terminate at finite steps. On the other hand, the algorithm does not terminate until there is no any “approved” swap-matching. Therefore, we can conclude that the final matching is swap-stable.

B. Power Control Stage

Since all the cellular channels are orthogonal, we can decouple the power control problem into \( K \) subproblems, where we consider each channel independently. For simplicity, we focus on the power control problem of channel \( k \). Similar to [5], [6], we adopt a pricing mechanism consisted of two steps. In the first step, the BS determines the virtual price factor \( c_k \) to control the received interference. In the second step, with the virtual price information, each D2D pair adjusts transmit power aiming to maximize its utility. To solve the two-step problem, the backward induction technique is adopted. We start with the transmit power determination problem, called lower problem. Then we investigate the price factor adjustment problem, called upper problem.

1) Lower Problem: Because each D2D pair \( d \in D_k \) maximizes its own utility independently with local information, it is natural to model the lower problem as non-cooperative game. The power control game model is defined as \( G_k = \{ D_k, \{ A_d \}_{d \in D_k}, \{ R_d \}_{d \in D_k} \} \), where \( D_k = \{ d_1, \cdots, d_{D_k} \} \) is the set of \( D_k \) D2D pairs assigned to channel \( k \). \( A_d = [0, P_m] \) is the set of joint action profiles of all players, and \( R_d : \mathbb{R} \rightarrow \mathbb{R^k} \) is the payoff function of player \( d \). The payoff function is defined as follows:

\[
R_d(p_k) = \ln(\gamma_d^D(p_k)) - c_k h_d^k p_d,
\]

where \( \gamma_d^D(p_k) \) is defined in (1) and \( p_k = (p_{d_1}, \cdots, p_{d_{D_k}})^T \) is the action profile of all players. The first term can be considered as reward, which is an approximation of achievable rate. The second term is the cost charged by the BS, which is proportional to the interference caused by this D2D pair to cellular link.

We will adopt a well-studied solution notion known as Nash Equilibrium (NE) [13], from which no players has intention to unilaterally deviate. A NE of our game model is given in Theorem 2.

Theorem 2. Given \( c_k \), \( p_k = (p_{d_1}, \cdots, p_{d_{D_k}})^T \) is a NE of proposed power control game, where

\[
p_d = \min(P_m, \frac{1}{c_k h_d^k}), \forall d \in D_k.
\]

Proof: Let \( p_{-d} \) denote the joint action profile of all players except player \( d \). Given \( c_k \) and \( p_{-d} \), player \( d \) would like to maximize its utility as follows:

\[
\max_{p_d} \ln(\gamma_d^D(p_d, p_{-d})) - c_k h_d^k p_d
\]

s.t. \( 0 \leq p_d \leq P_m \).

The objective function is concave in \( p_d \). After solving problem (9), we can obtain the best response of player \( d: B_R^d(p_{-d}) = \min(P_m, \frac{1}{c_k h_d^k}) \). Note that this best response implies that a rational player will always take a fixed action no matter what actions are taken by its opponents. Consequently, we can conclude that in NE, each player \( d \in D_k \) would take the action \( p_d = \min(P_m, \frac{1}{c_k h_d^k}) \).
Algorithm 2 Stage 2: Power Control for channel \( k \)

1. Initialization: given channel \( k, D_k \), let \( c_k = c_{max}, c_l = 0; \)
2. while \( |c_u - c_l| \geq \epsilon \) do
3. The BS calculates \( c_k = (c_u + c_l)/2 \) and broadcasts it;
4. Each D2D pair \( d \in D_k \), calculate \( p_d^{*} \) according to (2);
5. if \( \sum_{d \in D_k} p_d^{*} h_d^k < Q_k \) then
6. \( c_u = c_k; \)
7. else
8. \( c_l = c_k; \)
9. end if
10. end while
11. \( c_k' = c_k; \)

such that the power profile obtained in the following lower problem is Pareto optimal, which is defined as follows:

Definition 4. A power profile \( p_k = (p_d, \ldots, p_{d_{D_k}}) \) satisfying constraint (2) is Pareto optimal if there exists no power profile \( p_k' \) satisfying constraint (2) could improve one D2D pair’s rate without deteriorating other D2D pairs’ rates.

Theorem 3. If a power profile \( p_k \) satisfying \( \sum_{d \in D_k} p_d h_d^k = Q_k \), then it is Pareto optimal.

Proof: We will prove the theorem by contradiction.

Suppose there is another power profile \( p_k' \) which can increase or maintain the performance of all D2D pairs. Then there must exist a set of D2D pairs \( M \subset D_k \) such that for any D2D pair \( d \in M \), \( p_d \) decreases. Let \( m = \arg \min_{d \in M} \frac{p_d}{p_d'} \) and \( \alpha = \frac{p_m}{p_m'} < 1 \). Consequently, \( p_d' \geq \alpha p_d \) for all \( d \in D_k \).

Hence

\[
\gamma_{mk}^D(p_k) \leq \frac{\alpha p_m g_{km}^k}{n_0 + q_k g_{km}^k + \alpha \sum_{d \in D_k \setminus \{d\}} p_d g_{km}^k} < \frac{p_m g_{km}^k}{n_0 + q_k g_{km}^k + \sum_{d \in D_k \setminus \{d\}} p_d g_{km}^k} = \gamma_{mk}^D(p_k),
\]

which is incompatible with our assumptions.

Theorem 3 implies that the virtual price factor \( c_k \) is “appropriate” if it can lead to a power profile which makes the interference constraint (2) tight. Additionally, from [8], it is easy to find out that \( p_d' \) is a non-increasing function of \( c_k \). So a simple bisection algorithm can be used to find the “appropriate” \( c_k \) according to the received interference at the BS. The algorithm solving the power control problem is depicted in Algorithm 2, where \( c_{max} \) is the price such that \( \sum_{d \in D_k} p_d'(c_{max}) h_d^k < Q_k \). According to Theorem 3 and the monotonicity of \( p_d'(c) \), Algorithm 2 will converge to the price factor leading to a Pareto optimal power profile. We consider non-trivial case, where the interference at the BS exceed \( Q_k \) if all D2D pairs transmit using \( P_m \), otherwise we just set \( c_k = 0 \).

IV. NUMERICAL SIMULATIONS

The performance of our proposed algorithms is investigated through simulation in this section. The channel used in simulation is \( h = \beta L^{-\eta} \), where \( \beta \) is fast fading gain with exponential distribution, \( \eta \) is the pathloss exponent and \( L \) is the distance between transmitter and receiver. The D2D pairs and CUs are distributed uniformly within the cell. We set \( \theta = \xi_1 = \xi_2 = 1 \) and \( w = 6 \times 10^6 \). Other configuration parameters are depicted in Table I.

At first, we evaluate the performance of our proposed scheme with different interference tolerance levels, \( K = 4, D = 10 \).

Fig. 2: Performance evaluation of our proposed scheme with different interference tolerance level.

Fig. 3: Performance of different schemes with different interference tolerance level, \( K = 1, D = 6 \). with \( K = 2, D = 6 \).

TABLE I: Simulation Configure Parameters

| Parameters        | Value     |
|-------------------|-----------|
| Cell radius       | 500 m     |
| Noise power \( n_0 \) | -100 dBm  |
| Pathloss exponent \( \eta \) | 4         |
| Transmit power of CU \( q_k \) | 20 mW      |
| Maximum D2D power \( P_m \) | 20 mW      |
| Length of D2D links | 50 m   |
we can conclude that our scheme is an efficient distributed resource allocation scheme in large scale D2D underlaid cellular networks.

V. CONCLUSION

In this paper, we propose a distributed resource allocation scheme for D2D underlaid cellular networks where each channel can be shared by one CU and several D2D pairs. We try to maximize the sum rate of D2D pairs while limiting the interference to cellular links. To solve the problem, we decompose the problem into two cascaded subproblems: channel allocation and power control problem, and a two-stage algorithm is proposed. Firstly, we model the channel allocation problem as a many-to-one matching game with externalities and try to find a strongly swap-stable matching. Secondly, we adopt price mechanism and propose an iterative two-step algorithm to solve the problem. Finally we present numerical results to verify the efficiency of our scheme. However, the interference information between D2D pairs is not fully utilized. In future work, such information can be used to design a more efficient algorithm for power distribution.

ACKNOWLEDGMENT

This work was supported by the NSF of China (No. 61501124, No.71731004).

REFERENCES

[1] A. Asadi, Q. Wang, and 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.
[2] D. Feng, L. Lu, Y. W. Yi, and G. Y. Li, “Device-to-device communications underlaying cellular networks,” IEEE Trans. Commun., vol. 61, no. 8, pp. 3541–3551, 2013.
[3] W. Zhao and S. Wang, “Resource sharing scheme for device-to-device communication underlaying cellular networks,” IEEE Trans. Commun., vol. 63, no. 12, pp. 4838–4848, 2015.
[4] T. D. Hoang, L. B. Le, and T. Le-Ngoc, “Resource allocation for D2D communications under proportional fairness,” in Proc. IEEE GLOBECOM, 2015, pp. 1259–1264.
[5] S. Maghsudi and S. Staczak, “Hybrid centralized -distributed resource allocation for device-to-device communication underlaying cellular networks,” IEEE Trans. Veh. Technol., vol. 65, no. 4, pp. 2481–2495, April 2016.
[6] Q. Ye, M. Al-Shalash, C. Caramanis, and J. G. Andrews, “Distributed resource allocation in device-to-device enhanced cellular networks.” IEEE Trans. Commun., vol. 63, no. 2, pp. 441–454, 2015.
[7] R. Yin, G. Yu, C. Zhong, and Z. Zhang, “Distributed resource allocation for D2D communication underlaying cellular networks,” in Proc. IEEE ICC Workshops, 2013, pp. 138–143.
[8] M. Hasan and E. Hossain, “Distributed resource allocation in D2D-enabled multi-tier cellular networks: An auction approach,” in Proc. IEEE ICC, 2015, pp. 2949–2954.
[9] H. H. Nguyen, M. Hasegawa, and W. J. Hwang, “Distributed resource allocation for D2D communications underlay cellular networks,” IEEE Communications Letters, vol. 20, no. 5, pp. 942–945, May 2016.
[10] A. E. Roth and A. Marilda Oliveira, Two-Sided Matching: A Study in Game-Theoretic Modeling and Analysis. Cambridge University Press, 1992.
[11] Y. Gu, W. Saad, M. Bennis, M. Debbah, and Z. Han, “Matching theory for future wireless networks: fundamentals and applications.” IEEE Commun. Mag., vol. 53, no. 5, pp. 52–59, May 2015.
[12] E. Bodine-Baron, C. Lee, A. Chong, B. Hassibi, and A. Wierman, “Peer effects and stability in matching markets,” in Proc. of InIt Conf. on Algorithmic game theory, 2011, pp. 117–129.
[13] M. J. Osborne and A. Rubinstein, A course in game theory. MIT Press, 1994.