Joint Power Control and Channel Assignment in D2D Communication System

Xin Song, Xiuwei Han, and Siyang Xu
Engineering Optimization and Smart Antenna Institute, Northeastern University, Qinhuangdao and 066004, China
Email: sxin78916@neuq.edu.cn; xiuweihan@stumail.neu.edu.cn; 1670738@stu.neu.edu.cn

Abstract —D2D communication has been proposed as an effective way to improve the spectrum utilization of the cellular network. In this paper, we study resource allocation problem to maximize the overall system capacity while maintaining the signal-to-noise ratio for D2D users and Cellular Users (CUs). The optimization problem can be broken down into two sub-problems: power control and channel assignment. We first prove that the objective function of power control problem is a convex function to get the optimal transmit power. Then, we designed two search algorithms for channel assignment. The numerical results can show that, compared with the random selection algorithm, our schemes can improve the performance of the system.

Index Terms—Device-to-device, load mode, power control, channel assignment, system capacity

I. Introduction

With the unprecedented growth in mobile internet applications and intelligent devices, the cellular systems are suffering an enormous pressure imposed by the massive increasing in the number of interconnected devices [1]-[3]. In order to alleviate this pressure, D2D communication technology was introduced to improve the spectrum utilization of cellular networks [4], [5]. Under the control of the base station, any two neighboring users can establish direct transmission by using D2D communication. [6], [7].

D2D transmitter sends signal to the D2D receiver by using the same spectrum resource with the cellular links, which can improve the system capacity and spectrum utilization [8]. However, when the spectrum resources are allocated unreasonably, co-channel interference between the CUs and D2D pairs will reduce the performance. Therefore, resource allocation has become a research hotspot in academia. In order to solve this challenging issue, various resource allocation methods have been explored in D2D communication to enhance the performance, including mode selection, power control and channel assignment [9]-[16]. Reference [9] mentions that in order to achieve the maximum total data transmission rate, a series of methods, such as joint mode selection, range division, are needed to optimize the resource allocation. In [10], a dynamic resource allocation scheme for D2D communication based on cellular network is proposed. The proposed scheme is applied in the system to maximize the number of D2D communication pairs and to avoid the strong interference of D2D communication to the cellular communication. The authors formulate an optimization problem by maximizing the effectiveness of the D2D user devices, and propose a novel algorithm based on the many-to-one matching game with companion effects in [11]. In [12], a game-theoretic scheme is proposed to solve the resource allocation problem of multi-cell D2D communications in cellular network. Joint mode selection and power control are studied in [13]-[15] to further improve performance. In [16], dynamic resource allocation is studied, which allows the D2D pairs to utilize all sub-channels. However, the adjacent D2D pair will inevitably suffer from severe mutual interference.

Inspired by the existing research, we first divide the system into three categories based on the network load. Secondly, we consider the resource allocation problem under the medium load mode, and aim at maximizing system capacity by allocating resources. We divide the objective function into two sub-problems: power control and channel assignment. We prove that the objective function is a convex function and propose power control algorithm. Finally, we design two search algorithms for channel assignment.

The rest of the paper is organized as follows. In Section II, we introduce the system model, load mode and objective function of the proposed optimal problem. Then, in Section III, we joint power control and channel assignment problem. Furthermore, the formulated optimization problem is resolved. After that, the experimental results are provided in Section IV to demonstrate the performance of the proposed schemes. Finally, Section V briefly concludes this manuscript.

II. System Model and Problem Formulation

In this section, we first propose the system model and three D2D load modes, then we formulate the optimization problem.

A. System Model

In this paper, we consider the single cell scenario in Fig. 1, in which the cell comprises K D2D

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Corresponding author email: xiuweihan@stumail.neu.edu.cn
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communication pairs, M CUs, and a base station (BS). D_A is the transmitter of the D2D pair and D_B is the receiver. In particular, we assume that the licensed uplink spectrum is reused by D2D users and the cell's radius is R, where the BS located at the center of the cell. Moreover, we assume that each of the CU has been pre-allocated orthogonal sub-channel in order to reduce the inter-CU-interference. Meanwhile, we assume that each D2D link is allowed to reuse no more than one sub-channel and the number of D2D pairs is less than the number of CUs, i.e. $K < M$.

We consider the slow fading concluding shadowing and the fast fading due to multi-path propagation. Thus, the channel gain between D2D pair j can be expressed as

$$g_{jj}^{d} = \kappa \beta_{jj} \varsigma_{jj} d_{jj}^{-\alpha} \tag{1}$$

where constant κ is determined by the system parameters, β_{jj} is the fast fading gain with exponential distribution, ς_{jj} is the slow fading gain with log-normal distribution, α is the path-loss exponent, and d_{jj} is the distance of D2D pair j. Similarly, we can express the channel gain between CU i and the BS as g_{iB}^{c}, the channel gain between CU i and the receiver of D2D pair j as h_{ij}^{c}, and the channel gain between the transmitter of D2D pair j and the BS as h_{jB}^{d}. The power of additive Gaussian white noise on each channel is assumed to be σ^2.

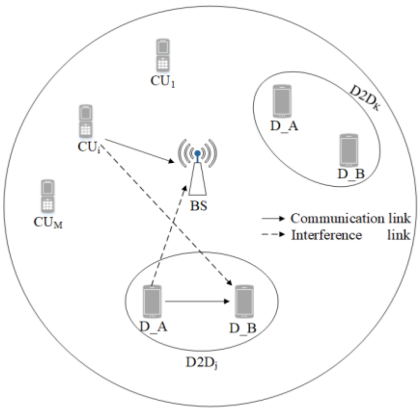

Fig. 1. System model of D2D communication

B. Load Mode

We first divide the system into three categories based on the network load: light load, medium load, full load, as shown in Table I. In the light load case, the number of idle channels is greater than the number of D2D pairs, i.e. $N - M > K$ .In this case, each D2D pair can work in the dedicated or the cellular mode and use orthogonal sub-channel to avoid co-channel interference with CUs. In the medium load case, the number of D2D pairs is more than the number of idle channels, i.e. $N - M < K$. For this reason, some D2D pairs can use dedicated channels, while others must work in the reuse mode and share the same channel with CUs. In the full load case, all channels have already been occupied by CUs, i.e. $N - M = 0$. In this case, all D2D pairs can only select the reuse mode.

TABLE I: THREE CATEGORIES OF LOAD MODE

light load	$N-M>K$	cellular or dedicated
medium load	$N-M<K$	reuse and dedicated
full load	$N-M=0$	reuse mode only

1) Cellular Mode: In this mode, D2D pair will communicate as conventional CUs through BS. The *signal-to-noise ratio* (SNR) of D2D pair j can be expressed as

$$\xi_{j}^{d} = \frac{P_{j}^{d} h_{jB}^{d}}{\sigma^2} \tag{2}$$

where P_j^d is the transmit power of D2D pair j in the cellular mode.

2) Dedicated Mode: In this mode, D2D pair use the channel that is not occupied by CUs currently to communicate, this mode consumes less channel resources than the cellular mode. The SNR of D2D pair j can be expressed as

$$\xi_{jj}^{d} = \frac{P_{jj}^{d} g_{jj}^{d}}{\sigma^2} \tag{3}$$

where P_j^d is the transmit power of D2D pair j in the dedicated mode.

3) Reuse Mode: In this mode, D2D pair can further improve the spectrum utilization by reusing the occupied channel which is used by CU, but it needs to deal with co-channel interference problems. The *signal-to-noise-plus-interference ratio* (SINR) of CU i, when it is interfered by D2D pair j, can be expressed as

$$\xi_{ij}^{c} = \frac{P_{ij}^{c} g_{iB}^{c}}{P_{ij}^{d} h_{jB}^{d} + \sigma^2} \tag{4}$$

where P_{ij}^c and P_{ij}^d are the transmit power of CU i and D2D pairs j when the channel of CU i is reused by D2D pair j.

On the other hand, the SINR of D2D pair j when reusing the channel of CU i can be expressed as

$$\xi_{ij}^{d} = \frac{P_{ij}^{d} g_{jj}^{d}}{P_{ij}^{c} h_{ij}^{c} + \sigma^2} \tag{5}$$

C. Problem Formulation

We consider the channel resource allocation problem under the medium load condition. We maximize overall system capacity while maintaining SINR for CUs and D2D pairs by jointing power control and channel assignment.

$X=\{X^{(1)},X^{(2)}\}$ denotes the mode matrix, $X^{(1)}$ and $X^{(2)}$ are indication vectors of the dedicated mode and reuse mode, respectively. It is should be noted that $X^{(1)}$ and $X^{(2)}$ are 0-1 variable matrixes.

Define $P=\{P^{(1)},P^{(2)}\}$ as the power matrix, and use it to indicate the transmit power when a corresponding mode is chosen.

Then, the overall system capacity optimization problem can be expressed as

$$P1:\left(P^*,X^*\right)=\arg\max_{P,X}\{\sum_{j\in D}X^{(1)}\log_2(1+\xi_{jj}^d) + \sum_{i\in C}\sum_{j\in D}X^{(2)}[\log_2(1+\xi_{ij}^c)+\log_2(1+\xi_{ij}^d)]\} \quad (6)$$

It can be easily seen that the throughput optimization problem in (6) is non-concave and contains binary variables, it is difficult to get the solution directly. Therefore, we assume that all D2D pairs are share the channels of the CUs, then P1 can be converted to P2, i.e. $X^{(1)}=0, X^{(2)}=1$.

$$P2:P^*=\arg\max_{P}\{\sum_{i\in C}\sum_{j\in D}[\log_2(1+\xi_{ij}^c)+\log_2(1+\xi_{ij}^d)]\} \quad (7)$$

subject to

$$\xi_{ij}^c\geq\xi_{\min} \quad (8)$$

$$\xi_{ij}^d\geq\xi_{\min} \quad (9)$$

$$0<P_{ij}^d<P_{\max} \quad (10)$$

$$0<P_{ij}^c<P_{\max} \quad (11)$$

In the above, $\xi_{\min}$ denote the minimum SINR requirements of CU i and D2D pair j, P_{ij}^d and P_{ij}^c denote the transit power of D2D pair and CU, respectively. Constraints (8) and (9) denote that the SINR thresholds of CUs and D2D pairs should be guaranteed. Constraints (10) and (11) denote that the transmit power of D2D pairs and CUs cannot exceed their maximum values. In the following section, we will divide the problem P2 into two sub-problems and solve them one by one.

III. Resource Allocation Algorithm

In this section, we present an optimal method to solve the problem (7). First of all, we can divide the original one into two sub-problems and solve them individually:

1) Sub-problem of *power control*;

2) Sub-problem of *channel assignment*.

A. Power Control

Assume that D2D link j is allowed to reuse the resource of cellular link i, the power control problem can be expressed as

$$P3:\left(P_{ij}^{c*},P_{ij}^{d*}\right)=\arg\max_{P_{ij}^c P_{ij}^d}\{\log_2(1+\frac{P_{ij}^c g_{iB}^c}{P_{ij}^d h_{jB}^d+\sigma^2} + \log_2(1+\frac{P_{ij}^d g_{jj}^d}{P_{ij}^c h_{ij}^c+\sigma^2})\} \quad (12)$$

subject to (8),(9),(10),(11).

In order to meet the minimum QoS requirement, the SINR of both CUs and D2D pairs links must be bigger than the threshold $\xi_{\min}$. The transmit power of CUs and D2D pairs cannot exceed its maximum value. According to restrictions (8), (9), (10) and (11), we have

$$P_L<P_{ij}^d<P_H \quad (13)$$

where

$$P_L=\max\left\{0,\frac{\xi_{\min}(P_{ij}^c \mathrm{h}_{ij}^c+\sigma^2)}{g_{jj}^d}\right\} \quad (14)$$

$$P_H=\min\left\{P_{\max},\frac{P_{ij}^c g_{iB}^c-\xi_{\min}\sigma^2}{\xi_{\min}h_{jB}^d}\right\} \quad (15)$$

In light of this fact that $\arg\max_x[\log_2(1+f(\mathrm{x}))+\log_2(1 \quad +g(\mathrm{x}))]$ is equivalent to $\arg\max_x[(1+f(\mathrm{x})) \ (1+g(\mathrm{x}))]$, (12) can be rewritten as

$$P4:\left(P_{ij}^{c*},P_{ij}^{d*}\right)=\arg\max_{P_{ij}^c P_{ij}^d}\{(1+\frac{P_{ij}^c g_{iB}^c}{P_{ij}^d h_{jB}^d+\sigma^2})(1+\frac{P_{ij}^d g_{jj}^d}{P_{ij}^c h_{ij}^c+\sigma^2})\} \quad (16)$$

Then we prove the following lemma 1.

Lemma1: (16) is a convex function with respect to P_{ij}^d when the other variable P_{ij}^c is fixed at its maximal power.

Proof: See Appendix A.

According to the property of convex function, we notice that the maximum of the convex function is obtained at the boundary points. So when $P_{ij}^{c*}=P_{\max}$, the optimal P_{ij}^{d*} in (12) can be obtained by evaluating the objective function at two points of the constraint $P_{ij}^{d*}\in\{\mathrm{P}_L,\mathrm{P}_H\}$ in (13) by taking the one which the value is bigger.

B. Channel Assignment

In the above, we have discussed the optimal power control schemes. Now, When the D2D pair *j* shares the channel of the CU i, the achievable system capacity can be expressed as

$$R_{ij}=\log_2(1+\frac{P_{ij}^{c*}g_{iB}^c}{P_{ij}^{d*}h_{jB}^d+\sigma^2})+\log_2(1+\frac{P_{ij}^{d*}g_{jj}^d}{P_{ij}^{c*}h_{ij}^c+\sigma^2}) \quad (17)$$

where $(P_{ij}^{c*},P_{ij}^{d*})$ is given by sub-problem of power control.

For different multiplexing methods, we can get the system capacity matrix

$$\Re = \begin{bmatrix} R_{1,1} & \cdots & R_{i,1} & \cdots & R_{1,M} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ R_{j,1} & \cdots & R_{j,i} & \cdots & R_{j,\mathrm{M}} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ R_{K,1} & \cdots & R_{K,\mathrm{i}} & \cdots & R_{K,M} \end{bmatrix} \tag{18}$$

In order to maximize the system capacity to carry out the channel resource assignment, we develop two algorithms to solve the problem.

1) Algorithm 1

The basic idea of the algorithm 1 is to select $K-(N-M)$ channels with larger system capacity for D2D pairs to reuse, and the remaining $N-M$ D2D pairs are allocated to idle channels.

Step 1: Search for the maximum capacity in the $K \times M$ system capacity matrix and mark the corresponding D2D pair and CU as j^*, i^*. The j_{th}^* D2D pair is allocated the i_{th}^* CU's channel.

Step 2: Next, search for the maximum capacity in the system capacity matrix, which is composed by the remaining D2D pairs that have not been allocated channels and the CUs whose channels have not been reused. Furthermore, mark the corresponding D2D pair and CU, allocate the corresponding channel.

Step 3: Repeat this step for $K-(N-M)$ times until the number of remaining D2D pairs which have not been assigned channels is $N-M$. The remaining idle channels are allocated to the D2D pairs.

The details of the algorithm 1 are summarized in Table II.

TABLE II: OPTIMAL RESOURCE ALLOCATION ALGORITHM 1

Algorithm 1 Matrix capacity search algorithm
initialization
$K=\{D_1, D_2 \ldots\ldots D_K\}$, $M=\{CU_1, CU_2, \ldots, CU_M\}$
Calculate $P_{ij}^{d*} \in \{\mathrm{P}_L, \mathrm{P}_H\}$
for $i = 1:K$
for $j = 1:M$
calculate $\Re_{K\times M}$
end
end
for $k = 1:K-(N-M)$
$R\_max = max(max(\Re_{K\times M}))$
end

2) Algorithm 2

The basic idea of the algorithm 2 is to sequentially traverse all CUs' channels with each D2D pair. Sort all the system capacity and select the larger $K-(N-M)$ channels to be reused. And the remaining $N-M$ D2D pairs are allocated idle channels.

Step 1: For D2D pair $j(1<j<K)$, traverse all CUs' channels $i(1<i<M)$. Calculate the maximum system capacity when the first D2D pair multiplexes all CUs' channels, and mark the corresponding CU as i^*. The 1_{th} D2D pair is allocated to the i_{th}^* CU's channel.

TABLE III: OPTIMAL RESOURCE ALLOCATION ALGORITHM 2

Algorithm 2 Channel traversal search algorithm
initialization
$K=\{D_1, D_2 \ldots\ldots D_K\}$, $M=\{CU_1, CU_2, \ldots, CU_M\}$
Calculate $P_{ij}^{d*} \in \{\mathrm{P}_L, \mathrm{P}_H\}$
for $i = 1:K$
for $j = 1:M$
calculate $\Re_{K\times M}$
end
end
for $k=1:K$
$R\_max = max((k,:))$
end
$Temp = sortrows(R\_max)$
$RR\_max = Temp(1:K-(N-M))$

Step 2: For the second D2D pair, traverse all CUs' channels and search for the maximum capacity, which is composed by the second D2D pair and the CU whose channels have not been reused. Furthermore, mark the corresponding CU and allocate the channel.

Step 3: Repeat this step for K times until the number of D2D pairs with unassigned channels is 0.

Step 4: Sort all the system capacity and select the larger $K-(N-M)$ channels to be reused. The remaining $N-M$ D2D pairs are allocated to idle channels.

The details of the algorithm 2 are summarized in Table III.

From the above discussion, we define two algorithms to solve the channel assignment problem. Matrix capacity search algorithm, i.e. algorithm 1 has a high complexity and searches for all multiplexing methods, which can bring better system capacity. Then, we develop a suboptimal search algorithm to solve the channel assignment problem, named channel traversal search algorithm.

IV. NUMERICAL ANALYSIS

In this section, the performance of the channel allocation methods proposed in matrix capacity search algorithm and channel traversal search algorithm are verified by numerical simulation results.

A. Simulation Parameters

We consider a single cellular network area with a radius of 500m. There are one BS, 20 uplink CUs, 15 D2D pairs, and 25 available uplink channels in the system. CUs and D2D pairs distribute uniformly in the cell. Simulation parameters are elaborated on in Table IV.

The performance of the following algorithms is compared in the simulation diagrams:

Matrix capacity search algorithm: the proposed heuristic algorithm for channel assignment is described as Algorithm 1. Channel traversal search algorithm: the proposed heuristic algorithm for channel assignment is described as Algorithm 2. Random selection algorithm: the random algorithm for channel assignment. It allocates CUs' channel resource to D2D pairs randomly.

TABLE IV: OPTIMAL RESOURCE ALLOCATION ALGORITHM 2

Parameter	Value
Cell radius R	500m
D2D distance r	30-60m
Uplink bandwidth W	0.5MHz
Noise spectral density σ^2	-144dBm
Pathloss exponent α	4
Pathloss constant κ	0.01
SINR threshold $\xi_{\min}$	13dB
Maximum transmit power $P_{\max}$	27dBm
Number of CUs M	20
Number of D2D pairs K	15
Number of uplink channels N	25

B. Simulation Results

Fig. 2 shows the performance of system capacity is evaluated versus the number of D2D reuse pairs. For algorithm 1 can search the entire matrix of the system capacity, it can bring better system capacity. In order to reduce the complexity of the algorithm 1, we design algorithm 2. Channel assignment is accomplished by traversing all CUs' channels for the D2D pairs. We can infer from the figure that both algorithms 1 and 2 are better than the random selection algorithm, and algorithm 1 has better performance than 2. From the figure, system capacity decreases as the number of D2D pairs of the multiplexed channel increases.

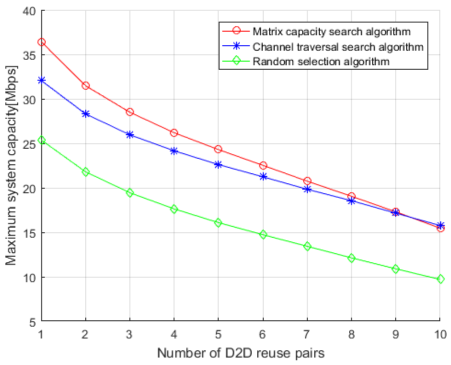

Fig. 2. System capacity and the number of D2D reuse pairs.

Fig. 3 evaluates the performance of system capacity versus the number of D2D reuse pairs. It can be seen that the proposed algorithm performance declines as the CUs maximum transmitted power decreases. This is because, according to formula (13), (14), (15), the reduction of the maximum transmit power of the CUs leads to the decline of the optimal transmit power of D2D pairs. The effect of reducing the transmit power not only decreases its SINR but also mitigates the interference.

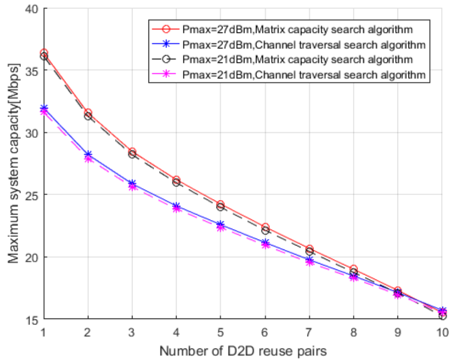

Fig. 3. System capacity for different maximum transmit power of CUs and the number of D2D reuse pairs.

Fig. 4 compares the performance of the three algorithms in the condition of different distance of D2D pairs and different number of D2D resume pairs. It is seen that the performance of the proposed algorithms decreases as the distance of D2D pairs increases. This is because the channel gain decreases with the D2D pairs spacing increasing. And it is not conducive to multiplexing CUs' channels.

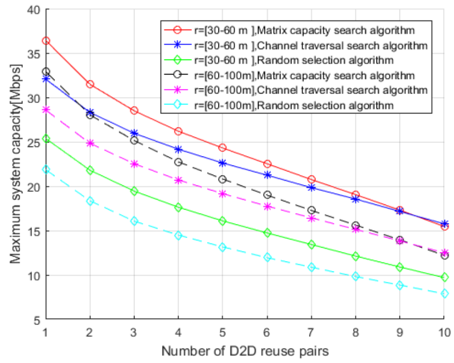

Fig. 4. System capacity for different distances of D2D reuse pairs and the number of D2D reuse pairs.

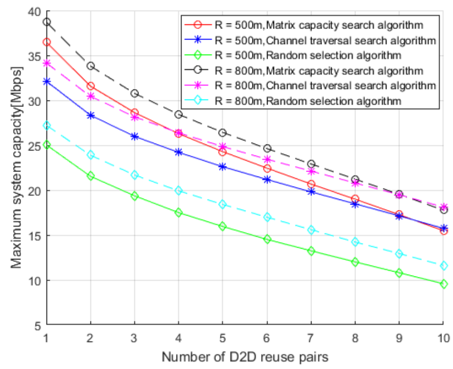

Fig. 5. System capacity for different radius of the cell and the number of D2D reuse pairs.

Fig. 5 compares the performance of the three algorithms in the cell of different radius. It can be seen from the figure that the throughput performance of these three algorithms in the condition of $R = 800m$ is better than $R = 500m$. This is because the distance between users reduces the interference between CU users and D2D users, which helps to improve throughput performance.

V. CONCLUSIONS

To conclude, we divide the load pattern into three categories based on the number of idle channels and we consider the medium load mode. We build functions with the goal of maximizing system capacity, and divide the objective function into two sub-problems: power control and channel assignment. In the power control problem, we prove the objective function is convex, and the optimal transmit power of the D2D pairs is obtained. In the channel assignment problem, we design two algorithms to achieve the system capacity maximization. Simulation results show that in terms of maximization system capacity, our schemes always perform better than random selection algorithm in D2D communication. In further work, we will consider the scenario where resource allocation in different load modes.

APPENDIX A PROOF OF LEMMA 1

Proof:

Denoting $f(\mathrm{P}_{ij}^{c}, \mathrm{P}_{ij}^{d}) \triangleq (1+\frac{P_{ij}^{c} g_{iB}^{c}}{P_{ij}^{d} h_{jB}^{d}+\sigma^2})(1+\frac{P_{ij}^{d} g_{jj}^{d}}{P_{ij}^{c} h_{ij}^{c}+\sigma^2})$,

when $P_{ij}^{c} = P_{\max}$, seeking a first derivative of $f(\mathrm{P}_{\max}, \mathrm{P}_{ij}^{d})$,

$$\frac{\partial f(\mathrm{P}_{\max}, \mathrm{P}_{ij}^{d})}{\partial \mathrm{P}_{ij}^{d}} = \frac{A\mathrm{P}_{ij}^{d2} + 2B\mathrm{P}_{ij}^{d} + C}{D} \tag{19}$$

where

$$A = g_{jj} h_{jB}^2 \tag{20}$$

$$B = g_{jj} h_{jB} \sigma^2 \tag{21}$$

$$C = g_{jj}\sigma^2 (P_{\max} g_{iB} + \sigma^2) - P_{\max} g_{iB} h_{jB} (P_{\max} h_{ij} + \sigma^2) \tag{22}$$

$$D = (P_{\max} h_{ij} + \sigma^2)(P_{ij}^{d} h_{jB} + \sigma^2)^2 \tag{23}$$

Obviously D is always positive, so P_{ij}^{d} such that $\frac{\partial f}{\partial \mathrm{P}_{ij}^{d}} = 0$ can be found as the solution to $A\mathrm{P}_{ij}^{d2} + 2B\mathrm{P}_{ij}^{d} + C = 0$, yielding

$$P_{ij}^{d} = \frac{1}{A}(-B \pm \sqrt{B^2 - AC}) \tag{24}$$

According to the condition (10) $P_{ij}^{d} \in [0, P_{\max}]$. By inspecting (24) we know that a real and non-negative P_{ij}^{d} can only occur for $C \le 0$, since $A, B > 0$.

Next, we calculate the second derivative of $f(\mathrm{P}_{\max}, \mathrm{P}_{ij}^{d})$,

$$\frac{\partial f^2(\mathrm{P}_{\max}, \mathrm{P}_{ij}^{d})}{\partial \mathrm{P}_{ij}^{d2}} = \frac{2P_{\max} h_{jB} g_{iB} [h_{jB}(P_{\max} h_{ij} + \sigma^2) - g_{jj}\sigma^2]}{(P_{\max} h_{ij} + \sigma^2)(P_{ij}^{d} h_{jB} + \sigma^2)^3} \tag{25}$$

By $C \le 0$, we can know,

$$P_{\max} g_{iB} h_{jB} (P_{\max} h_{ij} + \sigma^2) \ge g_{jj}\sigma^2 (P_{\max} g_{iB} + \sigma^2) \tag{26}$$

Dividing by $P_{\max} g_{iB}$ on both sides of (26) we obtain,

$$h_{jB}(P_{\max} h_{ij} + \sigma^2) \ge g_{jj}\sigma^2 (1 + \frac{\sigma^2}{P_{\max} g_{iB}}) \ge g_{jj}\sigma^2 \tag{27}$$

thus showing $\frac{\partial f^2(\mathrm{P}_{\max}, \mathrm{P}_{ij}^{d})}{\partial \mathrm{P}_{ij}^{d2}} \ge 0$.

Lemma 1 is proved.

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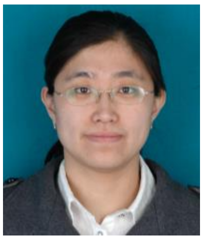

Xin Song was born in Jilin Province, China, in 1978. She received her PhD degree in Communication and Information System in Northeastern University in China in 2008. She is now a teacher working in Northeastern University at Qinhuangdao, China. Her research interests are in the area of robust adaptive beamforming and wireless communication

Xiu-Wei Han was born in Shandong Province, China, in 1995. He received the B.S. degree from the Binzhou University (BZU), Binzhou, in 2017. He is currently pursuing M.S degree with Engineering Optimization and Smart Antenna Institute from Northeastern University. His research interests include resource allocation in D2D communication

Si-Yang Xu was born in Liaoning Province, China, in 1993. He received the B.S. degree from the University of Science and Technology LiaoNing (USTL), Anshan, in 2016 and the M.S. degree from the Northeastern University (NEU), Shenyang, in 2018. He is currently pursuing the Ph.D. degree with school of computer science and engineering, NEU. His research interests include relay selection based on energy acquisition