KSII TRANSACTIONS ON INTERNET AND INFORMATION SYSTEMS VOL. 18, NO. 11, Nov. 2024 3177

Energy Efficiency Optimization for D2D Communication with Statistical Channel State Information and QoS Awareness

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Received March 20, 2024; revised July 4, 2024; revised August 8, 2024; accepted October 27, 2024; published November 30, 2024

Abstract

Since the energy efficiency (EE) optimization of communication systems brings extremely significant economic benefits in mobile communication networks, this study conducts the device-to-device (D2D) communication EE optimization considering statistical channel state information (CSI) and quality of service (QoS) awareness. First of all, a D2D access control strategy is implemented to determine the set of cellular users that can all be feasible for each pair of D2D users. However, as the instantaneous channel state information is often unavailable, a modified access control strategy based on statistical channels is proposed. Subsequently, in the power control issue, an iterative power control algorithm with the constraint of users' QoS awareness is put forward to obtain the optimal transmit power combination based on partial fractional programming. Finally, a rapid channel allocation algorithm is provided to solve the channel assignment problem, resulting in an enhancement of the access rate and a reduction of complexity. Simulation results show that: i) Our proposed algorithm has advantages in enhancing the EE for D2D communication with statistical CSI; ii) In the case of increasing EE, the user's QoS awareness is guaranteed; iii) The algorithm increases the access rate of D2D users while achieving resource allocation fairness.

Keywords: D2D communication, EE, statistical channel state information, QoS awareness.

This paper is found by Zhengzhou University of Light Industry Doctoral Research Fund Project under Grants 2021BSJJ026 and 2020BSJJ068, and is partly found by the Science and Technology Research Projects of Henan Province under Grants 242102210112.

http://doi.org/10.3837/tiis.2024.11.005 **ISSN : 1976-7277**

1. Introduction

Emerging tech like Internet of Things and Virtual Reality is boosting demand for high-speed, low-latency mobile networks [1]. By 2020, over 50 billion devices were expected, with data traffic growing 42% annually to 110 EB by 2023 [2]. This growth puts financial pressure on operators, with power costs at 20-30% of expenses [3]. Energy efficiency is key for green networks and mobile devices with limited battery life, driving innovation for sustainable data handling [4]. D2D, which enables the direct exchange of data between neighboring users, bypassing the base station is expected to make a beneficial complement to cellular networks. Because of its simple and efficient operation, D2D communication is designed to use less power than other technologies. This makes D2D an energy-efficient communications solution, in line with the development trend of future mobile communication.

However, research on optimizing EE of D2D-enabled communication has lagged behind spectral efficiency (SE). Traditional cellular network designs have historically prioritized achieving specific (QoS) standards or maximizing SE, rather than emphasizing EE improvements [5-7]. Sequentially, EE has become a critical design factor for next-generation 5G/6G systems as wireless data applications proliferate [8].

1.1 Related Works

In recent years, researchers have studied various essential aspects of EE of D2D systems, including various optimization objectives, different optimization methods, and multiple optimization models. Specifically, the issue of mode selection and power control for D2D communication with a focus on EE is investigated in [9]. The study considers a communication scenario involving a single D2D user pair and a single cellular user. The authors provide optimal transmit power for D2D communication in overlay, underlay, and BS forwarding modes. Finally, the optimal operating mode and transmit power are selected by comparing the EE under the three modes. In [10], to minimize D2D users' total transmission power while satisfying D2D and cellular users' transmission rate requirements, the authors investigate the global joint optimization problem under D2D communication mode selection, resource allocation, and power control. The authors of [11] proposed an iterative algorithm that uses fractional programming and penalty function methods to deal with resource allocation and power control separately. The mechanism is structured in two layers to achieve an optimal global solution. Authors of [12] proposed a comprehensive framework to optimize the EE of D2D communications, which is achieved through dynamic mode selection, resource allocation, and power control. This study validates the effectiveness of the proposed algorithm under low, medium, and high-load network conditions. The article in [13] discusses the EE optimization problem for vehicle-to-everything communication networks based on D2D communication. The authors propose a new methodology for power allocation that satisfies both QoS and energy harvesting constraints by jointly optimizing the resource reuse of vehicle users and power control for D2D links. This study employs Lagrangian dual programming and the Dinkelbach method to simplify and solve this non-convex fractional planning problem and designs a triple-loop iterative algorithm. Author in [14] investigates the optimization problem of EE under two scenarios. Unlike the previously mentioned optimizations, which only aim to optimize the total individual EE, an optimization problem is proposed by the authors to optimize the total system EE. Additionally, another optimization problem is proposed that aims to optimize the sum of individual energy efficiencies.

In [15], due to the dynamic nature of D2D communication and environment, obtaining accurate CSI in real-time is challenging. The author proposed an approach based on statistical

CSI to minimize total power consumption while meeting QoS requirements, but the algorithm's complexity may be a bottleneck. In [16], authors focus on maximizing area SE and EE by adjusting density and D2D user transmission power, using stochastic geometry tools for closed-form analytical expressions. In [17], a resource management mechanism to improve EE of one-to-many D2D communication based on cellular networks is proposed. In [18], a novel game-theoretic algorithm is proposed for each D2D pair to choose transmission power and power allocation ratio to maximize utility. Two power control algorithms and two pricing-based strategies are proposed to address the problem.

In addition, novel D2D transmission models and artificial intelligence-based approaches have been proposed. Specifically, in [19] a new grouping D2D model with two transmitters and one receiver was proposed to improve the user's QoS and maximize the system's EE. However, the algorithms proposed rely on accurate measurement and assessment of social ties, which can be complex to quantify and may require continuous updates, adding to the system's overhead. In [20], the authors address the coordination problem among machine learning tools for EE-oriented D2D radio resource management. While the study claims low computational complexity, the actual deployment of deep neural networks (DNNs) in mobile networks, especially with real-time processing requirements, might demand significant computational resources. In [21], a deep learning-based improved D2D communication model was proposed. The model uses explainable artificial intelligence for analyzing communication needs and resource allocation in D2D communication. However, the integration of explainable artificial intelligence and deep learning into existing 5G infrastructure could be complex and may require significant changes to current systems. In [22], D2D technology is extended to unlicensed spectrum, and a distributed adaptive joint power and spectrum allocation scheme is proposed. Specifically, the study operates under incomplete channel state information, which might not fully capture the dynamics of real-world D2D communications, potentially affecting the accuracy of the proposed algorithms. In [23], a joint load balancing scheme of mobility vehicle-to-vehicle and user association is studied. The authors present a distributed power and spectrum allocation scheme for D2D communication in unlicensed spectrum within a 5G new radio system. The study assumes that each D2D unlicensed link has access to perfect CSI, which is challenging to obtain in practical scenarios due to the dynamic nature of wireless channels and the cost and complexity of channel estimation.

1.2 Motivation

Despite extensive efforts that have been made on this topic, there are still some shortcomings that need to be addressed. Firstly, the existing EE optimization algorithms primarily focus on the BSs that have a knowledge of the instantaneous CSI of all links, which leads to significant EE improvement in theory rather than the real world. Secondly, by introducing D2D users, the interfering links between cellular users and D2D users require additional BS signaling overhead to obtain. Even if the BS obtains the interference link CSI, it may still be outdated. Consequently, the statistical CSI becomes a more realistic assumption. Finally, most of the channel allocation algorithms in the multiuser scenario are based on the Hungarian algorithm of global search, which is not only highly complex but also fails to ensure fairness in channel allocation. Herein, in our article, for the first time, we propose the statistical CSI and statistical QoS awareness-based EE optimization for D2D communication.

1.3 Contributions

The main contributions of our work can be summarized as follows

- A power control algorithm is introduced that works with limited CSI, accounting for the BS's inability to obtain perfect cross-layer interference CSI due to D2D users sharing cellular channels. It ensures optimal power transmission under the constraint of not exceeding the maximum allowable cellular user interruption probability.

- Secondly, a channel allocation algorithm is presented to boost D2D user access rates and ensure fair resource distribution. It integrates the Hungarian algorithm to enhance allocation fairness and system EE performance, balancing low complexity with effective allocation.
- Finally, simulation results confirm the proposed joint channel allocation and power control algorithm's superiority in improving system EE, demonstrating practical advantages in real-world D2D networks where perfect CSI is often unattainable.

2. System Model

Our paper considers a single-cell D2D-enabled cellular network where D2D users can share the downlink channel with cellular users. The network contains N cellular users and M D2D pairs, denoted by sets $\mathbf{C}=\{i \mid i=1,2,\ldots,N\}$ and $\mathbf{D}=\{j \mid j=1,2,\ldots,M\}$. It addresses the resource allocation problem under full load. D2D users can only reuse cellular users' channels. Each D2D pair can reuse no more than one, and each cellular user's channel can be shared with no more than one D2D pair. Fig. 1 shows the system model. Notations are in Table 1.

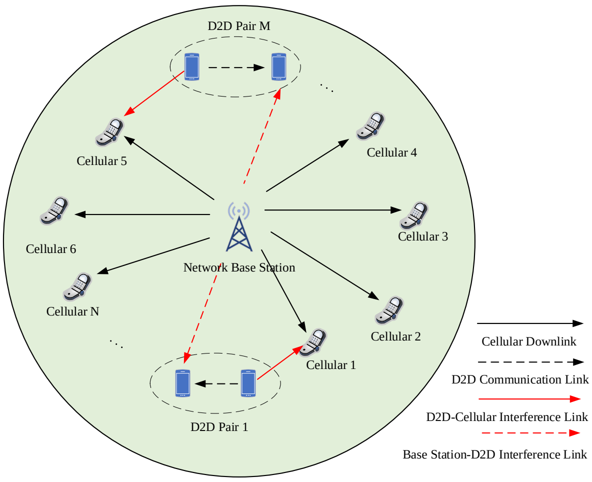

Fig. 1. Downlink of D2D with one-to-one reusing.

Table 1. Summary of important notations

Symbol	Definition
$\mathbf{C}$	Cellular users set
$\mathbf{D}$	D2D pairs set
$g_{B,i}$	Channel gain of BS to the cellular user i link
g_j^i	Channel gain of D2D j transmitter to receiver link
$h_{B,j}^i$	Channel gain from BS to D2D j receiver link
$h_{j,i}$	Channel gain from D2D j to the cellular user i link
P_i^c	Transmission power from BS to cellular user i
P_j^d	Transmission power of D2D transmitter

P_j^{total}	The total power consumption of D2D user j
$f(i,j)$	Channel allocation indicator
ω_j	The inverse of the amplification efficiency
$\chi_{B,i}$	Channel fading component
κ	Channel attenuation constant
α	Channel attenuation exponent
$d_{B,i}$	Transmission distance between BS and cellular user
$\gamma_{i,\min}^c$	Cellular user minimum SINR requirements
$\gamma_{j,\min}^d$	D2D user j minimum SINR requirements
δ	Cellular user interrupt violation probability threshold
η_j^{ee}	EE of D2D user j
R_i^c	Cellular user transmission rate
R_j^d	D2D user transmission rate

We consider frequency-selective channel environment, including large-scale path loss based on the transmission distance model, and the channel fading model based on multipath transmission with Doppler effect. Meanwhile, this paper assumes that the fading of channel gains of all channels on the time scale is manifested as block fading. The channel gain $g_{B,i}$ between BS and cellular user i is formulated as

$$g_{B,i} = \kappa \chi_{B,i} d_{B,i}^{-\alpha} \tag{1}$$

where κ and α denote the attenuation constant and attenuation exponent, respectively., $d_{B,i}$ denotes transmission distance between BS and cellular user i. $\chi_{B,i}$ denotes fading component.

Similarly, the channel gain of the D2D pair j when reusing the cellular user's i channel g_j^i , channel gain from BS to D2D pair j at receiver $h_{B,j}^i$, and the channel gain from D2D pair j at transmitter to cellular user i $h_{j,i}$ can be obtained. It should be pointed out that since the interference channel $h_{j,i}$ from the D2D pair j transmitter to the cellular user i does not establish direct communication with the BS, the BS cannot grasp its instantaneous CSI, but only its positional state information, i.e., path loss information. However, its channel fading information, i.e., large-scale and small-scale fading information is assumed out of its ability.

Let P_i^c and P_j^d refer to transmission power from BS to the cellular user i and D2D pair j transmitter, respectively, and in the one-to-one underlay mode, cellular user i and D2D pair j SINR is denoted as

$$\gamma_i^c = \frac{P_i^c g_{B,i}}{\sigma_n^2 + \sum_{j\in\mathbf{D}} f(i,j) P_j^d h_{j,i}} \tag{2}$$

$$\gamma_j^d = \frac{P_j^d g_j^i}{\sigma_n^2 + \sum_{i\in\mathbf{C}} f(i,j) P_i^c h_{B,j}^i} \tag{3}$$

where, σ_n^2 refers to Additive White Gaussian Noise (AWGN) power, and $f(i,j)$ denotes the channel allocation indicator function.

$$f(i,j)=\begin{cases}1 & \text{When D2D user } j \text{ multiplexes the channel of user } i\\ 0 & \text{Other}\end{cases} \tag{4}$$

In accordance with the definition given above, cellular and D2D user transmission rates can be described as

$$R_i^c = W_0 \log_2\left(1+\gamma_i^c\right) \tag{5}$$

$$R_j^d = W_0 \log_2\left(1+\gamma_j^d\right) \tag{6}$$

where, W_0 denotes the channel bandwidth. the power consumption of a D2D user j can be formulated as

$$P_j^{total} = 2P_0 + \omega_j P_j^d \tag{7}$$

where P_0 represents the fixed circuit power consumption of the D2D user, and ω_j represents the inverse of the amplification efficiency of the power amplifiers $\omega_j \geq 1$.

Therefore, the mathematical expression for the EE of D2D user is

$$\eta_j^{ee} = \frac{R_j^d}{P_j^{total}} = \frac{W_0 \log_2\left(1+\frac{P_j^d g_j^i}{\sigma_n^2 + \sum_{i\in\mathbf{C}} f(i,j) P_i^c h_{B,j}^i}\right)}{\omega_j P_j^d + 2P_0} \tag{8}$$

3. Problem formulation

Since the cellular user is the primary user in the cell, the D2D user can only access the network as a secondary user, which first needs to ensure the minimum data rate required by the cellular user. The D2D user will not be allowed to share the channel if the D2D user is reusing a cellular user's channel and causing severe co-channel interference to the paired cellular user. Similarly, even if the D2D user has the right to reuse the channel, the paired D2D and cellular user are required to adopt appropriate transmit power (P_i^c, P_j^d) to optimize the EE.

Let $\gamma_{i,\min}^c$ and $\gamma_{j,\min}^d$ refer to cellular user i and D2D user j minimum SINR requirements respectively, which are used to guarantee their QoS requirements. Since the BS has defective knowledge of the interfering link between the D2D transmitter and the cellular user, we formulate the cellular users' QoS guarantee as a statistical model of interrupt violation probability with a threshold of δ . $P_{\max}^c$ denote the maximum power of the BS on the channel i . $P_{\max}^d$ refers to the maximum power of D2D user j . Then the power control and channel allocation problem for EE optimization of D2D have the form of

$$\max_{f(i,j),(P_i^c,P_j^d)} \sum_{i=1}^{N}\sum_{j=1}^{M} f(i,j)\eta_j^{ee} \tag{9}$$

$$\text{s.t.}\quad \text{Prob}\left\{\gamma_i^c = \frac{P_i^c g_{B,i}}{\sigma_n^2 + \sum_{j\in\mathbf{D}} f(i,j) P_j^d h_{j,i}} \leq \gamma_{i,\min}^c\right\} \leq \delta, \forall i\in\mathbf{C} \tag{10}$$

$$\gamma_j^d = \frac{P_j^d g_j^i}{\sigma_n^2 + \sum_{i\in\mathbf{C}} f(i,j) P_i^c h_{B,j}^i} \geq \gamma_{j,\min}^d, \forall j\in\mathbf{D} \tag{11}$$

$$\sum_{j\in\mathbf{D}} f(i,j)\le 1, \forall i\in\mathbf{C} \tag{12}$$

$$\sum_{i\in\mathbf{C}} f(i,j)\le 1, \forall j\in\mathbf{D} \tag{13}$$

$$0\le P_i^c \le P_{\max}^c, \forall i\in\mathbf{C} \tag{14}$$

$$0\le P_j^d \le P_{\max}^d, \forall j\in\mathbf{D} \tag{15}$$

In the problem, (10) and (11) ensure cellular QoS and D2D user's rate. (12)-(15) handle channel and power constraints. The overall system EE of D2D communication isn't considered; the target is to optimize the sum of individual EE, as it's more realistic. Analyzing the problem shows it's a coupled, nonlinear, and integer-variable MINLP problem.

Inspired by [24], this paper splits the coupled EE optimization problem into three subproblems: D2D access control, power control, and channel assignment. Firstly, in the access control problem, the feasible set of cellular users for each D2D pair is found by checking whether there exists a feasible solution for the transmit power (P_i^c, P_j^d) in the feasible domain formed by the QoS and maximum transmit power constraint. Secondly, in the power control problem, the non-convex EE problem is converted and an iterative algorithm is proposed. Finally, in the channel allocation problem, an algorithm for fast allocation is considered to improve the D2D access rate.

3.1 Access Control Strategy

The possibility of D2D user access to the cellular network depends on whether the transmit power combination (P_i^c, P_j^d) can satisfy the feasible domain consisting of (10), (11), (14), and (15).

$$\begin{cases} \text{Prob}\left\{\gamma_i^c = \dfrac{P_i^c g_{B,i}}{\sigma_n^2 + \sum_{j\in\mathbf{D}} f(i,j) P_j^d h_{j,i}} \le \gamma_{i,\min}^c\right\} \le \delta, \forall i\in\mathbf{C} \\ \gamma_j^d = \dfrac{P_j^d g_j^i}{\sigma_n^2 + \sum_{i\in\mathbf{C}} f(i,j) P_i^c h_{B,j}^i} \ge \gamma_{j,\min}^d, \forall j\in\mathbf{D} \\ 0\le P_i^c \le P_{\max}^c, \forall i\in\mathbf{C} \\ 0\le P_j^d \le P_{\max}^d, \forall j\in\mathbf{D} \end{cases} \tag{16}$$

Assuming that the cellular user i allows the D2D pair j to share its channel resource, i.e., $f(i,j)=1$ meet, by first checking that the transmit power combination (P_i^c, P_j^d) of BS and D2D user is satisfied, when a cellular user and D2D pair are ensured with only the minimum QoS demand

$$\begin{cases} \text{Prob}\left\{\gamma_i^c = \dfrac{P_i^c g_{B,i}}{\sigma_n^2 + P_j^d h_{j,i}} \le \gamma_{i,\min}^c\right\} = \delta \\ \gamma_j^d = \dfrac{P_j^d g_j^i}{\sigma_n^2 + P_i^c h_{B,j}^i} = \gamma_{j,\min}^d \end{cases} \tag{17}$$

For cellular users i, when the minimum QoS demand is satisfied, it can be obtained from (17) (P_i^c, P_j^d) and is determined by the following equation

$$\begin{aligned}\text{Prob}\left\{\gamma_i^c=\frac{P_i^c g_{B,i}}{\sigma_n^2+P_j^d h_{j,i}}\le\gamma_{i,\min}^c\right\}&=\text{Prob}\left\{h_{j,i}\ge\frac{P_i^c g_{B,i}-\gamma_{i,\min}^c\sigma_n^2}{P_j^d\gamma_{i,\min}^c}\right\}\\&=1-\text{Prob}\left\{h_{j,i}\le\frac{P_i^c g_{B,i}-\gamma_{i,\min}^c\sigma_n^2}{P_j^d\gamma_{i,\min}^c}\right\}\\&=1-\text{Prob}\left\{\chi_{j,i}\le\frac{P_i^c g_{B,i}-\gamma_{i,\min}^c\sigma_n^2}{P_j^d\gamma_{i,\min}^c\left(\kappa d_{j,i}^{-\alpha}\right)}\right\}\\&=\delta\end{aligned}\tag{18}$$

The equation can be rewritten as

$$\text{Prob}\left\{\chi_{j,i}\le\frac{P_i^c g_{B,i}-\gamma_{i,\min}^c\sigma_n^2}{P_j^d\gamma_{i,\min}^c\left(\kappa d_{j,i}^{-\alpha}\right)}\right\}=1-\delta\tag{19}$$

A Rayleigh fading channel is assumed as the channel fading model and its fading component $\chi_{B,i}$ obeys an exponential distribution and is assumed to have a mean of 1. Its cumulative distribution function is

$$F(x)=\begin{cases}1-e^{-x} & x\ge 0\\ 0 & x<0\end{cases}\tag{20}$$

Substitution (19) into (20), we get the following linear relationship

$$P_i^c g_{B,i}-\gamma_{i,\min}^c\sigma_n^2=-P_j^d\gamma_{i,\min}^c\left(\kappa d_{j,i}^{-\alpha}\right)\ln(\delta)\tag{21}$$

For the D2D user j , when the minimum QoS demand is satisfied, it can be obtained from (17) that (P_i^c,P_j^d) has the following linear relationship

$$\frac{P_j^d g_j^i}{\sigma_n^2+P_i^c h_{B,j}^i}=\gamma_{j,\min}^d\tag{22}$$

The above equation is rewritten as

$$P_j^d g_j^i=P_i^c h_{B,j}^i\gamma_{j,\min}^d+\sigma_n^2\gamma_{j,\min}^d\tag{23}$$

It can be observed from (21) and (23) that when paired cellular and D2D users fulfill the minimum QoS requirement, (P_i^c,P_j^d) satisfies two linear relationships. The intersection indicates the attainment of the minimum value. The closed-form expression for the minimum transmits power combination (P_i^c,P_j^d) can be derived by associating (21) with (13).

$$\begin{cases}P_{i,\min}^c=\dfrac{\gamma_{i,\min}^c\sigma_n^2 g_j^i-A\gamma_{j,\min}^d\sigma_n^2}{g_{B,i}g_j^i+A\gamma_{j,\min}^d h_{B,j}^i}\\[2ex] P_{j,\min}^d=\dfrac{\gamma_{j,\min}^d\sigma_n^2(g_{B,i}+h_{B,j}^i)}{g_{B,i}g_j^i+A\gamma_{j,\min}^d h_{B,j}^i}\end{cases}\tag{24}$$

in which,

$$A=\gamma_{i,\min}^c\left(\kappa d_{j,i}^{-\alpha}\right)\ln(\delta)\tag{25}$$

if and only if

$$P_{i,\min}^c\in\left(0,P_{\max}^c\right]\tag{26}$$

$$P_{j,\min}^{d} \in \left(0, P_{\max}^{d}\right] \tag{27}$$

When both hold, the D2D user j is permitted to reuse the cellular user's channel resources i. Thus (26) and (27) constitute the access control policy for D2D users. By checking the access conditions, all candidate cellular users can be found for each D2D pair.

3.2 Power Control Algorithm

The access control strategy can reduce the search range for the power control algorithm. Assuming that the channel allocation for D2D users has been completed, only the subproblem of power control of paired cellular users with D2D users is taken into account. For any cellular and D2D pair combination, its EE optimization problem can be rewritten as

$$\max_{(P_i^c, P_j^d)} \eta_j^{ee} \tag{28}$$

$$\text{s.t.} \quad \text{Prob}\left\{\gamma_i^c = \frac{P_i^c g_{B,i}}{\sigma_n^2 + P_j^d h_{j,i}} \le \gamma_{i,\min}^c\right\} \le \delta, \forall i \in \mathbf{C} \tag{29}$$

$$\gamma_j^d = \frac{P_j^d g_j^i}{\sigma_n^2 + P_i^c h_{B,j}^i} \ge \gamma_{j,\min}^d, \forall j \in \mathbf{D} \tag{30}$$

$$0 \le P_i^c \le P_{\max}^c, \forall i \in \mathbf{C} \tag{31}$$

$$0 \le P_j^d \le P_{\max}^d, \forall j \in \mathbf{D} \tag{32}$$

η_j^{ee} can be rewritten as

$$\eta_j^{ee} = \frac{R_j^d}{P_j^{total}} = \frac{W_0 \log_2\left(1 + \frac{P_j^d g_j^i}{\sigma_n^2 + P_i^c h_{B,j}^i}\right)}{\omega_j P_j^d + 2P_0} \tag{33}$$

It can be seen that when the transmission power P_j^d of the D2D pair j fixed, as P_i^c decreases, the EE increases. That is when (P_i^c, P_j^d) satisfying the linear relationship of (21), the D2D user can achieve the optimal EE. i.e., if and only if,

$$P_i^c = \frac{\gamma_{i,\min}^c \sigma_n^2 - P_j^d \gamma_{i,\min}^c \left(\kappa d_{j,i}^{-\alpha}\right) \ln(\delta)}{g_{B,i}} \tag{34}$$

the EE η_j^{ee} achieves its maximum value when it holds.

From the above analysis, the following lemma can be obtained

Lemma 1. When η_j^{ee} is maximized, the optimal transmit power combination (P_i^{c*}, P_j^{d*}) satisfies the following linear relationship

$$P_i^{c*} = \frac{\gamma_{i,\min}^c \sigma_n^2 - P_j^{d*} \gamma_{i,\min}^c \left(\kappa d_{j,i}^{-\alpha}\right) \ln(\delta)}{g_{B,i}} \tag{35}$$

The feasible domain intervals (P_i^c, P_j^d) according to (29), (30), (31), and (32), as well as the linear relationship of the optimal transmit power combinations (P_i^{c*}, P_j^{d*}) in the above-cited reasoning, can be depicted in **Fig. 2**.

In **Fig. 2**, the horizontal and vertical coordinates represent the transmit power of BS and D2D users, respectively, where the rectangular region is enclosed by the maximum transmit power combination $(P_{\max}^{c}, P_{\max}^{d})$, and the straight lines $l_{i,j}^{c}$ and $l_{i,j}^{d}$ represent the linear relationship between the cellular user and D2D user. The intersection of the two lines represents the minimum transmit power combination. The shaded area represents all the feasible regions. The line segment represented by the solid red line is the possible region of the optimal transmit power (P_i^{c*}, P_j^{d*}). Therefore, in order to find (P_i^{c*}, P_j^{d*}), it is only necessary to search within this line segment. **Fig. 2(a)** and **Fig. 2(b)** represent two possible feasible domain scenarios, where **Fig. 2(a)** represents the case the D2D user can obtain the maximum transmit power $P_{\max}^{d}$ and **Fig. 2(b)** shows the situation where the D2D user's maximum power is outside the feasible range. The maximum power the D2D user can currently use is given by (34)

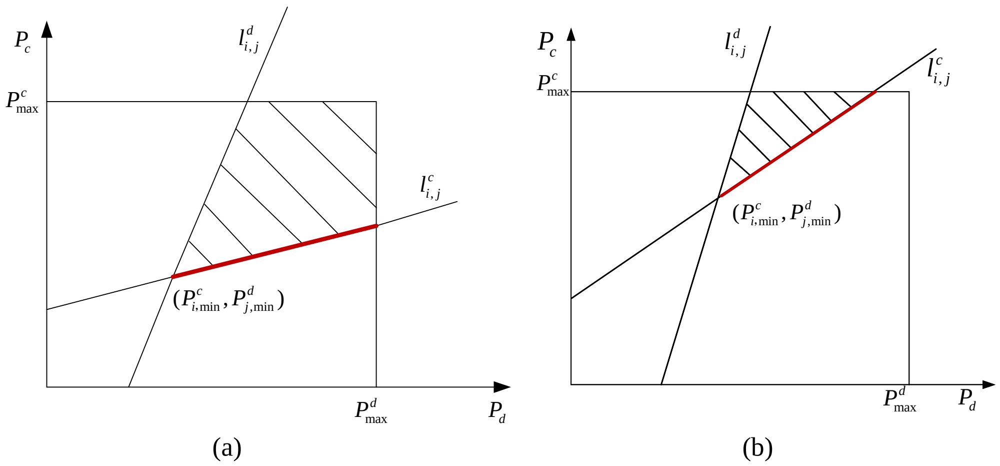

Fig. 2. Feasible domains for BS and D2D.

$$P_{j,\max}^{d} = \frac{\gamma_{i,\min}^{c}\sigma_n^2 - P_{\max}^{c} g_{B,i}}{\gamma_{i,\min}^{c}\left(\kappa d_{j,i}^{-\alpha}\right)\ln(\delta)} \tag{36}$$

As described in **Lemma 1**, the power control problem can be simplified to a power control problem with only the D2D user transmit power P_j^d. The optimization problem can be rewritten as

$$P_j^{d*} = \arg\max_{P_j^d} \eta_j^{ee} \tag{37}$$

It can be found that the objective function η_j^{ee} is a nonlinear fractional programming problem, which is difficult to resolve directly. According to [25], it is shown that the nonlinear fractional planning problem can be resolved by converting it into the form of the difference between the numerator and the denominator by the Dinkelbach algorithm. Thus, (37) is equivalent to solving the following optimization problem

$$\begin{aligned} \arg\max_{P_j^d} \eta_j^{ee} &\Leftrightarrow \arg\max_{P_j^d} \left\{ R_j^d - \eta_j^{ee*} P_j^{total} \right\} = 0 \\ &\Leftrightarrow \arg\max_{P_j^d} \left\{ W_0 \log_2\left(1 + \frac{P_j^d g_j^i}{\sigma_n^2 + P_i^c h_{B,j}^i}\right) - \eta_j^{ee*}\left(\omega_j P_j^d + 2P_0\right) \right\} = 0 \end{aligned} \tag{38}$$

where, η_j^{ee*} denotes the optimal EE. The proof is given in Appendix A.

The above equation shows that a sufficiently necessary condition for optimal EE to be achieved is the following equation holds, if and only if

$$\max_{P_j^d}\left\{W_0\log_2\left(1+\frac{P_j^d g_j^i}{\sigma_n^2+P_i^c h_{B,j}^i}\right)-\eta_j^{ee*}\left(\omega_j P_j^d+2P_0\right)\right\}=0 \tag{39}$$

Meanwhile, the D2D user transmits power satisfying (39) is the optimal transmit power P_j^{d*}.

So far, the original power control problem has been transformed into the solution of (39) by variable substitution and nonlinear fractional transformation equivalence. Also, for the objective function expression in (39), the following derivation is made:

Lemma 2. The objective function expression

$$W_0\log_2\left(1+\frac{P_j^d g_j^i}{\sigma_n^2+P_i^c h_{B,j}^i}\right)-\eta_j^{ee*}\left(\omega_j P_j^d+2P_0\right)$$

is a concave function of the transmit power P_j^d .

The proof is given in Appendix B.

Herein, the power control problem can be transformed into a single-variable solution for the D2D user's transmit power P_j^d and transformed into the solution of a convex optimization problem, so that the solution can be further obtained by using the bisection method, and an iterative power based on the nonlinear fractional transformation and bisection method is proposed. The specific implementation steps are shown in Algorithm 1.

Algorithm 1: Iterative power control algorithm based on nonlinear fractional transforms and bisection
1. Initialize the number of iterations $k=1$ and the iteration termination error Δ , $\eta_j^{ee}(1)=0$;
2. **repeat**
3. Solve for $P_j^d(k+1)=\arg\max_{P_j^d}\left\{R_j^d-\eta_j^{ee}(k)P_j^{total}\right\}$;
4. Bisection method for the convex optimization problem in step 3;
5. **if** $\left\|R_j^d\left(P_j^d(k+1)\right)-\eta_j^{ee}(k)P_j^{total}\left(P_j^d(k+1)\right)\right\|\le\Delta$ **then**
6. $\eta_j^{ee*}=\eta_j^{ee}(k)$, $P_j^{d*}=P_j^d(k+1)$;
7. **break**
8. **else**
9. Updating EE $\eta_j^{ee}(k+1)=\left.\frac{R_j^d}{P_j^{total}}\right\|_{P_j^d=P_j^d(k+1)}$, $k=k+1$;
10. **end if**
11. **until** converge
12. **return Optimal** Transmit Power P_j^{d*} and Maximum EE η_j^{ee*} .

The convergence analysis for Algorithm 1 can be given by the following lemma

Lemma 3. During each iteration, the EE $\eta_j^{ee}(k)$ monotonically increases with the sequence of generated transmit power $P_j^d(k)$ and eventually converges to the optimal EE η_j^{ee*} .

The proof is given in Appendix C.

3.3 Channel allocation algorithm

Next, it is necessary to design an effective channel allocation strategy to optimize the performance of the whole system. At this point, the channel allocation problem is simplified as follows

$$\max_{f(i,j)} \sum_{i=1}^{N} \sum_{j=1}^{M} f(i,j)\eta_j^{ee*} \tag{40}$$

$$\sum_{j\in \mathbf{D}_{i,j}} f(i,j) \le 1, \forall i \in \mathbf{C} \tag{41}$$

$$\sum_{i\in \mathbf{C}_{i,j}} f(i,j) \le 1, \forall j \in \mathbf{D} \tag{42}$$

where $\mathbf{D}_{i,j}$ denotes the D2D pairs set that satisfies the reuse condition of cellular users i according to the access control strategy, and $\mathbf{C}_{i,j}$ denotes cellular users set which can be reused for D2D users j.

The above channel allocation problem can be found as an optimal solution by performing a global search with the Hungarian algorithm [26] or the weighted bipartite graph matching algorithm [27]. However, the algorithmic complexity is high, for example, the Hungarian algorithm has an algorithmic complexity of $O(\max(N,M)^3)$. Meanwhile, the existing algorithms take the overall performance optimization as the allocation objective, which makes the D2D users with lower EE unable to access, resulting in the decrease of the D2D users' access rate, as well as the deterioration of the fairness of the system allocation.

The fairness of EE among D2D users can be expressed by the following fairness index

$$F = \frac{\left[\sum_{j=1}^{M} \eta_j^{ee*}\right]^2}{M\sum_{j=1}^{M}\left[\eta_j^{ee*}\right]^2} \tag{43}$$

Among them, the fairness index F denotes a real number taking the value of $(0,1]$. When $F=1$ indicates that the optimal EE between D2D users is equal, and the distribution fairness is optimal; on the contrary, when F tends to 0, the optimal EE between D2D users differs greatly, and the distribution fairness between users is the worst.

This section proposes a fast channel allocation algorithm with guaranteed fairness. In this algorithm, the main steps include: in each allocation process, finding the set of D2D users with the lowest number of reusable cellular user channels, and using the Hungarian algorithm for optimal channel allocation between the D2D users involved and the cellular users, and then deleting the paired users, and repeating the above steps until the allocation is completed. The advantages of the above algorithm are: that it ensures the possibility of D2D users with poor access performance to access the cellular network and reduces algorithm complexity by performing the optimal allocation of smaller matrices several times.

Algorithm 2: Fast channel allocation algorithm based on allocation fairness guarantee
1. Find the set of D2D reusable cellular users $\mathbf{C}_{i,j}$ according to (24), (26), and (27);
2. Calculate the number of channels that can be multiplexed per D2D user $Num_j = \lvert \mathbf{C}_{i,j} \rvert$;
3. Find $j = \arg\min\{Num_j\}$;
4. Implementation of the Hungarian algorithm;
5. Delete the paired users i and j;

6. **if** $|M| = 0$ or $|N| = 0$ **then**
7. The allocation is completed with the output $f(i, j)$;
8. **break**
9. **else**
10. Update the users i , j and repeat step 1;
11. **end if**

4. Numerical simulations

The simulation takes into account a single-cell network, in which the BS is situated at the center and has a coverage radius of 1000 meters. All the transmitters of both cellular users and D2D users are randomly distributed at any radius and angle. The receivers of D2D are randomly distributed at any angle within a circle centered on the transmitter of D2D, with a maximum transmission distance ranging from 20 to 100 meters. The specific parameters are presented in **Table 2**.

Table 2. Simulation parameters

Simulation Parameters	retrieve value
Cell radius	1000 m
Maximum transmit power of BS on each channel $P^c_{\max}$	23dBm
Maximum transmit power for D2D users $P^d_{\max}$	21dBm
Number of cellular users N	20
Path loss model for D2D pass-through links	$148 + 40\lg(d / Km)$ dB
Path loss model for other links	$128.1 + 37.6\lg(d / Km)$ dB
Riley fading channel	Exponential distribution with mean value 1
Fixed circuit power consumption P_0	10 dBm
Minimum SINR requirement for D2D users $\gamma^d_{j,\min}$	10dB
Minimum SINR requirement for cellular users $\gamma^c_{i,\min}$	0dB ~ 20dB
Cellular user interrupt threshold probability δ	0.1
Noise Power σ^2_n	-114dBm

To better demonstrate the performance advantages of the proposed algorithm, the following existing typical power control and channel algorithms are chosen for comparison, including similar to the power control algorithms in [18] that take the minimum energy consumption (MEC) as the optimization objective and the Hungarian algorithm based on the optimal channel allocation (KM); the Hungarian algorithm based on the Inverse Popularity Pairing Order (IPPO), where the D2D user with the smallest number of reusable channels and the cellular user with the least number of accessible users form a reuse partner; as well as a Random channel allocation algorithm (Random).

Fig. 3 compares the effect of utilizing different channel allocation algorithms on the EE of D2D under the proposed optimal power control algorithm. It shows that the Hungarian algorithm has the best allocation performance. However, as per the previous analysis, the Hungarian algorithm is marked by high algorithmic complexity and low allocation fairness. Our proposed algorithm has low complexity and still achieves a significant performance improvement compared to the other algorithms. The reason for this is that the algorithm grants higher priority to D2D users with fewer reusable channels to allow more D2D users to access the network and further enhances the allocation performance by combining with the Hungarian algorithm.

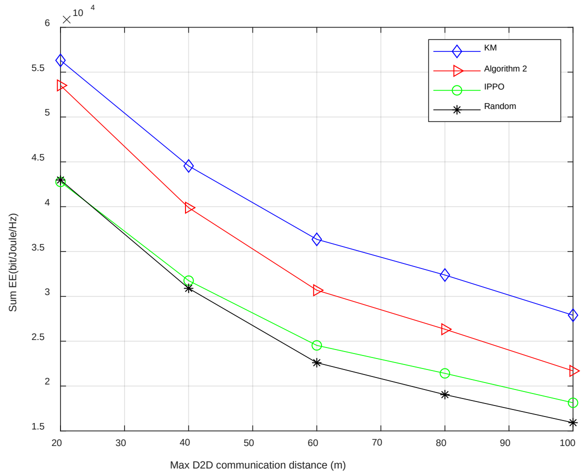

Fig. 3. EE with different D2D communication distances.

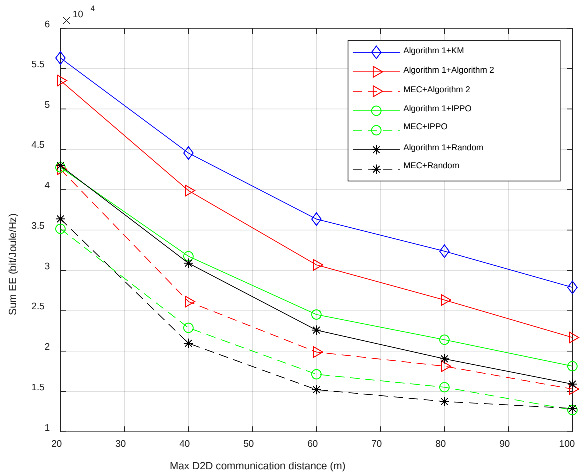

Fig. 4. EE under different joint power control and channel allocation algorithms.

A comparison of EE with different algorithms is given in **Fig. 4**. From the figure, the EE is greatly improved by the proposed algorithm 1 with different channel allocation algorithms compared to the MEC power control algorithm. This is because the power control algorithm that reduces the system energy consumption by minimizing the combination of transmit power does not necessarily bring about the optimality of the system energy EE, however, the proposed algorithm for controlling power has the optimization objective of optimizing the EE of the D2D communication users while guaranteeing the QoS of both cellular and D2D users.

Fig. 5 presents the influence of the minimum SINR requirement of cellular users on EE. From this figure, it can be observed that the EE of all algorithms declines as the SINR requirement of cellular users increases. There are three reasons for this phenomenon. Firstly, meeting the QoS guarantee of cellular users causes the number of D2D users capable of accessing the cell to decrease. Secondly, the increase in the transmit power of cellular users leads to enhanced cross-layer interference, thereby reducing the EE. Finally, the rise in the QoS requirements of cellular users results in a smaller feasible domain of transmit power for

D2D users, further worsening the system performance. Nevertheless, the figure still indicates that when the power control algorithm 1 proposed is adopted, all of them have varying degrees of performance improvement compared to the comparison algorithms. Meanwhile, the channel allocation algorithm 2 proposed has an EE that is second only to the Hungarian algorithm.

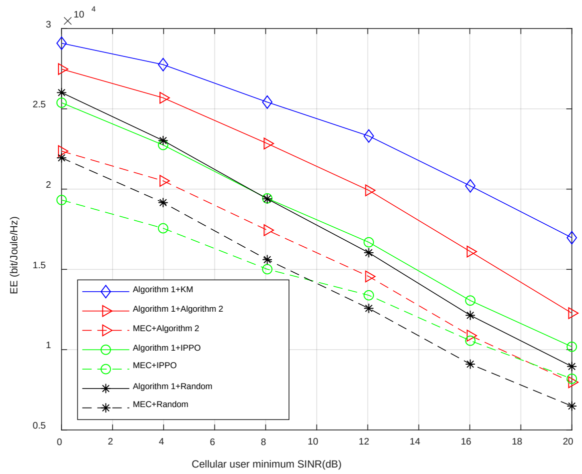

Fig. 5. Impact of cellular user minimum SINR on EE.

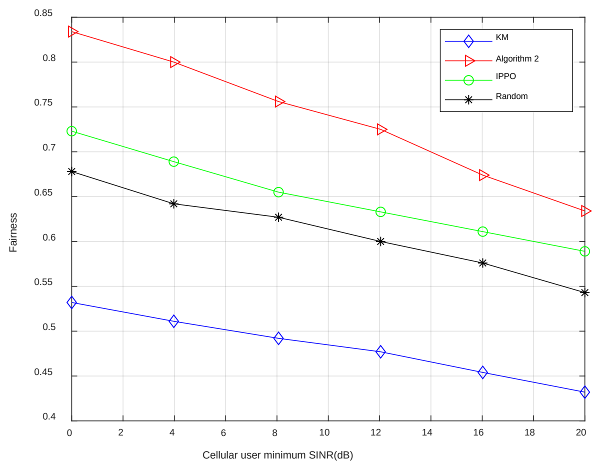

Fig. 6. Allocation fairness under different SINRs of cellular users.

Fig. 6 gives the allocation fairness under different cellular users' SINR requirements. The figure shows that the proposed channel allocation algorithm 2 further improves the allocation fairness compared to the comparison algorithm, thanks to the fact that the algorithm sets a higher allocation priority for the D2D users with a low number of reusable channels, and also allocates them with EE cellular channels, instead of allocating the worst-performing channels for the D2D users with poor access performance, as in the case of the IPPO algorithm.

Fig. 7 shows the impact of the number of D2D users on EE. From the figure, EE gradually increases as D2D users increase. We can also see that algorithm 2 obtains a performance second only to the Hungarian algorithm when the same power control algorithm is used. Moreover, it achieves performance close to the optimal allocation algorithm when the number of D2D users is not greater than the number of cellular users, which is because Algorithm 2 is a fairness-guaranteed allocation algorithm, and in the case of a small number of D2D users, it can improve the fairness of the allocation without minimizing the performance loss. Similarly, the power control algorithm proposed also leads to an improvement in EE when the same channel allocation algorithm is used.

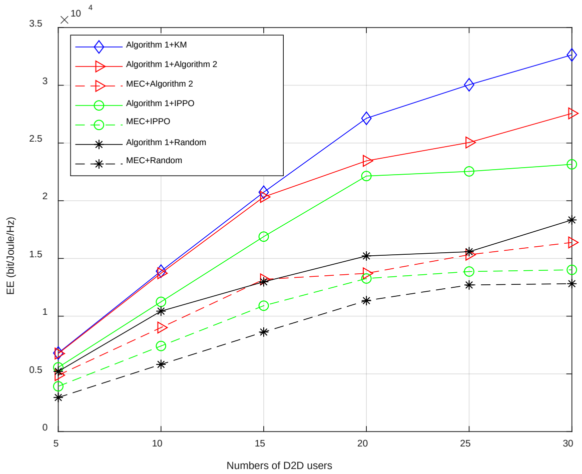

Fig. 7. EE under different numbers of D2D users.

5. Discussion

In centralized power control and channel allocation strategies for interference-limited D2D networks with a dense array of transceivers, acquiring comprehensive CSI is crucial. However, this process incurs substantial signaling overhead, which can become particularly burdensome in practical systems. As referenced in works [17], [18], [20], [21], [22], and [23], while it is feasible to develop centralized and scalable resource allocation policies for large-scale, dynamic D2D networks, the associated signaling costs can escalate rapidly with network expansion. This overhead encompasses the demands of both CSI estimation and the exchange of information between nodes. The process begins with nodes obtaining CSI for various wireless links, including those for direct communication and neighboring interference. Subsequently, nodes engage in multiple rounds of CSI exchange. In large-scale D2D networks, the signaling overhead can overshadow the benefits and adversely impact system performance. To address this, our research focuses on crafting distributed power allocation schemes that minimize signaling overhead by leveraging statistical CSI. Specifically, our approach requires nodes to estimate only the statistical properties of the CSI for indirect interference links, thereby simplifying the algorithm and eliminating the need for frequent and precise updates characteristic of perfect CSI. Additionally, the real-world measurement of instantaneous CSI can be delayed, particularly in rapidly changing environments, which diminishes its effectiveness. For instance, the subframe duration in 5G New Radio is as short as 1 ms, and the maximum frame duration in Wi-Fi 802.11ac is 5.5 ms. Given these timeframes, relying on statistical CSI, as proposed in this paper, presents a more practical assumption, aligning closely with the operational realities of modern communication networks.

6. Conclusion

In short, this paper puts forward a joint power control and channel allocation algorithm based on statistical CSI and QoS awareness. The algorithm takes into account that the BS is unable to grasp the perfect CSI of the cross-layer interference link between D2D users and cellular users; instead, it considers the statistics of its channel fading component, to ensure that the transmission rate requirement of the cellular user is lower than the maximum allowable interruption probability. The optimal transmit power combination between D2D users and potential cellular users is provided. Finally, to solve the channel allocation problem, a fast channel allocation algorithm is offered. Simulation results demonstrate that our proposed algorithm has advantages in enhancing the EE for D2D communication with statistical CSI and increases the access probability of D2D users while achieving the fairness of resource allocation. The algorithm proposed in this paper is closer to the real scenario and practical to some extent.

Appendix

Appendix A

The necessity proof is first given that for any feasible D2D user transmit power P_j^d , and $P_j^d \neq P_j^{d*}$, then the following equation holds

$$\eta_j^{ee*} = \frac{R_j^d\left(P_j^{d*}\right)}{P_j^{total}\left(P_j^{d*}\right)} > \frac{R_j^d\left(P_j^d\right)}{P_j^{total}\left(P_j^d\right)} \tag{44}$$

The above equation can be further rewritten as

$$R_j^d\left(P_j^{d*}\right) - \eta_j^{ee*} P_j^{total}\left(P_j^{d*}\right) = 0 \tag{45}$$

$$R_j^d\left(P_j^d\right) - \eta_j^{ee*} P_j^{total}\left(P_j^d\right) < 0 \tag{46}$$

Therefore, the maximum value $R_j^d - \eta_j^{ee*} P_j^{total}$ is 0, obtained when and only when the D2D user transmits power is the optimal transmit power P_j^{d*} .

A sufficiency proof is given next, assuming that any feasible D2D transmit power P' is satisfied

$$R_j^d\left(P_j^d\right) - \eta_j^{ee*} P_j^{total}\left(P_j^d\right) < R_j^d\left(P'\right) - \eta_j^{ee*} P_j^{total}\left(P'\right) = 0 \tag{47}$$

The transformation of (47) has

$$\eta_j^{ee*} = \frac{R_j^d\left(P'\right)}{P_j^{total}\left(P'\right)} > \frac{R_j^d\left(P_j^d\right)}{P_j^{total}\left(P_j^d\right)} \tag{48}$$

Thus P' is the optimal transmit power for D2D users, i.e., $P' = P_j^{d*}$. The proof is complete.

Appendix B

The $-\eta_j^{ee*}\left(\omega_j P_j^d + 2P_0\right)$ part of the expression is an affine function about P_j^d . From the literature [28], the affine function is both convex and concave, which does not affect the concavity of the overall expression. From **Lemma 1**, P_i^c and P_j^d satisfy the linear relationship, the expression in the first part is rewritten as

$$
\begin{aligned}
&W_0 \log_2\left(1+\frac{P_j^d g_j^i}{\sigma_n^2+P_i^c h_{B,j}^i}\right)\\
&=W_0 \log_2\left(1+\frac{P_j^d g_j^i g_{B,i}}{\sigma_n^2 g_{B,i}+\gamma_{i,\min}^c \sigma_n^2 h_{B,j}^i-P_j^d \gamma_{i,\min}^c\left(\kappa d_{j,i}^{-\alpha}\right)\ln(\delta) h_{B,j}^i}\right)\\
&=W_0 \log_2\left(1+\frac{P_j^d g_j^i g_{B,i}}{B-CP_j^d}\right)
\end{aligned}
\tag{49}
$$

among them

$$B=\sigma_n^2 g_{B,i}+\gamma_{i,\min}^c \sigma_n^2 h_{B,j}^i \tag{50}$$

$$C=\gamma_{i,\min}^c\left(\kappa d_{j,i}^{-\alpha}\right)\ln(\delta) h_{B,j}^i \tag{51}$$

A second-order derivation of (49) with respect to P_j^d gives the following expression for the numerator part of the second-order derivative

$$2BC-2C^2P_j^d-g_j^i g_{B,i}B+2g_j^i g_{B,i}CP_j^d \tag{52}$$

Since $B>0$, $C<0$ and $P_j^d>0$ are constant, the second-order derivative of (49) with respect to P_j^d is always less than 0. According to the theory of convex optimization introduced in [28], it can be seen that (49) is a concave function with respect to P_j^d . From the convexity-preserving operation, the sum of the concave function and the affine function is still a concave function. The proof is complete.

Appendix C

For any cellular user i multiplexed with D2D user j , assume that $P_j^d(k)$ denotes the transmit power of D2D user j during the k iteration, $\eta_j^{ee}(k)$ and $\eta_j^{ee}(k+1)$ represent the EE during the k iteration and $k+1$ iteration, respectively. η_j^{ee*} denotes the optimal EE and $\eta_j^{ee}(k)\neq\eta_j^{ee*}$.

From the definition of EE, the following equation holds

$$\eta_j^{ee}(k)=\left.\frac{R_j^d}{P_j^{total}}\right|_{P_j^d=P_j^d(k)} \tag{53}$$

$$\eta_j^{ee}(k+1)=\left.\frac{R_j^d}{P_j^{total}}\right|_{P_j^d=P_j^d(k+1)} \tag{54}$$

By variation of the equation, (53) and (54) are equivalent to

$$R_j^d\left(P_j^d(k)\right)=\eta_j^{ee}(k)P_j^{total}\left(P_j^d(k)\right) \tag{55}$$

$$R_j^d\left(P_j^d(k+1)\right)=\eta_j^{ee}(k+1)P_j^{total}\left(P_j^d(k+1)\right) \tag{56}$$

In Algorithm 1, the $k+1$ iteration of the transmit power $P_j^d(k+1)$ is given by the following equation

$$P_j^d(k+1)=\arg\max_{P_j^d}\left\{R_j^d\left(P_j^d(k)\right)-\eta_j^{ee}(k)P_j^{total}\left(P_j^d(k)\right)\right\} \tag{57}$$

That is, $P_j^d(k+1)$ is the solution that $R_j^d\left(P_j^d(k)\right)-\eta_j^{ee}(k)P_j^{total}\left(P_j^d(k)\right)$ obtains its maximum value, and thus the following equation holds

$$\begin{aligned}&R_j^d\left(P_j^d(k+1)\right)-\eta_j^{ee}(k)P_j^{total}\left(P_j^d(k+1)\right)\\&>R_j^d\left(P_j^d(k)\right)-\eta_j^{ee}(k)P_j^{total}\left(P_j^d(k)\right)\\&=0\end{aligned}\tag{58}$$

where the inequality part of the above equation is obtained from the proof of (57) $\eta_j^{ee}(k)\neq\eta_j^{ee*}$ and the equality part can be obtained from the definition of (55). Bringing (55) and (56) into (58), the following form can be obtained

$$\begin{aligned}&R_j^d\left(P_j^d(k+1)\right)-\eta_j^{ee}(k)P_j^{total}\left(P_j^d(k+1)\right)\\&=\eta_j^{ee}(k+1)P_j^{total}\left(P_j^d(k+1)\right)-\eta_j^{ee}(k)P_j^{total}\left(P_j^d(k+1)\right)\\&=\left(\eta_j^{ee}(k+1)-\eta_j^{ee}(k)\right)P_j^{total}\left(P_j^d(k+1)\right)\\&>R_j^d\left(P_j^d(k)\right)-\eta_j^{ee}(k)P_j^{total}\left(P_j^d(k)\right)\\&=0\\&\Rightarrow\eta_j^{ee}(k+1)>\eta_j^{ee}(k)\end{aligned}\tag{59}$$

where the first equation is obtained from the definitions of (55) and (56). Equation (59) proves that the EE η_j^{ee} monotonically increases during the iteration process and will eventually converge to the optimal EE η_j^{ee}. The proof is complete.

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