Joint Power, Altitude, Location and Bandwidth Optimization for UAV with Underlaid D2D Communications

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***Abstract*—In this letter, we aim to maximize the rate of a device-to-device (D2D) pair for a downlink unmanned aerial vehicle (UAV)-aided wireless communication system, where D2D users coexist in an underlaying manner. We jointly optimize the transmit power of the UAV and D2D users, the flying altitude and location of the UAV and ground terminals' allocated bandwidth. To solve this problem, an iterative algorithm with low complexity is accordingly proposed. Simulation results show that the altitude of the UAV has an important impact on the system performance.**

***Index Terms*—UAV communications, D2D communications, altitude and location optimization, power allocation, bandwidth allocation.**

I. Introduction

Recently, wireless communication assisted by unmanned aerial vehicles (UAVs) has been regarded as a promising technique which can provide economical wireless access for mobile devices without deploying fixed network infrastructure [1]. Different from conventional terrestrial communications, UAVs act as flying base stations (BSs) in UAV-aided wireless communications and bring plenty of benefits. Owing to their agility and mobility, UAVs can be deployed to support temporary or urgent events over a wide area, which enhances the quality of service for ground terminals (GTs). Moreover, links between UAVs and GTs are dominated by line-of-sight (LoS) connections, leading to enhanced data rate.

To fully reap the benefits of UAV-aided communications, it is crucial to exploit the UAV mobility in a three-dimensional space. To address the UAV deployment challenge, an efficient deployment approach based on the circle packing theory was proposed in [2]. For capacity enhancement, authors in [3] presented a cost function based multiple UAVs deployment model. By taking beamwidth into account, a joint UAV altitude and beamwidth optimization problem for UAV-aided multiuser communication systems was studied in [4]. Through jointly optimizing altitude, beamwidth and bandwidth, the sum power was further minimized in [5].

Apart from UAV-aided wireless communications, device-to-device (D2D) communication has been regarded as one of the crucial technologies in future wireless communication networks [6]. D2D communication allows direct transmissions between users in proximity, which is helpful in offloading network traffic and reducing end-to-end delay. Compared to the previous investigations on D2D communication underlaying cellular networks [7], the coexistence of UAVs and underlaid D2D communications will introduce new interference management challenges. One critical challenge is the spectrum sharing between D2D communications and UAV-aided networks, and the optimization problem becomes nonconvex due to the mutual interference, which makes it difficult to obtain the globally optimal solution. The other challenge is that, unlike traditional base stations with fixed locations, the altitude of the UAV is adjustable which needs to be carefully optimized in order to reap the full potential obtained from UAV-aided communications. Moreover, the impacts of the mobility of the UAV on D2D communications should be analyzed. In [8], a UAV flight pattern selection problem for D2D communications in disaster areas was studied. Authors in [9] focused on the performance analysis of the coexistence between the UAV and an underlaid D2D communication network in a downlink scenario. However, to our best knowledge, there is no existing work studying the performance of UAVs with underlaid D2D communications from the optimization point of view.

In this letter, we aim to maximize the rate of a D2D pair for a downlink UAV-aided wireless communication system, where D2D users coexist in an underlaying manner. We formulate the problem of joint power, altitude, location and bandwidth optimization. In order to solve this nonconvex rate maximization problem, we propose a low-complexity iterative algorithm. It turns out to have attractive closed-form solutions for power allocation subproblem and altitude planning subproblem.

II. System Model and Problem Formulation

We consider a downlink UAV-aided wireless communication system[1]the reduction of power consumption. with one flying UAV, K GTs and one D2D pair which coexists in an underlaying manner. The horizontal and vertical locations of the D2D receiver, D2D transmitter and GT k are denoted by $\boldsymbol{r} = (0, 0)$, $\boldsymbol{t} = (t(1), t(2))$ and $\boldsymbol{g}_k = (g_k(1), g_k(2))$, respectively. The altitude of the D2D pair and GTs are assumed to be zero. The UAV is deployed as a flying BS at an altitude H with horizontal and vertical location $\boldsymbol{u} = (x, y)$.

We consider the case that GTs and the D2D receiver are located outdoors, and the channel between the UAV and each GT (D2D receiver) is dominated by the LoS path. The

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[1]We consider the system where all terminals are equipped with a single isotropic antenna. When each user is equipped with one antenna, the optimization problem becomes more tractable. Moreover, it is appealing to equip each device with only one antenna to reduce the implementation complexity.

downlink channel power gain between the UAV and GT k is given by [4]

$$h_k^{\mathrm{u}} = \frac{\beta_0}{\left\|\boldsymbol{u} - \boldsymbol{g}_k\right\|^2 + H^2}, \tag{1}$$

where β_0 denotes the channel power gain between the UAV and GTs (D2D receiver) at the unit distance, and $\|\cdot\|$ is the Euclid norm. Similarly, the downlink channel power gain between the UAV and the D2D receiver is

$$h_0^{\mathrm{u}} = \frac{\beta_0}{\left\|\boldsymbol{u}\right\|^2 + H^2}. \tag{2}$$

The downlink achievable rate of GT k can be expressed as

$$r_k^{\mathrm{g}} = a_k \log_2 \left(1 + \frac{p_k^{\mathrm{u}}}{p_{\mathrm{d}} h_k^{\mathrm{d}} + \sigma^2} \frac{\beta_0}{\left\|\boldsymbol{u} - \boldsymbol{g}_k\right\|^2 + H^2}\right), \tag{3}$$

where a_k denotes the allocated bandwidth proportion for GT k, p_k^{u} denotes the transmit power from UAV to GT k, p_{d} is the transmit power of the D2D transmitter, h_k^{d} is the channel power gain between the D2D transmitter and GT k, and σ^2 is the power of the additive white Gaussian noise.

We aim for maximizing the rate of the D2D pair while satisfying the minimal rate requirements of all GTs via power, altitude, location and bandwidth optimization. Mathematically, the D2D pair achievable rate maximization problem is

$$\max_{p_{\mathrm{d}}, \mathbf{p}_{\mathrm{u}}, \mathbf{a}, \boldsymbol{u}, H} \quad \log_2 \left(1 + \frac{p_{\mathrm{d}} h_0^{\mathrm{d}}}{\sum\limits_{k=1}^{K} a_k p_k^{\mathrm{u}} \frac{\beta_0}{H^2 + \|\boldsymbol{u}\|^2} + \sigma^2}\right) \tag{4a}$$

$$\text{s.t.} \quad 0 \leq p_{\mathrm{d}} \leq P_{\mathrm{d}}^{\max}, \tag{4b}$$

$$0 \leq \sum_{k=1}^{K} p_k^{\mathrm{u}} \leq P_{\mathrm{u}}^{\max}, \tag{4c}$$

$$r_k^{\mathrm{g}} \geq R_{\min}, \quad \forall k = 1, \cdots, K, \tag{4d}$$

$$H_{\min} \leq H \leq H_{\max}, \tag{4e}$$

$$a_k \geq 0, \quad \forall k = 1, \cdots, K, \tag{4f}$$

$$\sum_{k=1}^{K} a_k = 1, \tag{4g}$$

where $\mathbf{p}_{\mathrm{u}} = (p_1^{\mathrm{u}}, \cdots p_K^{\mathrm{u}})$, $\mathbf{a} = (a_1, \cdots, a_K)$, h_0^{d} is the channel power gain between the D2D transmitter and the corresponding receiver, $[H_{\min}, H_{\max}]$ denotes the feasible region of the UAV's altitude H. It should be noted that the Doppler frequency shift is low and can be neglected for the slow speed of D2D devices, the D2D channel is frequency-flat over the whole bandwidth according to [10] and [11]. Note that the D2D pair reuses the whole bandwidth, which indicates that a_k is interpreted as the probability of receiving interference from GT k and the rate of the D2D can be modeled as (4a) according to [11]. The power restrictions for the D2D pair and GTs are respectively formulated in (4b) and (4c). (4d) ensures that each GT should satisfy the minimum rate requirement. (4f) and (4g) indicate bandwidth allocation requirements.

III. Solution Approach

Due to (4a) and (4d), Problem (4) is a nonconvex problem. It is difficult to obtain its globally optimal solution. In the following, we propose a low-complexity iterative algorithm.

Since (4a) is a monotonically decreasing function of p_k^{u}, the data rate constraints in (4d) for GTs should hold with equality at the optimal point. As a result, we have

$$p_k^{\mathrm{u}\,*} = \frac{2^{\frac{R_{\min}}{a_k}} - 1}{\beta_0} \left(\left\|\boldsymbol{u} - \boldsymbol{g}_k\right\|^2 + H^2\right) \left(p_{\mathrm{d}} h_k^{\mathrm{d}} + \sigma^2\right), \tag{5}$$

where $p_k^{\mathrm{u}\,*}$ denotes the optimal solution of p_k^{u}.

To ensure that Problem (4) is feasible, we employ the feasibility checking algorithm. The feasibility checking problem is the minimization of transmit power of the UAV subject to constraints (4b), (4d)-(4g). If the minimal sum power of the UAV is larger than $P_{\mathrm{u}}^{\max}$, Problem (4) is infeasible. Since $p_k^{\mathrm{u}\,*}$ is the minimal value of p_k^{u} according to (4d), the feasibility checking problem is equivalent to obtain the minimum value v^* of $\sum\limits_{k=1}^{K} p_k^{\mathrm{u}\,*}$, when $p_{\mathrm{d}} = 0$, $H = H_{\min}$, and constrains (4f) and (4g) are satisfied. An exhaustive algorithm can be adopted to solve it. With fixed $\boldsymbol{u}$, the optimal bandwidth allocation $\mathbf{a}$ can be obtained via the interior point method. The optimal $\boldsymbol{u}$ is obtained via the two-dimensional (2D) exhaustive search. As a result, Problem (4) is feasible if and only if when $P_{\mathrm{u}}^{\max} \geq v^*$.

Based on (5) and the fact that $\log_2(1+x)$ is a monotonically increasing function, Problem (4) is equivalent to

$$\max_{p_{\mathrm{d}}, \mathbf{a}, \boldsymbol{u}, H} \frac{p_{\mathrm{d}} h_0^{\mathrm{d}}}{\sum\limits_{k=1}^{K} a_k \left(2^{\frac{R_{\min}}{a_k}} - 1\right) \frac{\|\boldsymbol{u} - \boldsymbol{g}_k\|^2 + H^2}{H^2 + \|\boldsymbol{u}\|^2} \left(p_{\mathrm{d}} h_k^{\mathrm{d}} + \sigma^2\right) + \sigma^2} \tag{6a}$$

$$\text{s.t.} \quad 0 \leq \sum_{k=1}^{K} \frac{2^{\frac{R_{\min}}{a_k}} - 1}{\beta_0} \left(\left\|\boldsymbol{u} - \boldsymbol{g}_k\right\|^2 + H^2\right) \left(p_{\mathrm{d}} h_k^{\mathrm{d}} + \sigma^2\right) \leq P_{\mathrm{u}}^{\max}, \tag{6b}$$

$$(4b), (4e) - (4g). \tag{6c}$$

To solve Problem (6), an iterative algorithm is proposed.

A. Optimal Power Allocation

With fixed $\mathbf{a}$, $\boldsymbol{u}$ and H in Problem (6), the power allocation problem is given by

$$\max_{p_{\mathrm{d}}} \quad \frac{p_{\mathrm{d}} h_0^{\mathrm{d}} D_0}{p_{\mathrm{d}} M + \sigma^2 (N + D_0)} \tag{7a}$$

$$\text{s.t.} \quad 0 \leq p_{\mathrm{d}} \leq \bar{P}_{\mathrm{d}}^{\max}, \tag{7b}$$

where $D_0 = \|\boldsymbol{u}\|^2 + H^2$, $M = \sum\limits_{k=1}^{K} a_k A_k D_k h_k^{\mathrm{d}}$, $A_k = 2^{\frac{R_{\min}}{a_k}} - 1$, $D_k = \|\boldsymbol{u} - \boldsymbol{g}_k\|^2 + H^2$, $N = \sum\limits_{k=1}^{K} a_k A_k D_k$, and $\bar{P}_{\mathrm{d}}^{\max} = \min \left\{ P_{\mathrm{d}}^{\max}, \left\{ \frac{\beta_0 P_{\mathrm{u}}^{\max} - \sigma^2 \sum\limits_{k=1}^{K} A_k D_k}{\sum\limits_{k=1}^{K} A_k D_k h_k^{\mathrm{d}}} \right\} \right\}$.

Observing that (7a) is an increasing function of p_{d}, the optimal power solution of Problem (7) is $p_{\mathrm{d}}^* = \bar{P}_{\mathrm{d}}^{\max}$.

B. Altitude and Location Planning

Then, we investigate the altitude and location planning with fixed D2D transmit power and bandwidth allocation. Since $\frac{p_{\mathrm{d}} h_0^{\mathrm{d}}}{x + \sigma^2}$ is a decreasing function with $x > 0$, the altitude and location planning problem can be formulated as

$$\min_{\boldsymbol{u},H} \quad \sum_{k=1}^{K} B_k \frac{\|\boldsymbol{u}-\boldsymbol{g}_k\|^2 + H^2}{H^2 + \|\boldsymbol{u}\|^2} \tag{8a}$$

$$\text{s.t.} \quad \sum_{k=1}^{K} A_k C_k (\|\boldsymbol{u}-\boldsymbol{g}_k\|^2 + H^2) \le \beta_0 P_{\mathrm{u}}^{\max}, \tag{8b}$$

$$H_{\min} \le H \le H_{\max}, \tag{8c}$$

where $C_k = p_{\mathrm{d}} h_k^{\mathrm{d}} + \sigma^2$ and $B_k = a_k A_k C_k$. To solve Problem (8), we first obtain the optimal H under given $\boldsymbol{u}$, and then adopt the 2D exhaustive search to find the optimal solution of $\boldsymbol{u}$ to Problem (8). Under fixed $\boldsymbol{u}$, constraint (8b) is

$$H \le \sqrt{\frac{\beta_0 P_{\mathrm{u}}^{\max} - \sum\limits_{k=1}^{K} A_k \|\boldsymbol{u}-\boldsymbol{g}_k\|^2 C_k}{\sum\limits_{k=1}^{K} A_k C_k}} \triangleq H_0, \tag{9}$$

It should be noticed that in order to make the altitude planning problem feasible, $H_{\min}$ should satisfy $H_{\min} \le H_0$. Assuming it is satisfied, constraint (8c) is transferred to

$$H_{\min} \le H \le \bar{H}_{\max}, \tag{10}$$

where $\bar{H}_{\max} = \min\{H_{\max}, H_0\}$. Therefore, the altitude planning problem with fixed $\boldsymbol{u}$ becomes

$$\min_{H} \quad \sum_{k=1}^{K} B_k \frac{\|\boldsymbol{u}-\boldsymbol{g}_k\|^2 + H^2}{H^2 + \|\boldsymbol{u}\|^2} \tag{11a}$$

$$\text{s.t.} \quad (10). \tag{11b}$$

Defining function $b(x) = \sum\limits_{k=1}^{K} B_k \frac{\|\boldsymbol{u}-\boldsymbol{g}_k\|^2 + x}{x + \|\boldsymbol{u}\|^2}$, we have

$$b'(x) = \frac{\|\boldsymbol{u}\|^2 \sum\limits_{k=1}^{K} B_k - \sum\limits_{k=1}^{K} B_k \|\boldsymbol{u}-\boldsymbol{g}_k\|^2}{\left(x + \|\boldsymbol{u}\|^2\right)^2}, \tag{12}$$

and we consider the optimal altitude planning in the following two cases.

1) Case 1: $\sum\limits_{k=1}^{K} B_k \|\boldsymbol{u}\|^2 \ge \sum\limits_{k=1}^{K} B_k \|\boldsymbol{u}-\boldsymbol{g}_k\|^2$.

In this case, we have $b'(x) \ge 0$, and $b(x)$ is an increasing function. Since H^2 is an increasing function of H when $H_{\min} \le H \le \bar{H}_{\max}$, the optimal altitude of Problem (11) is

$$H^*(\boldsymbol{u}) = H_{\min}. \tag{13}$$

2) Case 2: $\sum\limits_{k=1}^{K} B_k \|\boldsymbol{u}\|^2 < \sum\limits_{k=1}^{K} B_k \|\boldsymbol{u}-\boldsymbol{g}_k\|^2$.

In this case, $b(x)$ is a monotonically decreasing function. The optimal altitude planning of Problem (11) is

$$H^*(\boldsymbol{u}) = \bar{H}_{\max}. \tag{14}$$

After obtaining the optimal $H^*(\boldsymbol{u})$, we adopt a 2D exhaustive search to find the optimal solution of $\boldsymbol{u}$ to Problem (8).

C. Optimal Bandwidth Allocation

For Problem (6) with fixed transmit power, altitude and location, the bandwidth allocation problem is given by

$$\min_{\mathbf{a}} \quad \sum_{k=1}^{K} a_k \left(2^{\frac{R_{\min}}{a_k}} - 1\right) C_k E_k \tag{15a}$$

$$\text{s.t.} \quad \sum_{k=1}^{K} \left(2^{\frac{R_{\min}}{a_k}} - 1\right) C_k Q_k \le \beta_0 P_{\mathrm{u}}^{\max}, \tag{15b}$$

$$(4f), (4g). \tag{15c}$$

where $E_k = \frac{Q_k}{H^2 + \|\boldsymbol{u}\|^2}$ and $Q_k = \|\boldsymbol{u}-\boldsymbol{g}_k\|^2 + H^2$. We define function $f(x) = x 2^{\frac{R_{\min}}{x}} - x$ for $x > 0$, and have

$$f''(x) = \frac{(\ln 2)^2 R_{\min}^2 2^{\frac{R_{\min}}{x}}}{x^3} > 0. \tag{16}$$

Based on (16), we observe that the objective function of Problem (15) is a convex function. Since constraint (15b) is convex, Problem (15) is a convex problem and it can be solved by analyzing the Karush-Kuhn-Tucker conditions with the same method adopted in [12, Appendix A].

D. Iterative Algorithm and Complexity Analysis

The iterative algorithm for solving Problem (4) is given in Algorithm 1, which yields a suboptimal solution. Due to the fact that the optimal solution is obtained for each subproblem in each step, Algorithm 1 is guaranteed to converge. For the feasibility checking in Algorithm 1, the complexity mainly lies in interior point method. Since the dimension of the variables of bandwidth allocation problem is K, the complexity of solving it by using the interior point method is $\mathcal{O}(L_{\mathrm{i}} K^3)$ [13, Pages 487, 569], where L_{i} denotes the number of iterations for the interior point method. Let X and Y respectively denote the maximum searching distances of the horizontal and vertical location, Δl_x and Δl_y respectively denote the searching steps of the horizontal and vertical location. Since the 2D exhaustive search method is used, the complexity of feasibility checking algorithm is $\mathcal{O}(\frac{L_{\mathrm{i}} K^3 XY}{\Delta l_x \Delta l_y})$. For each iteration in Algorithm 1, the major complexity mainly lies in solving the altitude and location planning problem. Since solving Problem (8) with fixed $\boldsymbol{u}$ involves a complexity of $\mathcal{O}(K)$ according to (13) and (14), the complexity of solving Problem (8) by 2D exhaustive search method is $\mathcal{O}(\frac{KXY}{\Delta l_x \Delta l_y})$. Therefore, the total complexity of Algorithm 1 is $\mathcal{O}\left(\frac{KXY}{\Delta l_x \Delta l_y}(L_{\mathrm{o}} + L_{\mathrm{i}} K^2)\right)$, where L_{o} is the number of the outer iteration.

IV. Numerical Results

We consider a scenario where there are $K = 3$ GTs and one D2D pair randomly distributed in a circle area with radius 300 m. The distance between the D2D transmitter and the corresponding receiver is set to 30 m. We set the total bandwidth of the system as 10 MHz, $\beta_0 = 1.42 \times 10^{-4}$, $\sigma^2 = -169$ dBm/Hz, $H_{\min} = 50$ m, $H_{\max} = 500$ m, $P_{\mathrm{d}}^{\max} = 10$ dBm and $P_{\mathrm{u}}^{\max} = 30$ dBm.

Similar to [14], the channel power gain h_k^{d} is modeled as $\beta_0 \eta d^{-3}$, $k = 0, 1, \cdots, K$, where d represents distance and η represents the Rayleigh fading coefficient, which follows the exponential distribution with unit mean. We compare the proposed algorithm with the following three algorithms: fixed altitude and location algorithm with optimized bandwidth (labeled as 'FAL'), fixed bandwidth algorithm with optimized altitude and location (labeled as 'FB'), and the near globally optimal algorithm via running the proposed iterative algorithm with 1000 initial points (labeled as 'NGO').

Algorithm 1: Iterative Algorithm

1: Check the feasibility of Problem (4). If Problem (4) is infeasible, terminate the algorithm. Otherwise, initialize a feasible solution $(p_{\rm d}^{(0)}, \mathbf{a}^{(0)}, \boldsymbol{u}^{(0)}, H^{(0)})$ and $(p_k^{\rm u})^{(0)}$ according to (5). Set the iteration number $n=1$.
2: **repeat**
3: With fixed $\mathbf{a}^{(n-1)}$, $\boldsymbol{u}^{(n-1)}$ and $H^{(n-1)}$, obtain the optimal $p_{\rm d}^{(n)}$ of Problem (7).
4: With fixed $p_{\rm d}^{(n)}$ and $\mathbf{a}^{(n-1)}$, obtain the optimal $\boldsymbol{u}^{(n)}$ and $H^{(n)}$ of Problem (8).
5: With fixed $p_{\rm d}^{(n)}$, $\boldsymbol{u}^{(n)}$ and $H^{(n)}$, obtain the optimal $\mathbf{a}^{(n)}$ of Problem (15), and $(p_k^{\rm u})^{(n)}$ according to (5).
6: Set $n=n+1$.
7: **until** the objective function (4a) convergence.
8: Output $\mathbf{p}_{\rm u}^* = \left((p_1^{\rm u})^{(n)}, \cdots, (p_K^{\rm u})^{(n)}\right)$, $p_{\rm d}^* = p_{\rm d}^{(n)}$, $\boldsymbol{u}^* = \boldsymbol{u}^{(n)}$, $H^* = H^{(n)}$ and $\mathbf{a}^* = \mathbf{a}^{(n)}$.

Firstly, we study the convergence behaviour of the proposed algorithm. Fig. 1 illustrates the achievable rate of the D2D pair versus the number of iterations when $H_{\min} = 50$ m. It shows that the achievable rate of the D2D pair increases monotonically and converges rapidly.

The achievable rate of the D2D pair with different approaches versus $R_{\min}$ when $H_{\min} = 50$ m and $H_{\min} = 200$ m is illustrated in Fig. 2. We observe that the achievable rate of the D2D pair decreases when $H_{\min}$ is increased for all algorithms. Moreover, the altitude of the UAV cannot be too high or too low. If the altitude of the UAV is too high, the coverage region of the UAV is enhanced while the channel gain is weak, which leads to high transmit power from the UAV to satisfy the rate demand of GTs and severe interference to the D2D pair. If the altitude of the UAV is too low, the channel gains are high from the UAV to GTs and the D2D receiver, which will result in terrible interference to the D2D pair. From Fig. 2, we observe that the proposed algorithm respectively achieves 20% and 10% average gain over the FB algorithm and the FAL algorithm when $H_{\min} = 50$ m. When $H_{\min} = 200$ m, the proposed algorithm respectively achieves 30% and 8% average gain over the FB algorithm and the FAL algorithm. This is because the proposed algorithm jointly optimizes transmit power, altitude, location and bandwidth. Considering the pre-allocated bandwidth of each GT, the FB algorithm performs worst among all approaches, which indicates that the bandwidth allocation dominates the altitude and location planning in enhancing the D2D achievable rate. It is also observed that the NGO algorithm outperforms the proposed algorithm at the cost of some additional computations.

V. Conclusions

In this letter, we aim to maximize the rate of a D2D pair with the coexistence between the UAV and an underlaid D2D communication network in a downlink scenario. Numerical results show that the proposed algorithm always outperforms the algorithms which partially optimize altitude, location or bandwidth. Moreover, the altitude of the UAV cannot be too high or too low because the altitude of the UAV has an important influence on the UAV-aided networks with underlaid D2D communications.

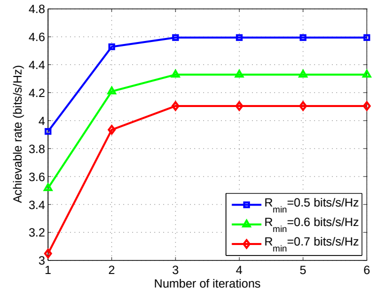

Fig. 1. Number of iterations using the proposed method.

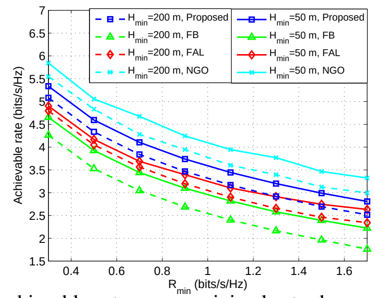

Fig. 2. D2D achievable rate versus minimal rate demand.

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