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Resource allocation method for device-to-device communications in cellular networks

Zhang Yuan[1] Wu Wenbin[1] Li Xin[2]

([1]National Mobile Communications Research Laboratory, Southeast University, Nanjing 210096, China)

([2]Department of Information Engineering, Liuzhou Railway Technical College, Liuzhou 545007, China)

Abstract: Based on the conflict graph model which is formulated as a binary integer optimization problem, a resource allocation method to support device-to-device (D2D) communications in cellular networks is proposed. First, a frequency resource assignment algorithm is presented which assigns each D2D link one frequency resource block. For this algorithm, frequency resource blocks are assigned so that the frequency resource spatial reuse opportunities in the cellular networks can be fully exploited. Then a slot scheduling algorithm is presented which schedules time slots among D2D links assigned the same frequency resource block. For this algorithm, time slot resources are scheduled so that the proportional fairness among D2D links which are assigned the same frequency resource block can be achieved. The performance of the proposed method is evaluated via computer simulations. The simulation results show that the proposed method can well support D2D communications in cellular networks.

Key words: cellular network; device-to-device (D2D) communication; resource allocation

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Device-to-device (D2D) communications refer to the technologies that enable devices to communicate directly. A typical example of D2D technology is Bluetooth working at unlicensed spectra. Recently, to meet the new trends in the mobile market, cellular operators are bringing the D2D function into cellular networks, so that user equipments (UEs) may communicate directly with each other over the D2D links[1].

D2D communications in cellular networks consist of two phases[1-4]. The first phase is peer discovery whose purpose is to identify whether a UE is in proximity of another or not. The design of D2D peer discovery includes control path establishment and maintenance, beacon, and access control. After successful peer discovery, the second phase is data transmission. The design of D2D data transmission includes synchronization, reference signal design, mode selection, power control, resource allocation, and interference coordination. This paper focuses on the data transmission phase.

During the data transmission phase, the D2D UEs exchange data traffic directly over the air. From the operators' view, the most critically challenging problem of D2D data transmission is the interference caused by D2D links. Interference occurs not only between D2D and non-D2D links but also among different D2D links. The D2D data transmission methods will ensure that the transmission quality of D2D links is kept on an acceptable level and at the same time the D2D links have little negative impact on the existing non-D2D links in cellular networks. The D2D data transmission methods proposed in the literature can be classified into four types: the signal processing-based method[5], the power control-based method[6], the interference coordination-based method[7], and the resource allocation-based method[8-9]. Each method achieves different tradeoffs between performance and complexity.

This paper studies the resource allocation-based D2D data transmission method and proposes a new hierarchical resource allocation method. Compared with existing works in the literature, this work has the following contributions. First, a conflict graph-based theoretical model for D2D communication resource allocation is proposed, which is still lacking in the literature. Secondly, a grouping algorithm is proposed which evenly allocates the total D2D traffic load among different parts of the licensed spectrum. Thirdly, a scheduling algorithm is proposed which schedules the time resource for all D2D links in each group in a fair manner. Simulation results verify that the new hierarchical resource allocation method can well support D2D communications in the cellular networks.

1 Problem Formulation

Consider a cellular network whose licensed spectrum is divided into J frequency resource blocks (FRB). We pick arbitrarily a cell and assume that there are Q D2D links in it. Let $x_q[j, t]$ denote the binary decision variable. If FRB j is allocated to D2D link q in slot t, $x_q[j, t]$ is equal to 1; otherwise, it is equal to 0. In the case that

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$x_q[j, t]$ is equal to 1, let $C_q[j, t]$ denote the throughput achieved by D2D link q on FRB j in slot t. Let R_q denote the total throughput of D2D link q and it can be written as

$$R_q = \lim_{T\to\infty} \frac{1}{T} \sum_{j=1}^{J} \sum_{t=1}^{T} x_q[j, t] C_q[j, t] \tag{1}$$

There are constraints on the value of $x_q[j, t]$. First, D2D links will have little negative impact on the existing non-D2D links in cellular networks. To model this constraint, let $J_q \subseteq \{1, 2, \dots, J\}$ denote the permission FRB set associated with D2D link q and contain the FRBs which are permitted to be used by D2D link q. Therefore, we have the constraint that

$$x_q[j, t] = 0 \qquad j \notin J_q \tag{2}$$

How to determine J_q is out of the scope of this paper and we just assume that J_q is determined for each D2D link q. Secondly, interference also occurs among different D2D links and neighbor D2D links will not reuse the same resource to avoid interference. Such contention relations among D2D links can be captured by constructing a conflict graph $G = (V, E)$ where each vertex in V represents a D2D link and each edge in E between two vertices denotes that the two corresponding D2D links cannot reuse the same resource. Therefore, we have the constraint that

$$x_q[j, t] + x_r[j, t] \leqslant 1 \qquad (q, r) \in E \tag{3}$$

where q and r represent two D2D links which cannot reuse the same resource. Finally, for simplicity, we assume that each D2D link is allocated at most one FRB each time. Therefore, we have the constraint that

$$\sum_{j=1}^{J} x_q[j, t] \leqslant 1 \tag{4}$$

A natural rule of resource allocation will be to achieve proportional fair throughput among D2D links. According to the theory established in Ref. [10], the optimization mathematical model can be formally stated as

$$\max \sum_{q=1}^{Q} \log_2 R_q \qquad \text{s. t. Eqs. (1) to (4)} \tag{5}$$

2 Resource Allocation Method

The problem of resource allocation for D2D communications in cellular networks is formulated as an optimization problem in (5). We denote this optimization problem as P. This section presents a method to solve the problem P. The method consists of two phases. In the first phase, the problem P is decomposed into J sub-problems (denoted as P_j, $1 \leqslant j \leqslant J$) via the proposed FRB assignment algorithm. In the second phase, each sub-problem P_j is solved via the proposed slot scheduling algorithm. Based on these two algorithms, a hierarchical resource allocation method can be proposed.

2.1 FRB assignment algorithm

Considering any two slots t_1 and t_2, it is possible that $x_q[j_1, t_1] = 1$ and $x_q[j_2, t_2] = 1$ with $j_1 \neq j_2$. To reduce the complexity, we heuristically limit the FRB on which each D2D link operates is fixed. Therefore, an algorithm which assigns one FRB to each D2D link is needed. Denoted by $G_j = (V_j, E_j)$, let the corresponding conflict graph on FRB j be G_j, where each vertex in V_j represents a D2D link to which FRB j is assigned. A heuristic FRB assignment algorithm is proposed as follows.

For each D2D link q, let the current conflict graph on FRB j be $G_{j,q} = (V_{j,q}, E_{j,q})$ where $j \in J_q$. If D2D link q is assigned FRB j, then the conflict graph on FRB j is updated to be

$$\tilde{G}_{j,q} = (V_{j,q} \cup \{q\}, \tilde{E}_{j,q}) \tag{6}$$

where each edge in the graph between two vertices denotes that the two corresponding D2D links cannot reuse the same resource. Define the difference as

$$d_{j,q} = |\tilde{E}_{j,q}| - |E_{j,q}| \tag{7}$$

We find the FRB index j_q which satisfies that

$$j_q = \arg\min_{j \in J_q} d_{j,q} \tag{8}$$

If j_q is not unique, we just pick the one with the smallest $|V_{j,q}|$ to break the tie. Having determined j_q, we can update

$$G_{j_q} \leftarrow \tilde{G}_{j_q,q} \tag{9}$$

Repeat the above steps until all D2D links have been assigned one FRB.

The philosophy behind the proposed FRB assignment algorithm is that, the self interference among D2D links will be balanced among FRBs so that the resource spatial reuse opportunities can be fully exploited. The self interference among D2D links can be captured by the value of $d_{j,q}$ as defined in Eq. (7). Therefore, we suggest to assign FRB j with the smallest $d_{j,q}$ to D2D link q as formulated in Eq. (8).

2.2 Slot scheduling algorithm

After the FRB assignment, each D2D link q has been assigned one FRB j_q. Therefore, the constraint in Eq. (2) can be updated to

$$x_q[j, t] = 0 \qquad j \neq j_q \tag{10}$$

Substituting the above constraint into the problem P, we can find that the problem P is decomposed into J sub-problems $\mathrm{P}_j(1 \leqslant j \leqslant J)$ as

$$\max \sum_{q \in Q_j} \log_2 R_q$$

$$\text{s. t.} \quad R_q = \lim_{T\to\infty} \frac{1}{T} \sum_{t=1}^{T} x_q[t] C_q[t]$$
$$x_q[t] + x_r[t] \leqslant 1 \qquad (q, r) \in E_j \tag{11}$$

where Q_j is the set of D2D links to which FRB j is assigned; $x_q[t]$ is the binary decision variable and is equal to 1 if FRB j_q is allocated to D2D link q in slot t and 0 otherwise; $C_q[t]$ is the throughput achieved by D2D link q on FRB j_q in slot t in the case that $x_q[t]$ is equal to 1.

The problem P_j involves a large number of binary variables. To reduce the complexity, we propose to adopt the method in Ref. [11] to decompose the whole slot scheduling process into consecutive T stages. In the t-th stage (i. e., slot t), the network will determine how to allocate slot t among $|Q_j|$ D2D links and then proceed to the next slot.

Let $R_q[t]$ denote the throughput of D2D link q up to slot t, $U_q[t]$ denote the logarithm of $R_q[t]$ to base 2, and $U[t]$ denote the sum of $U_q[t]$ over all D2D links in Q_j. Using the first-order Taylor approximation, $U[t]$ can be expressed as

$$U[t] \approx U[t-1] + \sum_{q\in Q_j} \frac{\partial U_q(R_q[t-1])}{\partial R_q}(R_q[t] - R_q[t-1]) \tag{12}$$

By the definition, the throughput of D2D link q up to slot t can be expressed as

$$R_q[t] = (1-\varepsilon_t)R_q[t-1] + \varepsilon_t x_q[t] C_q[t] \tag{13}$$

where ε_t is equal to $1/t$ and the initial $R_q[0]$ is set to be an arbitrary small positive constant. Therefore, for the sub-problem P_j, the optimization problem to be solved in slot t is

$$\max \sum_{q\in Q_j} w_q[t] x_q[t]$$
$$\text{s. t.} \quad x_q[t] + x_r[t] \leqslant 1 \qquad (q, r) \in E_j \tag{14}$$

where

$$w_q[t] = \frac{C_q[t]}{R_q[t-1]} \tag{15}$$

is the weight assigned to D2D link q in slot t.

It can be readily identified that problem (14) is actually the maximum weight independent set (MWIS) problem in the graph theory field. The MWIS problem has been well studied in the literature and many algorithms have been proposed to solve it. To reduce the complexity, this paper will adopt the greedy principle-based algorithm to solve problem (14) which works as follows. First, the algorithm will try to find the head vertex whose weight is larger than the weights of all its neighbor vertexes in graph G_j. Then, the D2D links associated with head vertexes will be allocated FRB j in slot t. At the end of slot t, the throughput of each D2D link q will be updated to be $R_q[t+1]$ according to Eq. (13) and the weight will be updated to be $w_q[t+1]$ according to Eq. (15) and then proceed to the next slot $t+1$.

2.3 Resource allocation method

Based on these two algorithms, a resource allocation method for D2D communications in cellular networks can be proposed as follows.

The base station (BS) of the cell will collect some information. First, the BS will have the knowledge of J_q for each D2D link q. Secondly, the BS will have the knowledge as to whether any two D2D links can reuse the same resource or not. Based on this knowledge, the BS can construct the conflict graph as needed. Thirdly, the BS will have the knowledge of $C_q[j, t]$ for D2D link q on FRB j in slot t. The method to obtain the information is out of the scope of this paper and we just assume that all the information has been available to the BS.

The proposed resource allocation method is a hierarchical one. It consists of two phases. In the first phase, the BS will perform the following steps:

1) For D2D link q, the BS determines for each FRB $j \in J_q$ the difference $d_{j,q}$ according to Eq. (7).

2) For D2D link q, the BS selects the FRB j_q according to Eq. (8) and assign it to D2D link q.

3) For D2D link q, the BS updates the conflict graph on FRB j_q according to (9).

4) Repeat the above steps until there is no unassigned D2D link.

In the second phase, the BS will perform the following steps:

1) For FRB j in slot t, the BS calculates $R_q[t]$ for each D2D link $q \in Q_j$ according to Eq. (13).

2) For FRB j in slot t, the BS determines the $w_q[t]$ for each D2D link $q \in Q_j$ according to Eq. (15).

3) For FRB j in slot t, the BS determines the value of $x_q[t]$ according to the greedy algorithm.

4) Repeat the above steps until every FRB j has been treated.

5) Update $t \leftarrow t+1$ and repeat the above steps.

3 Performance Evaluation

In this section, we evaluate the proposed resource allocation method via computer simulations. We first describe the simulation methodology and then present and analyze the simulation results.

We develop a simulator based on Matlab. The assumptions taken in the simulator are as follows.

1) The spectrum is divided into $J = 20$ FRBs.

2) For each D2D link q, the permission FRB set J_q consists of FRBs which are randomly selected from the set $\{1, 2, \ldots, J\}$. The number of FRBs in J_q is assumed the same for all D2D links. For the purpose of convenience, this value is denoted as J_0. The value of J_0 is set to be 5,

10, and 15 during the simulation.

3) For any two D2D links, if the distance between the transmitter of any one D2D link and the receiver of the other D2D link is less than the threshold, these two D2D links are not allowed to reuse the same resource. Based on this assumption, the conflict graph can be constructed. This threshold is denoted as d. The value of d is set to be 10, 20, and 30 m during the simulation.

4) For each D2D link q, if FRB j is allocated in slot t, it will gain the throughput of $C_q[j, t]$. Without loss of generality, we simply assume that $C_q[j, t]$ is the same for different q, j, and t is equal to C.

5) We assume that a total of Q D2D links are randomly located in a cell with a radius of 80 m. The value of Q is set to be 100, 200, and 300 during the simulation.

For the generated topology, we use the proposed method to allocate the radio resource among D2D links. For comparison purpose, we also use the Matlab function "bintprog" to solve the optimization problem (14). We collect the average throughput per D2D link of each FRB and then normalize the value with respect to the C bit/s. The procedure is repeated 20 times for each value of Q, each time with a new generated topology, and the results are averaged out. Finally, the simulation time for the second phase is set to be $T = 10^4$ slots.

The simulation results are plotted in Fig. 1. First, it can be observed that the throughput performance of D2D links is almost the same for different FRBs. It shows that resources can be evenly allocated for D2D links and the loads of different FRBs can be balanced under the proposed method. Secondly, it can be observed that the curves labeled with "greedy" have little difference from the curves labeled with "optimal", in which the curves labeled with "greedy" are generated by the proposed greedy slot scheduling algorithm while the curves labeled with "optimal" are generated by the Matlab function "bintprog". It shows that the proposed greedy slot scheduling algorithm can well approximate the optimal solution. Finally, it can be observed that, for different values of J_0, d, and Q, the normalized average throughput of each D2D link is no less than 0.8. For example, if $J_0 = 5$, $d = 30$ m, and $Q = 300$, the average throughput of each D2D link is about $0.8C$. In other words, if $J_0 = 5$, $d = 30$ m, and the throughput requirement of each D2D link is no less than $0.8C$, about 300 D2D links can be supported in the cell under the proposed resource allocation method. It shows that the proposed resource allocation method can well support D2D communications in cellular networks.

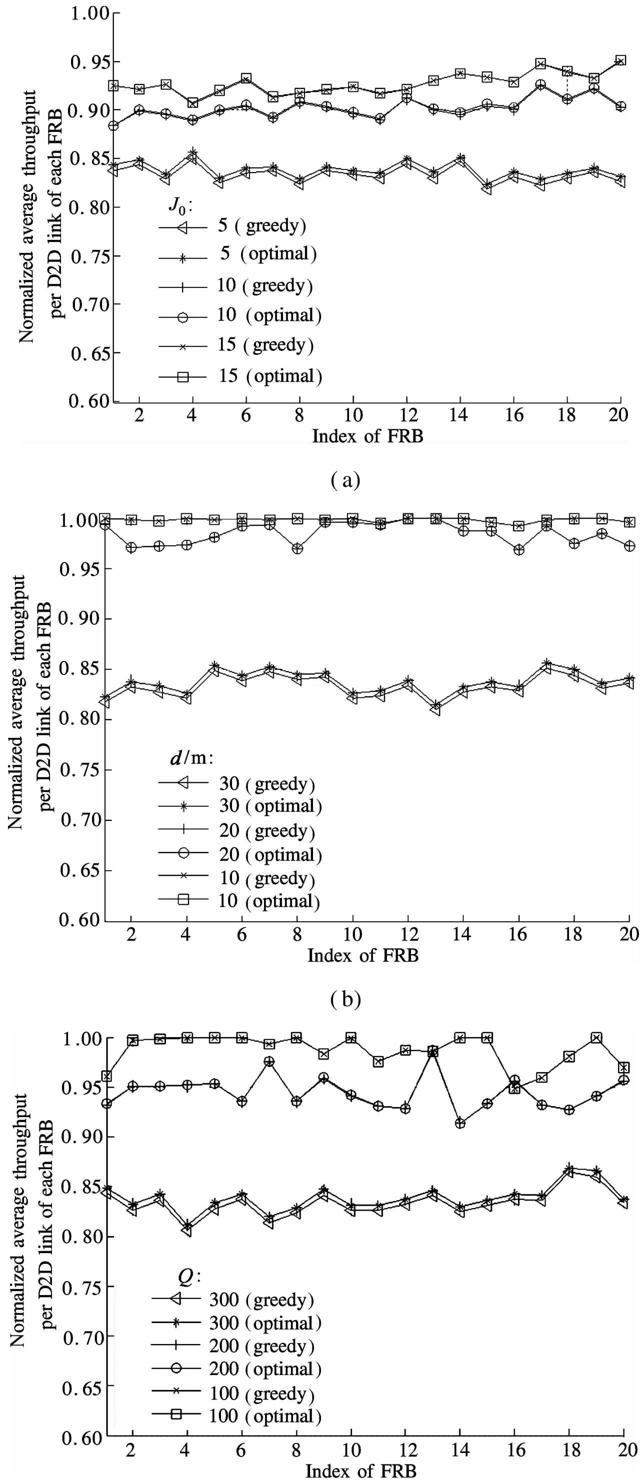

Fig. 1 Simulation results for the proposed resource allocation method. (a) $d = 30$ m, $Q = 300$; (b) $J_0 = 5$, $Q = 300$; (c) $J_0 = 5$, $d = 30$ m

4 Conclusion

This paper studies the resource allocation method to support D2D communications in cellular networks. First, the resource allocation problem is modeled as a binary integer optimization problem. To solve this problem, two algorithms are proposed, in which the FRB assignment algorithm decomposes the original optimization problem into smaller sub-problems and the slot scheduling algorithm solves the sub-problems in a proportional fair manner. Based on these two algorithms, a hierarchical resource allocation method for D2D communications in the cellular networks is proposed. Simulation results show that the proposed resource allocation method can well support D2D communications in the cellular networks.

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一种蜂窝网络中支持 D2D 通信的资源分配方法

张　源[1]　武文斌[1]　李　昕[2]

([1] 东南大学移动通信国家重点实验室,南京 210096)

([2] 柳州铁道职业技术学院信息工程系,柳州 545007)

摘要:基于冲突图模型形成的二进制整数规划,提出了一种蜂窝网络中支持 D2D 通信的无线资源分配方法. 首先,提出一种频率资源分配算法,即为每个 D2D 链路都分配一个频率资源块. 分配频率资源时将尽可能地利用蜂窝网络中的无线频率资源空间重用机会. 然后,提出一种时隙调度算法,即为所有分配同一频率资源块的 D2D 链路进行时隙资源调度. 调度时隙资源时将保证使用同一频率资源块的 D2D 链路之间达到长期平均吞吐率的比例公平. 通过计算机仿真对所提出方法的性能进行了验证,结果表明该方法能够在蜂窝网络中实现 D2D 通信功能.

关键词:蜂窝网络;D2D 通信;资源分配

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