A Resource Allocation Scheme for D2D Communication in Millimeter-Wave 5G Networks: Postprint

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Abstract

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Full Text

Preamble

Resource Allocation Scheme for D2D Communication in mmWave 5G Networks

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Abstract: In 5G systems, millimeter wave (mmWave) and device-to-device (D2D) communication technologies are beneficial for improving system capacity and spectrum utilization. This paper investigates D2D resource allocation in underlay cellular networks at 73 GHz. To reduce mutual interference, we first propose regional restrictions on the base station and D2D receiver locations. Second, we employ a linear correlation method to select reusable cellular users. Finally, under the quality-of-service (QoS) requirements for both cellular and D2D communications, we propose an interference-controlled resource allocation scheme to enhance system throughput. Simulation results demonstrate that the proposed algorithm outperforms reference algorithms and can effectively improve system throughput and spectrum efficiency.

Keywords: millimeter wave; D2D; resource allocation; throughput; interference

0 Introduction

The proliferation of smart terminals such as smartphones and tablets has driven rapid growth in mobile data traffic, making available spectrum increasingly scarce. To meet the escalating demand for diverse terminal services, wireless networks must substantially improve spectrum utilization and throughput. Fifth-generation (5G) communication technologies capable of dramatically increasing data transmission rates have become a research focus, with millimeter wave and D2D communication drawing particular industry attention [1].

Millimeter wave operates in the very high frequency band (30-300 GHz), where spectrum resources are abundant with large contiguous bandwidths available at 28 GHz, 60 GHz, 38 GHz, and E-band (71-76 GHz and 77-81 GHz), effectively alleviating spectrum scarcity [2]. Millimeter wave offers advantages including short single-hop communication distances, fewer interference sources, and gigabit-level communication services that can significantly boost system capacity and transmission rates. However, unfavorable channel characteristics such as high path loss, atmospheric absorption, and rain attenuation reduce service coverage. Recent research demonstrates that mmWave can be applied to outdoor scenarios like streets and stations [3,4].

D2D (device-to-device) communication, also known as terminal direct communication, enables direct communication between devices under base station control without requiring base station relay [5]. Integrating D2D communication into cellular networks offers several benefits: increased communication system capacity, improved spectrum efficiency, enhanced data transmission rates, and reduced base station load. Under base station control, D2D communication can use cell resources in either orthogonal mode or non-orthogonal mode (reuse mode), with most current research focusing on reuse mode [6]. Reuse mode generates severe interference that affects system performance, making interference mitigation a key research priority in D2D communication while ensuring QoS for both cellular and D2D users.

Resource reuse schemes are crucial for reducing D2D-to-cellular interference.

Reference [7] proposes interference constraints on D2D receivers to guarantee D2D communication quality and introduces a power control strategy based on D2D-to-base station distance. Reference [8] presents a joint resource allocation scheme for D2D communication based on interference control that improves system throughput, but restricts each cellular user’ s resource to be reused by only one D2D user, limiting spectrum utilization. Reference [9] investigates power control schemes based on interference-limited areas to mitigate interference in hybrid cellular networks, proposing a new resource allocation scheme with a “DT maximum/minimum power” criterion, but D2D user QoS is not well guaranteed and interference reduction is limited due to simple distance-based cellular user selection.

To ensure user QoS, several studies have addressed this issue. Reference [10] formulates channel allocation as a mixed-integer nonlinear programming problem and proposes a greedy heuristic algorithm to maximize total throughput while satisfying SINR requirements for all users. Reference [11] determines D2D transmitter power based on SNR thresholds for cellular and D2D users and maximum device transmit power. Reference [12] first selects D2D pairs using linear programming to ensure D2D interference does not affect cellular communication while guaranteeing QoS for both user types, then proposes a channel allocation scheme to maximize system throughput. While references [10,11] provide QoS guarantees, they offer limited throughput improvement. Reference [12] satisfies both QoS and throughput requirements but lacks interference control.

Integrating mmWave technology with D2D communication in 5G networks yields high bandwidth and spectrum efficiency advantages, making D2D communication in mmWave cellular networks increasingly attractive [13]. Reference [14] conducts resource allocation at 28 GHz to improve system throughput through interference value constraints but cannot effectively reduce interference. Reference [15] studies energy efficiency maximization under D2D user minimum QoS constraints, proposing adaptive power control based on cellular user interference thresholds, but this method cannot guarantee interference resolution.

This paper addresses the problem of maximizing system throughput through optimal D2D resource allocation in 73 GHz mmWave cellular networks. The proposed method first identifies D2D user sets through regional restrictions on base stations and D2D receivers, then selects reusable cellular users using linear correlation, and finally proposes an interference-controlled resource allocation scheme under cellular and D2D QoS constraints to enhance system throughput.

1.2 Transmission Model

The most studied mmWave bandwidths are 28, 38, 60, 71–76, and 81–86 GHz, which offer high throughput, high-quality wireless links, massive MIMO scheduling, and clear network design. Under actual outdoor transmission conditions at

73 GHz, reference [16] conducted large-scale measurements in New York City and obtained detailed channel spatial statistical models. Line-of-sight (LOS) transmission is impractical in such dense user and obstacle environments. Due to angular signal characteristics with different delays, the path loss model separates LOS and non-line-of-sight (NLOS) components, each with corresponding shadow fading.

The path loss (PL) model is calculated as:

$$PL(d) = 10\log_{10}(d) + \mu + \varepsilon$$

where ε represents log-normal shadowing following $N(0, \sigma^2)$; μ is the path loss coefficient; and α is the path loss exponent.

The D2D link PL model is:

$$PL_1 = p_{LOS}PL_{LOS} + (1 - p_{LOS})PL_{NLOS}$$

Other links follow the PL model:

$$PL_2 = p_{LOS}PL_{LOS} + (1 - p_{LOS})PL_{NLOS}$$

1.3 Problem Formulation

In mmWave outdoor network design, the objective is to maximize the total data rate of cellular and D2D users while satisfying their SINR requirements. In this paper, the SINR for cellular user c and D2D user d are respectively:

$$\lambda_{c,d} = \frac{p_c H_{c,B}}{r_c + \sum_{d=1}^{M} \lambda_{c,d} p_d H_{d,B} + N_0}, \quad c = 1, 2, ..., N$$

$$\lambda_d = \frac{p_d H_{d,d}}{r_d + \sum_{c=1}^{N} \lambda_{c,d} p_c H_{c,d} + \sum_{d' \neq d} \lambda_{c,d'} p_{d'} H_{d',d} + N_0}, \quad d = 1, 2, ..., M$$

where p_c and p_d are the transmit powers of cellular and D2D transmitters; $H_{i,j}$ is the channel gain of link $i - j$; and N_0 is additive white Gaussian noise.

The SINR thresholds for cellular and D2D users are $r_{th,c}$ and $r_{th,d}$. Let $\lambda_{c,d}$ indicate whether the d-th D2D pair reuses the c-th cellular user' s resource, where $\lambda_{c,d} = 1$ indicates reuse and $\lambda_{c,d} = 0$ indicates no reuse.

From Shannon' s formula, the rates are:

$$R_c = B\log_2(1+\lambda_c)$$

$$R_d = B\log_2(1+\lambda_d)$$

The maximization problem can be expressed as:

$$\max_{\lambda} \sum_{c=1}^{N} R_c + \sum_{d=1}^{M} R_d$$

subject to:

$$\lambda_c \geq r_{th,c}, \quad c = 1, 2, ..., N$$

$$\lambda_d \geq r_{th,d}, \quad d = 1, 2, ..., M$$

$$p_c \leq p_c^{max}, \quad c = 1, 2, ..., N$$

$$p_d \leq p_d^{max}, \quad d = 1, 2, ..., M$$

$$\sum_{c\in C} \lambda_{c,d} \leq 1, \quad \forall d \in D$$

$$\sum_{d\in D} \lambda_{c,d} \leq q_c, \quad \forall c \in C$$

where constraints (8a) and (8b) enforce SINR requirements for cellular and D2D users; (8c) and (8d) limit transmit powers; (8e) ensures each D2D user can share resources with only one cellular user; and (8f) indicates that cellular user c' s resources can be reused by multiple D2D users, with a maximum of q_c D2D users.

1.1 Scenario Description

We consider a 5G urban cellular network scenario where D2D and cellular users coexist, focusing on multiple D2D pairs reusing one cellular user' s resources in a 73 GHz mmWave cellular network. In this scenario, interference occurs between D2D and cellular users, and interference among D2D pairs is also non-negligible. Assuming each cellular user is allocated an orthogonal resource block (RB), the number of RBs equals the number of cellular users, denoted as $C = \{1, 2, 3, ..., N\}$, and the number of D2D pairs is $D = \{1, 2, 3, ..., M\}$.

[Figure 1: see original paper] illustrates the interference when D2D users DT1 and DT2 reuse the same cellular user UT1' s resources.

2.1.1 D2D Communication Restricted Area

To ensure D2D-to-cellular interference remains acceptable, we restrict the D2D communication area. Let $I_{th,B}$ denote the base station' s interference threshold. The interference from D2D transmitter to BS is:

$$I_{d,B} = p_d H_{d,B} \leq I_{th,B}$$

Considering the worst-case interference scenario where:

$$I_{d,B}^{max} = p_d^{max} H_{d,B} = p_d^{max} \times PL_0 \times d^{-\alpha}$$

where d is the distance from i to j; PL_0 is the path loss constant; α is the path loss exponent; and p_d^{max} is the maximum D2D transmit power. Substituting into the interference constraint yields the D2D communication restricted area radius r_1:

$$r_1 = \left(\frac{p_d^{max} \times PL_0}{I_{th,B}}\right)^{1/\alpha}$$

2.1.2 Cellular User Restricted Reuse Area

To guarantee D2D communication quality, we must control cellular-to-D2D receiver interference. The D2D receiver's SINR must exceed threshold $r_{th,d}$. Since D2D communication uses maximum transmit power p_d^{max}, the D2D link SINR primarily depends on cellular user interference, which must be limited below interference threshold $I_{th,d}$.

First, the D2D receiver SINR should satisfy:

$$\lambda_d = \frac{p_d^{max} H_{d,d}}{r_d + \sum_{c=1}^{N} \lambda_{c,d} p_c H_{c,d} + N_0} \geq r_{th,d}$$

In the worst-case interference scenario where all UTs using the same uplink resource lie on a circle of radius r_2, the cellular-to-D2D interference is:

$$I_{c,d} = \sum_{c \in \Omega_c} p_c H_{c,d} \leq I_{th,d}$$

Assuming cellular user UT uses maximum transmit power p_c^{max}, the maximum cellular-to-D2D interference is:

$$I_{c,d}^{max} = p_c^{max} H_{c,d} = p_c^{max} \times PL_0 \times r_2^{-\alpha}$$

From the SINR requirement we obtain:

$$r_{th,d} \leq \frac{p_d^{max} H_{d,d}}{I_{th,d} + N_0}$$

Substituting the interference expressions yields the cellular user restricted reuse radius r_2:

$$r_2 = \left(\frac{p_c^{max} \times PL_0 \times r_{th,d}}{p_d^{max} H_{d,d} - r_{th,d} N_0} \right)^{1/\alpha}$$

2.1 Restricted Areas

Since D2D users reuse cellular uplink resources, two interference scenarios arise: (1) D2D transmitters closer to the base station cause greater interference to BS reception of cellular signals; (2) Cellular users closer to D2D receivers cause greater interference when sharing resources. To reduce mutual interference between cellular and D2D communications, we impose regional restrictions on both user types.

[Figure 2: see original paper] illustrates the restricted zones: The D2D communication restricted area is a circular region centered at the base station with radius r_1. If a D2D user is located within this area, the base station prohibits D2D link establishment. The cellular user restricted reuse area is a circle centered at the D2D receiver D2Drx with radius r_2. If a cellular user lies within this region, its resources cannot be reused.

2.2 D2D User Reusable Cellular User Set

To further improve spectrum utilization, we select potential cellular users for D2D reuse using linear programming methods. As shown in [Figure 2: see original paper] and following reference [12], we determine the set of cellular users that can be reused by D2D users while ensuring QoS for both. If cellular user c belongs to set Ω_c, then cellular and D2D users must satisfy constraints (8a) and (8b), which can be expressed as:

$$\lambda_{c,d} = \frac{p_c H_{c,B}}{r_c + \sum_{d \in D} \lambda_{c,d} p_d H_{d,B} + N_0} \geq r_{th,c}$$

$$\lambda_d = \frac{p_d H_{d,d}}{r_d + \sum_{c \in C} \lambda_{c,d} p_c H_{c,d} + N_0} \geq r_{th,d}$$

From these inequalities, we can solve for intersection points A and B in [Figure 3: see original paper]:

$$A = \left\{ \frac{r_{th,d} H_{d,d} - r_{th,c} H_{c,B}}{H_{c,d} H_{d,B}} ; \frac{r_{th,c} H_{c,B} - r_{th,d} H_{d,d}}{H_{c,d} H_{d,B}} \right\}$$

$$B = \left\{ \frac{r_{th,d} H_{d,d} + r_{th,c} H_{c,B}}{H_{c,d} H_{d,B}} ; \frac{r_{th,c} H_{c,B} + r_{th,d} H_{d,d}}{H_{c,d} H_{d,B}} \right\}$$

The feasible region for p_c and p_d is the shaded area bounded by the dashed lines and axes in [Figure 3: see original paper]. Only when intersection point A exists and lies within this region can D2D users reuse cellular resources. Equation (18) indicates the available transmission power for all terminal users, with the base station power not exceeding its maximum.

2.3 Interference-Controlled Resource Allocation

To improve cellular system fairness, D2D users select which cellular user resource to reuse based on data rate considerations within the reusable cellular user set. This yields candidate D2D users for each cellular user, represented by the resource allocation indicator matrix λ.

For each D2D pair in Ω_d, we compute $H = \lambda_{c,d} R_d + R_c$. D2D pairs that achieve maximum H when reusing cellular user c' s resource are added to set Ω_c. Since multiple D2D pairs reusing the same resource cause mutual interference, and total D2D-to-BS interference must remain below threshold $I_{th,B}$, we must verify cellular user SINR requirements.

If $\sum_{d \in \Omega_c} I_{d,B} > I_{th,B}$, we remove the D2D pair causing maximum interference to the base station from Ω_c until the constraint is satisfied, then update the corresponding λ values. Next, we update the cellular user set as $C^* = C \setminus \{c\}$ and D2D user set as $D^* = D \setminus \Omega_c$, then check if D^* is empty. If empty, allocation ends; otherwise, we repeat the process for all D2D users in D^* until cellular resources are exhausted.

The proposed resource allocation scheme for D2D users proceeds as follows:

Step 1: The base station knows all cellular user coordinates, establishing cellular user set $C = \{1, 2, ..., N\}$.

Step 2: Determine if D2D transmitters lie within the circular region centered at the base station with radius r_1. If outside, establish D2D communication; otherwise, use cellular mode. This yields D2D user set $D = \{1, 2, ..., M\}$.

Step 3: For each D2D user d, determine if cellular user c lies within the circle centered at D2Drx with radius r_2. If inside, c is not a potential reuse candidate; if outside, calculate intersection point A from equation (17) and verify if it satisfies equation (18). If satisfied, c is a potential reuse cellular user for d. Iterate through all cellular users to find all potential reuse users and store them in set Ω_c. Set $\lambda_{c,d} = 0$ for cellular users not in Ω_c. Repeat for all D2D users in set D to find their respective potential reuse sets Ω_d.

Step 4: Based on H, identify the D2D set Ω_c that maximizes throughput for each cellular user c' s resources.

Step 5: Check if all D2D users in Ω_c satisfy $\sum_{d \in \Omega_c} I_{d,B} \leq I_{th,B}$. If not, remove the D2D pair causing maximum interference to the base station from Ω_c and add it to set D', until the constraint is met, then update the corresponding λ values.

Step 6: Update cellular user set as $C^* = C \setminus \{c\}$, $D = D^*$, and check if D^* is empty. If empty, end allocation; otherwise proceed.

Step 7: Return to Step 4 for all D2D users in set D^* until the cellular user set is empty.

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3 Simulation Verification

3.1 Simulation Parameters

To verify the effectiveness of the proposed resource allocation algorithm, we conduct MATLAB simulations in a mmWave 5G cellular network scenario. The main simulation parameters are listed in .

Table 1: Main Simulation Parameters - RB bandwidth: 180 KHz - Number of cellular users: 5, 8, 11, ···, 20 - Number of D2D pairs: 5, 8, 11, ···, 20 - Cellular user transmit power: 25 dBm - D2D transmit power: 21 dBm - Predefined effective SINR: 21 dBm - Noise power density: -174 dBm/Hz - Path loss parameters LOS: (69.8, 2, 5.8) - Path loss parameters NLOS: (86.6, 2.45, 8.0) -

D2D link path loss probability: $P_1 = 0.8$ - Non-D2D link path loss probability: $P_2 = 0.2$ - Rician channel K parameter: (value not specified in original)

3.2 Simulation Results

[Figure 4: see original paper] depicts the cumulative distribution function (CDF) of system throughput across different frequency bands. With 20 D2D pairs and 10 m D2D distance, we compare cellular system throughput at 73 GHz and 2.4 GHz. The results show that the 73 GHz CDF outperforms 2.4 GHz, demonstrating that high-frequency performance surpasses low-frequency when appropriate interference control is applied.

[Figure 5: see original paper] illustrates the relationship between total system throughput and D2D user distance with 20 D2D users, comparing the proposed algorithm with random allocation and heuristic algorithms. When distance $d < 30$ m, total throughput decreases significantly as D2D pair distance increases. When $d > 30$ m, throughput changes minimally with distance because at small distances, D2D link quality is good and significantly impacts total throughput, while at large distances, D2D link quality becomes poor and has negligible effect. The proposed algorithm consistently outperforms the other two algorithms, clearly demonstrating effective improvement in cell total throughput.

[Figure 6: see original paper] shows the relationship between total system throughput and the number of D2D pairs at 10 m D2D distance. With fixed cellular user quantity, total throughput initially increases with D2D pair count but the growth rate gradually slows because increasing D2D pairs raise both D2D-to-cellular and D2D-to-D2D interference. The random allocation algorithm even shows a downward trend due to unresolved interference issues. The proposed algorithm outperforms both reference algorithms.

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4 Conclusion

The integration of D2D communication and mmWave technology can increase data transmission rates, system throughput, and spectrum efficiency, but D2D communication also introduces interference to cellular systems. To address this issue, this paper proposes a joint region restriction and interference-controlled resource allocation scheme that improves system throughput. Simulation results demonstrate that the proposed algorithm enhances system performance while guaranteeing QoS for both cellular and D2D users.

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Note: Figure translations are in progress. See original paper for figures.