Resource Allocation for Device-to-Device Communication Underlaying Cellular Networks: An Alternating Optimization Method

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***Abstract*—In this letter, we study the resource allocation in cellular networks with device-to-device (D2D) communication enhancement, where multiple D2D pairs can share subchannels with cellular users (CUs). Our optimization task is to maximize the sum rate of the cellular system while satisfying the rate requirements of all CUs. We propose an alternating optimization method to address the formulated problem efficiently. Numerical results show that our proposal can significantly increase the throughput of the cellular network.**

***Index Terms*—Alternating optimization, cellular network, D2D communication, resource allocation.**

I. Introduction

DEVICE-TO-DEVICE (D2D) communication is deemed as a promising technique to improve the spectrum usage efficiency of cellular networks and has received much attention recently. In a D2D communication underlaying cellular network, D2D pairs can share radio resources with cellular users (CUs) and communicate directly with each other under the control of base stations (BSs) [1]. However, there inevitably exists mutual interference between the CUs and the D2D pairs, resulting that radio resource allocation becomes a challenging issue.

In [2], [3], efficient resource sharing schemes are developed to control the interference to the CU who shares a subchannel with a D2D pair. In [4], [5], the D2D pair is permitted to use the subchannels being used by multiple CUs. Multiple D2D pairs sharing subchannels with multiple CUs is investigated in [6], [7]. It is noteworthy that only the mutual interference between the CUs and the D2D pairs is considered in [2]–[7]. The interference among the D2D pairs is ignored because they are restricted to use different subchannels, resulting that the number of the D2D pairs is always smaller than that of the subchannels. It is not spectrum-efficient because the throughput could be improved if the D2D pairs can use the same subchannels. On the other hand, most of previous researches on multiple D2D pairs sharing the same subchannels concentrated on fixed power allocation among the CUs [8] and the D2D pairs [9]–[11], which cannot achieve optimal solutions from the viewpoint of the system. In [12], dynamic resource allocation is studied, where the D2D pairs are allowed to utilize all subchannels. However, the D2D pairs in close proximity will inevitably suffer heavy mutual interference.

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In this letter, we try to maximize the sum rate of the CUs and the D2D pairs which can use the same subchannels, while satisfying the rate requirement of each CU. We solve the formulated optimization task by dividing it into two sub-problems: subchannel assignment and power distribution. For a given power distribution, we prove that each D2D pair should be allocated to the subchannel that can yield the maximum throughput over all subchannels. Then we show that the power distribution among the D2D pairs is a D.C. (Difference of Convex) programming problem and develop an efficient algorithm to address it. Last, we employ an alternating optimization method to work out the solution to the original problem. Simulation results show that our proposed algorithm enhances the spectrum efficiency significantly and outperforms other representative schemes.

II. System Model and Problem Formulation

Consider a cellular system supporting D2D communication, which includes a BS, N CUs and M D2D pairs. The D2D pairs reuse the uplink resource of the CUs. The sets of the CUs and the D2D pairs are denoted by $\mathcal{N}$ and $\mathcal{M}$, respectively. Generally, the CUs have the priority to transmit signals without being interfered. The CU n requires a minimal transmission rate $R^C_{n,min}$. The available spectrum of the system is divided into N subchannels. Without loss of generality, we assume that n-th subchannel is assigned to the CU n. So $\mathcal{N}$ also denotes the set of subchannels. Let $\omega_{m,n}$ inform whether the D2D pair m uses the n-th subchannel or not: $\omega_{m,n} = 1$, the D2D pair m uses the n-th subchannel; $\omega_{m,n} = 0$, otherwise. We collect all $\omega_{m,n}$'s into one vector $\bar{\omega}$.

Let p_n and $p_{m,n}$ be the transmission powers of the CU n and the D2D transmitter (D2D-Tx) m on the n-th subchannel. We collect all p_n's and $p_{m,n}$'s into one vector $\bar{p}$. Denote H_n and $H_{m,n}$ as the channel power gains of the CU n and the D2D pair m on the n-th subchannel. $\widetilde{H}^D_{m,n}$ is the power gain of the interference link from the D2D-Tx m to the BS on the n-th subchannel. The signal to interference plus noise ratio (SINR) of the BS on the n-th subchannel can be written as

$$\gamma^C_n = \frac{p_n H_n}{\sum_{m\in\mathcal{M}} \omega_{m,n} p_{m,n} \widetilde{H}^D_{m,n} + \sigma_0^2}, \tag{1}$$

where σ_0^2 is the noise power. Denote $\widetilde{H}^C_{m,n}$ and $\widetilde{H}^n_{m',m}$ as the power gains of the interference link from the CU n to the D2D receiver (D2D-Rx) m and the interference link from the D2D-Tx m' to the D2D-Rx m on the n-th subchannel. The SINR of the D2D-Rx m on the n-th subchannel is

$$\gamma^D_{m,n} = \frac{p_{m,n} H_{m,n}}{\sum_{m'\in\mathcal{M}\setminus\{m\}} \omega_{m',n} p_{m',n} \widetilde{H}^n_{m',m} + p_n \widetilde{H}^C_{m,n} + \sigma_0^2}, \tag{2}$$

where $\mathcal{A} \setminus \mathcal{B} = \{x | x \in \mathcal{A}, x \notin \mathcal{B}\}$. The sum rate on the n-th subchannel is

$$R_n = \log_2\left(1+\gamma_n^C\right) + \sum_{m\in\mathcal{M}} \omega_{m,n} \log_2\left(1+\gamma_{m,n}^D\right). \quad (3)$$

Our goal is to maximize the total transmission rate of the CUs and the D2D pairs, while satisfying the rate requirements of all CUs. Mathematically, the optimization problem can be formulated as follows,

$$\begin{aligned} \max_{\bar{\omega},\bar{p}} \quad & \sum_{n\in\mathcal{N}} R_n \\ s.t.\ C_1: \quad & \log_2\left(1+\gamma_n^C\right) \geq R_{n,min}^C, \quad \forall n \in \mathcal{N}, \\ C_2: \quad & P_m^D \geq p_{m,n} \geq 0, \quad \forall m \in \mathcal{M}, n \in \mathcal{N}, \\ C_3: \quad & P_n^C \geq p_n \geq 0, \quad \forall n \in \mathcal{N}, \\ C_4: \quad & \omega_{m,n} \in \{0,1\}, \quad \forall m \in \mathcal{M}, n \in \mathcal{N}, \\ C_5: \quad & \sum_{n\in\mathcal{N}} \omega_{m,n} = 1, \quad \forall m \in \mathcal{M}, \end{aligned} \quad (4)$$

where P_n^C and P_m^D are the maximum transmission powers of the CU n and the D2D-Tx m, respectively. C_1 ensures the required rate of the CUs. C_2 and C_3 are the transmission power budgets for the D2D pairs and the CUs. C_4 and C_5 indicate that each D2D pair can use at most one subchannel.

III. Our Proposed Resource Allocation Algorithm

Equation (4) is generally hard to solve because it defines a mixed integer programming problem that is NP-hard. Even if we relax the intractable integer variable $\omega_{m,n}$, it is still difficult to obtain the global optimum because the relaxed form is non-concave for both $\omega_{m,n}$ and $p_{m,n}$. In this letter, we convert (4) into an equivalent form.

First, we modify the C_2 in (4) as

$$\omega_{m,n} P_m^D \geq p_{m,n} \geq 0, \qquad \forall m \in \mathcal{M}, n \in \mathcal{N}. \quad (5)$$

We can see that $p_{m,n} = 0$ if $\omega_{m,n} = 0$. As a result, the $\omega_{m,n}$'s in (1) and (2) can be safely removed. Combine (5) with C_5 in (4), we have

$$\sum_{n\in\mathcal{N}} \omega_{m,n} P_m^D = P_m^D \sum_{n\in\mathcal{N}} \omega_{m,n} = P_m^D \geq \sum_{n\in\mathcal{N}} p_{m,n}. \quad (6)$$

Then, based on (1), C_1 in (4) can be written as follows:

$$\sum_{m\in\mathcal{M}} p_{m,n} \widetilde{H}_{m,n}^D \leq p_n G_n - \sigma_0^2, \qquad \forall n \in \mathcal{N}, \quad (7)$$

where $G_n = H_n / (2^{R_{n,min}^C} - 1)$. The equivalent form of (4) can be rewritten as

$$\begin{aligned} \max_{\bar{\omega},\bar{p}} \quad & \sum_{n\in\mathcal{N}} R_n \\ s.t. \quad C_1: \quad & \sum_{m\in\mathcal{M}} p_{m,n} \widetilde{H}_{m,n}^D \leq p_n G_n - \sigma_0^2, \quad \forall n \in \mathcal{N}, \\ C_2: \quad & \sum_{n\in\mathcal{N}} p_{m,n} \leq P_m^D, \quad \forall m \in \mathcal{M}, \\ C_3: \quad & p_{m,n} \geq 0, \quad \forall m \in \mathcal{M}, n \in \mathcal{N}, \\ C_4: \quad & P_n^C \geq p_n \geq 0, \quad \forall n \in \mathcal{N}, \\ C_5: \quad & \omega_{m,n} \in \{0,1\}, \quad \forall m \in \mathcal{M}, n \in \mathcal{N}, \\ C_6: \quad & \sum_{n\in\mathcal{N}} \omega_{m,n} = 1, \quad \forall m \in \mathcal{M}. \end{aligned} \quad (8)$$

Note that the SINRs of the CU n and the D2D-Rx m are only the functions of the powers on the n-th subchannel in (8).

For given p_n's and $p_{m,n}$'s, finding optimal subchannel assignment is to solve the following optimization problem:

$$\begin{aligned} \max_{\bar{\omega}} \quad & \sum_{n\in\mathcal{N}} \left[\log_2\left(1+\gamma_n^C\right) + \sum_{m\in\mathcal{M}} \omega_{m,n} \log_2\left(1+\gamma_{m,n}^D\right)\right] \\ s.t. \quad & C_5 \sim C_6 \text{ in (8)}. \end{aligned} \quad (9)$$

As mentioned before, γ_n^C and $\gamma_{m,n}^D$ are only functions of the given powers on the n-th subchannel in (9). Therefore, the optimal solution to (9) is

$$\omega_{m,n} = \begin{cases} 1 & n = \arg\max_{n'\in\mathcal{N}} \log_2\left(1+\gamma_{m,n'}^D\right), \\ 0 & \text{otherwise}, \end{cases} \quad \forall m \in \mathcal{M}, \quad (10)$$

which indicates that the D2D pair m should be assigned to the subchannel which yields the maximum transmission rate among all subchannels with the given power allocation.

For the given $\omega_{m,n}$'s, the optimal power allocation is the solution to the following problem:

$$\begin{aligned} \max_{\bar{p}} \quad & \sum_{n\in\mathcal{N}} R_n(\bar{p}_n) \\ s.t. \quad & C_1 \sim C_4 \text{ in (8)}, \end{aligned} \quad (11)$$

where $\bar{p}_n = (p_n, p_{1,n}, \ldots, p_{M,n})^T$ and we use $R_n(\bar{p}_n)$ as the replacement of R_n to highlight that the sum rate on the n-th subchannel is only a function of $\bar{p}_n$. (11) is a non-convex optimization problem, which is still hard to tackle. Note that $R_n(\bar{p}_n) = f_n(\bar{p}_n) - g_n(\bar{p}_n)$, where $f_n(\bar{p}_n)$ and $g_n(\bar{p}_n)$ are given in (12) and (13), shown at the bottom of the page. Since $f_n(\bar{p}_n)$ and $g_n(\bar{p}_n)$

$$f_n(\bar{p}_n) = \log_2\left(p_n H_n + \sum_{m\in\mathcal{M}} p_{m,n} \widetilde{H}_{m,n}^D + \sigma_0^2\right) + \sum_{m\in\mathcal{M}} \omega_{m,n} \log_2\left(p_{m,n} H_{m,n} + \sum_{m'\in\mathcal{M}\setminus\{m\}} p_{m',n} \widetilde{H}_{m',m}^n + p_n \widetilde{H}_{m,n}^C + \sigma_0^2\right) \quad (12)$$

$$g_n(\bar{p}_n) = \log_2\left(\sum_{m\in\mathcal{M}} p_{m,n} \widetilde{H}_{m,n}^D + \sigma_0^2\right) + \sum_{m\in\mathcal{M}} \omega_{m,n} \log_2\left(\sum_{m'\in\mathcal{M}\setminus\{m\}} p_{m',n} \widetilde{H}_{m',m}^n + p_n \widetilde{H}_{m,n}^C + \sigma_0^2\right) \quad (13)$$

are concave for $p_{m,n}$'s, (11) is a D.C. programming problem. One approach to address such kind of problems is to solve a sequence of concave optimization problems [13], [14]. A concave lower bound of $R_n(\bar{p}_n)$, which is parametrized by a given power allocation $\bar{p}'_n = (p'_n, p'_{1,n}, \ldots, p'_{M,n})^T$, is given by

$$\underline{R}_n\left(\bar{p}_n, \bar{p}'_n\right) = f_n(\bar{p}_n) - g_n\left(\bar{p}'_n\right) - \left\langle \nabla g_n\left(\bar{p}'_n\right), \bar{p}_n - \bar{p}'_n \right\rangle, \quad (14)$$

where ∇g_n is the gradient of g_n.

Lemma 1: Given $\bar{p}'_n$ that satisfies $C_1 \sim C_4$ in (8), $\underline{R}_n(\bar{p}_n, \bar{p}'_n)$ is a tight lower bound of $R_n(\bar{p}_n)$.

Proof: Since $g_n(\bar{p}_n)$ is concave, based on the first-order condition for a concave function, we have $g_n(\bar{p}_n) \le g_n(\bar{p}'_n) + \langle \nabla g_n(\bar{p}'_n), \bar{p}_n - \bar{p}'_n \rangle$. Thus, $R_n(\bar{p}_n) \ge \underline{R}_n(\bar{p}_n, \bar{p}'_n)$. Moreover, when $\bar{p}'_n = \bar{p}_n$, we have $R_n(\bar{p}_n) = \underline{R}_n(\bar{p}_n, \bar{p}_n)$, which implies that $\underline{R}_n(\bar{p}_n, \bar{p}'_n)$ is a tight lower bound of $R_n(\bar{p}_n)$. □

Consider the following optimization problem,

$$\max_{\bar{p}} \quad \sum_{n \in \mathcal{N}} \underline{R}_n\left(\bar{p}_n, \bar{p}'_n\right)$$
$$s.t. \quad C_1 \sim C_4 \text{ in (8)}. \quad (15)$$

Equation (15) defines a convex optimization problem and can be solved by using standard algorithms or softwares, such as CVX [15]. More importantly, it can be proved that the sum rate achieved by the optimal solution to (15) is always no worse than the sum rate achieved by $\bar{p}'$:

Theorem 1: Denote $\bar{p}^*$ as the optimal solution to (15), we have $\sum_{n \in \mathcal{N}} R_n(\bar{p}^*_n) \ge \sum_{n \in \mathcal{N}} R_n(\bar{p}'_n)$.

Proof: Based on Lemma 1, we can obtain

$$\sum_{n \in \mathcal{N}} R_n\left(\bar{p}^*_n\right) \ \ge \ \sum_{n \in \mathcal{N}} \underline{R}_n\left(\bar{p}^*_n, \bar{p}'_n\right) \ge \sum_{n \in \mathcal{N}} \underline{R}_n\left(\bar{p}'_n, \bar{p}'_n\right)$$
$$= \sum_{n \in \mathcal{N}} R_n\left(\bar{p}'_n\right). \quad (16)$$

The first inequality follows that $\underline{R}_n(\bar{p}^*_n, \bar{p}'_n)$ is the lower bound of $R_n(\bar{p}^*_n)$. The second inequality follows that $\bar{p}^*_n$ is the optimal solution to (15). □

Since an improved solution to (11) can always be obtained by maximizing the lower bound, we develop an iterative algorithm to work out a near optimal solution to (11). Let $\bar{p}^{(l)}$ be the optimal solution to (15) with $\bar{p}' = \bar{p}^{(l-1)}$. Specially, $\bar{p}^{(0)}$ is an initial power allocation which satisfies $C_1 \sim C_4$ in (8). A possible initialization of power allocation on the n-th subchannel is to set $p_n = P^C_n$ for the CU n and $p_{m,n} = P^D_m/N$ for all D2D pairs. If the achievable rate of the CU n is lower than $R^C_{n,min}$, decrease the power of the D2D-Tx which yields the heaviest interference on the n-th subchannel. Repeat the procedure until the achievable rate of the CU n is no less than $R^C_{n,min}$.

Start with an initial power allocation, we can solve (15) to update the power of each subchannel with $\bar{p}' = \bar{p}^{(l-1)}$ at the l-th iteration. The procedure repeats until the Euclidean distance between $\bar{p}^{(l)}$ and $\bar{p}^{(l-1)}$ is less than the predefined accuracy parameter ϵ. The algorithm is summarized in Table I, where L is the maximum number of iterations. Note that Algorithm 1 can always find a local optimal solution to (11). As suggested in [14], heuristic algorithms, such as genetic algorithm and simulated annealing, can be employed to yield a good solution with a number of iterations.

TABLE I
ALGORITHM 1: POWER ALLOCATION ALGORITHM

1: *Initialization*: $l = 0$, $\bar{p}^{(0)}$ is a feasible solution to (11);
2: **repeat**
3: $l = l + 1$;
4: $\bar{p}' = \bar{p}^{(l-1)}$;
5: Obtain the optimal solution $\bar{p}^{(l)}$ to (15);
6: **until** $||\text{vec}(\bar{p}^{(l)} - \bar{p}^{(l-1)})|| \le \epsilon$ or $l \ge L$
7: **return** $\bar{p}^{(l)}$

TABLE II
SIMULATION PARAMETERS

Parameter	Value
Cellular layout	Isolated cell, 1-sector
Coverage area	The radius of the cell is 500 m
Maximum distance of D2D	50 m
Number of subchannels/CUs	5
Maximum power of CU	20 dBm
Rate requirement of CU	1 bps/Hz
Number of D2D pairs	$1 \sim 20$
Maximum power of D2D-Tx	20 dBm
Pass loss (in dB)	$15.3 + 37.6 \log_{10} D$ (D in m)
Noise power	-100 dBm

Then we employ alternating optimization [16] to solve the original problem. First, we initialize $\omega_{m,n} = 1/N, \forall m \in \mathcal{M}$, $n \in \mathcal{N}$. It is worth noticing that all D2D pairs can use all subchannels in these circumstances and the total transmission power of the D2D-Tx m is limited to $P^D_m, \forall m \in \mathcal{M}$. Then we can obtain the solution to (11) with the initial $\bar{\omega}$ by using Algorithm 1. Based on the power allocation, we can update the subchannel assignment by using (10). Finally, the power allocation for the updated subchannel assignment can be obtained by using Algorithm 1 again. The outline of our proposed algorithm is summarized as follows:

Step 1: Initialize $\omega_{m,n} = 1/N, \forall m, n$;
Step 2: Obtain $p_{m,n}$'s with the $\omega_{m,n}$'s by using Algorithm 1;
Step 3: Update the $\omega_{m,n}$'s by using (10);
Step 4: Obtain the $p_{m,n}$'s with the updated $\omega_{m,n}$'s by using Algorithm 1.

IV. SIMULATION RESULTS

We conduct a series of experiments to evaluate the proposed resource allocation scheme. The main simulation parameters are listed in Table II. We take the optimal solution to the relaxation of (8) as an upper bound, which is obtained by in-built *fmincon* solver of *Matlab*. Three representative schemes are also given for comparison. Scheme 1 and Scheme 2 are proposed in [6], where each subchannel can be used by at most one D2D pair. If $M \le N$, Scheme 1 and Scheme 2 can always find the optimal subchannel and power allocation. If $M > N$, Scheme 1 chooses N D2D pairs to maximize their sum rate; Scheme 2 randomly selects N D2D pairs to use all subchannels. Scheme 3 randomly allocates each D2D pair over all subchannels and distributes power among them by using Algorithm 1.

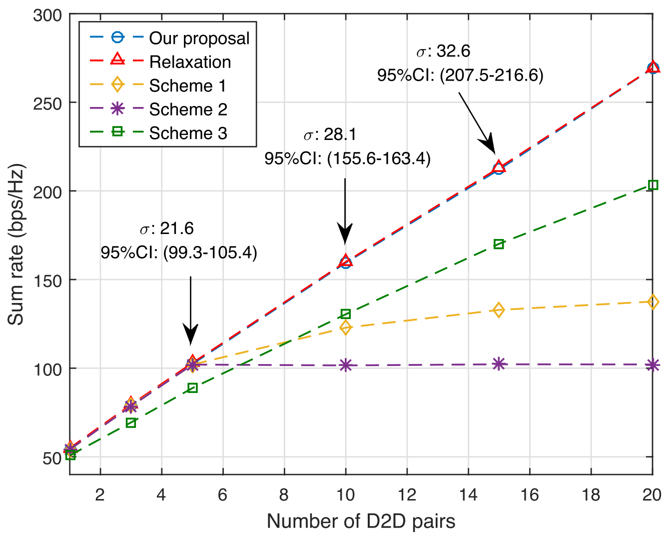

Fig. 1. Sum rate as a function of M.

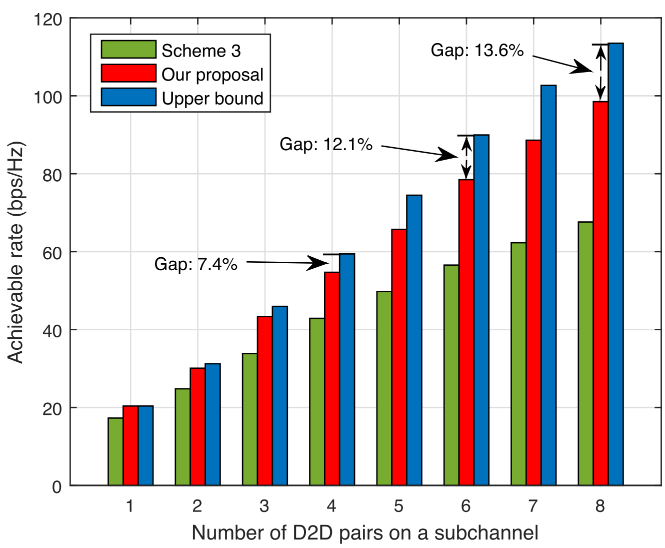

Fig. 2. Comparison of sum rate on a subchannel.

The sum rate as a function of the number of D2D pairs is illustrated in Fig. 1, where the 95% confidence intervals (95% CI) and the standard deviations σ of the sum rate are also given. As shown in Fig. 1, the performance of our proposed algorithm is close to the upper bound obtained by solving the relaxed form of (8). We can conclude that our proposal is close to the optimum. It can be also seen from Fig. 1 that our proposed algorithm outperforms other three schemes significantly when $M > N$. Specifically, the throughput obtained by our proposal grows approximately linearly with the increase of the D2D pairs, indicating that it can be widely used in different scenarios.

We also investigate the mutual interference among the D2D pairs on a subchannel for the case that $M = 20$. The sum rate on a subchannel with different numbers of the D2D pairs is illustrated in Fig. 2. We record the rate and the number of the D2D pairs on each subchannel for each instance. Then we calculate the average rate on each subchannel as a function of the number of the D2D pairs over 500 Monte Carlo simulations. Our proposed algorithm is compared with Scheme 3 and an upper bound, which is obtained by (3) with ignoring the mutual interference among the D2D pairs. It can be observed from Fig. 2 that the achievable rate yielded by our proposed algorithm is close to the upper bound when the number of the D2D pairs on a subchannel is small. Even for the case that a subchannel is shared by 8 D2D pairs, the gap is less than 14%. Note that the upper bound is not tight since the mutual interference is ignored. Again, our proposed algorithm outperforms Scheme 3 in all scenarios. We can conservatively conclude that our proposal can suppress the mutual interference among the D2D pairs effectively.

V. Conclusion

In this letter, we studied the resource allocation for a D2D communication underlaying cellular network. We employ an alternating optimization method to exploit the spatial reuse gains of the D2D pairs. Simulation results verify that our proposed algorithm can significantly enhance the system capacity of the considered cellular network.

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