

Energy-Efficient Resource Allocation for High-Rate Underlay D2D Communications With Statistical CSI: A One-to-Many Strategy

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Abstract—For the prominent superiorities in energy and spectrum efficiency, Device-to-Device (D2D) communication has become a hot topic among the 5th generation (5G) technologies. However, the widely adopted mode that one or more D2D links reuse one cellular user's uplink spectrum may lead to severe limitation on D2D communication rate, especially when cellular user's uplink spectrum is very limited. In this paper, we will face the high rate requirements of D2D pairs (DPs), with the help of carrier aggregation technology, each DP can reuse the uplink spectrum of multiple cellular users when needed. More practically, we consider that only statistical channel state information (CSI) of certain communication links is available here. Then, we formulate the problem to minimize the total power consumption of the mobile devices to obtain an energy-efficient resource allocation result, including spectrum and power allocation. Meanwhile, the quality of service (QoS) requirements of cellular and high-rate D2D communications are both ensured. The formulated problem is mathematically a non-convex mixed-integer nonlinear programming (MINLP) problem, which is NP-hard. To solve it, we first tighten the constraints and deploy transformation methods on it to make it convex. Then, we propose a two-layer algorithm, the independent-power greedy-based outer approximation (IPGOA), to solve the transformed problem. Besides, to handle the involved uniform power allocation circumstance in the carrier aggregation process, a uniform-power GOA (UPGOA) algorithm, which can be regarded as a simplified version of IPGOA, is also proposed. The simulation results show that in different scenarios, our proposed scheme is approximately optimal.

Index Terms—D2D communications, spectrum and power allocation, high-rate, carrier aggregation, outage probability, non-convex MINLP.

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I. INTRODUCTION

THE upcoming 5th generation (5G) communication has put forward higher requirements on cellular systems, especially in the aspects of transmission rate, system capacity, etc [1], and these new requirements have inspired researchers to develop more promising communication paradigms. Device-to-Device (D2D) communication, as a communication pattern that enables direct communication between user equipments (UEs), has attracted much attention for the benefit of helping cellular networks to achieve higher energy and spectrum efficiency, etc [2], [3]. With D2D communications, the UEs that are within certain proximity to each other do not need to pass through the base station (BS) to share contents. Moreover, D2D communications are also enabled to reuse the spectrum allocated to cellular users (CUs), which is effective for alleviating the scarcity of licensed spectrum and has attracted much attention [4].

In D2D communications, the underlay D2D communication [2], [5] is mostly investigated for the feature of reusing some of the spectrum allocated to cellular communications. In underlay mode, one crucial issue is the interference coordination between CUs and D2D pairs (DPs) [6]–[10]. Within the spectrum reusing modes in underlay D2D communication, reusing the uplink spectrum of cellular users is usually preferred, because the BS may cause serious interference to D2D communications during downlink transmission if D2D links reuse the downlink spectrum of CUs [5]. Most published literatures adopted the one-to-one (one DP reuses one CU's spectrum) or many-to-one (many DPs reuse one CU's spectrum) spectrum reusing scheme for various purposes, like simplicity of deployment or purely for higher spectrum efficiency, etc [6]–[14]. While the popularity of mobile social media sharing has put forward unprecedented demand for higher transmission rate to ensure users' Quality of Experience (QoE), but the cruel reality is that the cellular uplink spectrum is usually scarce, and the uplink spectrum allocated to each CU is usually narrow [15]. Thus both schemes above come with an inherent drawback, i.e., a DP is generally not able or allowed to transmit with high data rate due to the limited bandwidth of a CU, simply increasing the transmit power cannot bring significant improvements under the interference and power limits. Therefore, it is exigent to investigate how to meet the increasing demand of higher transmission rate in D2D communications.

The technology focusing on aggregating multiple spectrum is called carrier aggregation (CA), and it has been developed in the past years and implemented in cellular networks like the Long Term Evolution-Advanced (LTE-A) systems [16]–[18]. CA was also proposed to integrated into D2D communication systems [19]. With the aid of CA techniques, a DP will be able to reuse the uplink spectrum of multiple CUs, thus this provides us a new inspiration to deal with the above problem. Moreover, the increasing demand on high-rate communication may also lead to the increase of power consumption, while only little progress has been made in battery technologies. Thus, energy-efficient methods should be deployed to make full use of the limited energy in UEs while guaranteeing the QoS of communications.

In this paper, we propose to combine the CA technology to meet the high rate requirements of DPs, where the one-to-many strategy is considered, i.e., a DP can reuse no less than one CU's uplink spectrum. However, full channel state information (CSI) is generally unavailable due to the time-varying characteristic of channels [20], [21]. Thus, we consider that only partial instantaneous CSI of links is available here [20], as for the D2D and interference links, only statistical CSI is available. In order to obtain an energy-efficient resource allocation result, we aim to minimize the total power consumption of CUs and DPs while meeting their QoS requirements with only statistical (partial) CSI. Therefore, the major contributions can be summarized as follows:

- 1) We propose to use the CA technology in D2D communications to meet the high rate requirements of DPs, and we aim to accomplish the spectrum and power allocation to minimize the total power consumption of mobile devices under only statistical (partial) CSI. Especially, the QoS requirements of DPs, where each DP may reuse the uplink spectrum of multiple CUs, are ensured in the form of outage probability from the entire DP's perspective, rather than separately from each reused spectrum's perspective. To the best of our knowledge, it is the first time that this synthesis issue is considered. And the formulated problem is mathematically a MINLP problem which has been proven to be NP-hard.
- 2) To address the formulated problem, due to the difficulty of directly solving it, we first deploy transformation and variable substitution methods to make the problem more tractable. After that, the resource allocation of CUs is coupled into the resource allocation of DPs, and the problem becomes concave under specific conditions. Then we propose a two-layer algorithm, the independent-power greedy-based outer approximation (IPGOA), to solve the transformed problem. Furthermore, we have also considered the uniform power allocation circumstance in CA technology, and then propose the uniform-power GOA (UPGOA) algorithm.
- 3) At last, simulation results are presented to assess the effectiveness of the proposed methods. The proposed IPGOA algorithm can closely approach the optimal result, and the UPGOA can also obtain distinguished results in some circumstances. Further more, deployment scenarios are also distinguished in the comparison results.

The remainder of this paper is organized as follows. Some related works are presented in Section II. In Section III, the system model is depicted in the aspect of network and spectrum reusing model, channel model, problem formulation respectively. Section IV focuses on the analysis and transformation of the mathematical problem. In Section V, the two proposed methods IPGOA and UPGOA as well as a space compression method for spectrum allocation are elaborated in detail. Numerical simulations and comparison results are shown in Section VI. Finally, Section VII concludes this paper.

II. RELATED WORKS

Researchers have been working on the spectrum and power allocation issue in D2D communications [6]–[9], where maximizing the communication rates has received much attention. Hoang *et al.* [6] took the proportional fairness of communication rate into consideration during resource allocation. Luo *et al.* [7] proposed an iterative algorithm as well as a heuristic one with lower complexity to maximize the system sum rate in energy harvesting scenario, but a single D2D link can only reuse one CU's uplink spectrum. Authors in [8] proposed to maximize the sum rate of D2D communications with optimization and game theoretical methods in centralized and distributed manner respectively. Sun *et al.* [9] used a cheating strategy in Gale-Shapley algorithm to maximize the sum rate of D2D communications. In terms of the work combining D2D communication with CA technology, only few literatures have considered the resource allocation issue. For example, the authors [19] considered a balance between power minimization and UE target rate while spectrum allocation and mode selection in D2D communications, where CA is only considered in the BS. Nevertheless, the above literatures are all based on the technically impractical assumption that full CSI is available to devices. Besides, few of the schemes in these literatures are suitable for high-rate D2D communications, one-to-one or many-to-one modes are mostly adopted therein.

In addition, the energy efficiency issue in D2D communications has also received considerable attention, especially under the background that mobile devices still suffer from the poor capacity and slow development of batteries. The energy efficiency in D2D communications is usually investigated in two ways, including the energy efficiency of links and the energy consumption of links [10]–[14], [22]. Wang *et al.* [10] proposed to maximize the energy efficiency of D2D links in energy harvesting scenario, an iterative method is presented to solve the resource allocation problem. Similarly, the energy efficiency maximization problem is also investigated in [11]–[13]. Different from the above optimization objectives, some other researchers focus on minimizing the power consumption of D2D communications or the whole system [14], [22], and this is also the objective of our work in this paper. Ying *et al.* [14] took the social relationships into consideration and then came up with a power efficient method to accomplish relay selection in multi-hop D2D communication. In [22], the authors proposed to decompose the joint subcarrier and power allocation problem into two subproblems, through solving

two subproblems, they obtained an energy-efficient allocation result.

With the aim of achieving higher energy efficiency in D2D communications, the above literatures mostly assume that the BS or DPs know the full CSI of communication links [8]–[14], [22]. However, in real communication scenarios, full CSI is usually impractical and only partial CSI is available. Some work has been done on utilizing partial CSI to accomplish resource allocation [20], [21], [23], [24]. Wang et al. [20] investigated the expected transmission rate maximization problem in Rayleigh fading channels with partial CSI, and the so called “one-to-many” case is simplified as independent one-to-one cases. In [21], authors proposed an optimal dynamic programming algorithm to finish the channel assignment under partial CSI, where the BS is assumed to be able to acquire partial CSI of cellular, D2D and interference links. Sun et al. [23] aimed to minimize the D2D transmit power to reduce the interference caused by D2D communications, as well as optimize the selection of access threshold with statistical (partial) CSI. However, none of them considered or are suitable for the resource allocation with high rate requirements of DPs, the D2D transmission were only considered independently on reused spectrum instead of from an entire DP’s perspective, and the total power minimization issue was not considered either.

III. SYSTEM MODEL

In this section, we depict the network and spectrum reusing model in the first part. Then, we give explanations of the statistical CSI model and the channel model. At the end, communication QoS requirements are expressed as the outage probability constraints, and the mathematical model of the energy-efficient spectrum and power allocation problem is formulated.

A. Network and Spectrum Reusing Model

In our model, we consider a cellular area illustrated in Fig. 1 where the CUs and DPs coexist in the area and the number of CUs is much more than DPs. The BS is in the center of the round cellular area with omnidirectional antennas, and CUs are uniformly distributed within the cellular area. The set of all the CUs is denoted by $\Phi_C = \{c|c = 1, 2, \dots, N_C\}$, where N_C is the number of CUs. And the DPs exist near the edge of the cellular area, here we denote the set of DPs by $\Phi_D = \{d|d = 1, 2, \dots, N_D\}$, where N_D is the number of DPs.

In this scenario, each CU is allocated a chunk of spectrum with bandwidth B for uplink transmission, where each CU’s spectrum is called a component carrier (CC), and those CCs are orthogonal to each other. For the DPs, each DP is equipped with CA techniques to aggregate multiple CCs for a broader bandwidth [16]. Here, each DP can activate up to M sublinks to aggregating M CCs for higher transmission rate. In a DP, each sublink can be activated to reuse the uplink spectrum of a CU, or simply shut down if not needed. Moreover, we introduce a binary variable $x_{c,d,k} = \{0, 1\}$ to indicate the spectrum reusing relationship between CU c and DP d ’s k -th sublink. When $x_{c,d,k} = 1$, it means the k -th sublink of DP d is activated to reuse the uplink spectrum of CU c , and the value “0” means that the reusing relationship does not exist. Besides, if $\sum_c x_{c,d,k} = 0$,

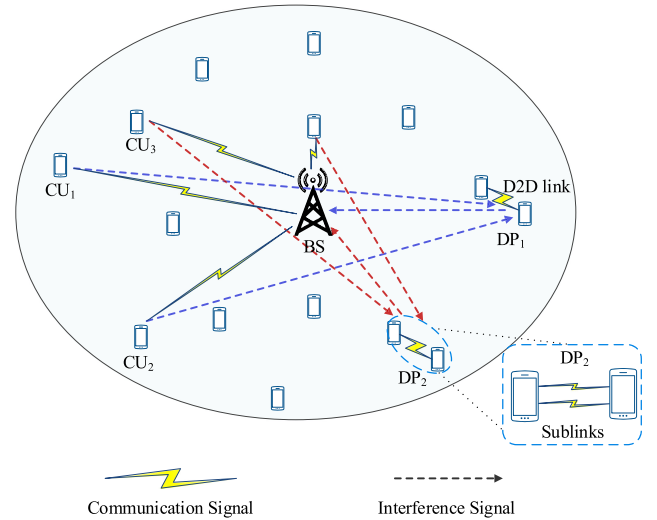


Fig. 1. System model of underlay DPs reusing the uplink spectrum of CUs in a cell. Each CU transmits in uplink mode, DP₂ activates two sublinks to transmit with higher rate.

it means the k -th sublink of DP d is shut down. Here, we assume that each sublink can either transmit by reusing one CU’s uplink spectrum or simply shut down, and the uplink spectrum of a CU can only be reused by up to one sublink to avoid multiple interference sources. Thus the above assumptions can be expressed by the following constraints on $x_{c,d,k}$:

$$\sum_d \sum_k x_{c,d,k} \leq 1, \quad (1a)$$

$$\sum_c x_{c,d,k} \leq 1, \quad (1b)$$

$$\sum_c \sum_k x_{c,d,k} = M_d, (M_d \leq M), \quad (1c)$$

where M_d is introduced to denote the number of the activated sublinks in DP d , and it is also called as DP d ’s reusing number. Specifically, M_d is a variable here, which can be at most M because of the physical limits in DPs [18].

In addition, we denote the transmit power of CU c by p_c , and $p_{d,k}$ denotes the transmit power of the k -th sublink of DP d , where the power consumption of the receiver is not considered because of the low-power property of the decode process. For a DP d , the transmit power on its sublinks can be independent or uniform on the reused CCs [16], [18], we choose to consider the independent-power circumstance first, then the uniform-power scenario will be referred at the ending part.

B. Statistical CSI and Channel Model

In this paper, we conduct our work under the Rayleigh fading channels, which can characterize a large class of wireless communication channels and have been widely adopted in literatures [25], [26]. The Rayleigh fading channel gain obeys an exponential distribution [27]–[29], whose probability density function (PDF) is depicted as:

$$f(x) = \lambda e^{-\lambda x} u(x), \quad (2)$$

where the parameter λ is the distribution coefficient, and x is the random variable. $u(x)$ is the unit step function, which takes 1 when $x \geq 0$, or 0 otherwise.

Assume that BS can only obtain statistical information of certain links, including the channel gain of the interference links and the communication links that are not directly connected to the BS. To be specific, the BS has statistical information $h_d \sim \exp(\lambda_d)$, $h_{c,d} \sim \exp(\lambda_{c,d})$ and $h_{d,c} \sim \exp(\lambda_{d,c})$, which represent the channel gain between DP d 's transmitter, the interference channel gain from DP d to CU c and from CU c to DP d respectively.

For the channel gain of cellular links, they are assumed to be timely and perfectly estimated by the BS within the coherent time [27]. Here we denote the uplink channel gain of CU c by h_c , it is perfectly estimated by the BS and supposed to be fixed during a time slot [30], [31]. For h_c , it can be expressed as $h_c = L_c^{-\alpha} \cdot |h_0|^2$, where L_c is the distance between CU c and the BS, α is the path loss coefficient, and $h_0 \sim \mathcal{CN}(0, 1)$ is a zero mean Gaussian random variable with unit variance.

Thus, based on the above conditions, the achievable communication rate of cellular links and D2D links are separately formulated according to the Shannon formula as:

$$r_c = B \cdot \log \left(1 + \frac{p_c h_c}{n + \sum_k \sum_d x_{c,d,k} p_{d,k} h_{c,d}} \right), (\forall c \in \Phi_C), \quad (3)$$

$$r_d = B \cdot \sum_k \log \left(1 + \frac{p_{d,k} h_d}{n + \sum_c x_{c,d,k} p_c h_{d,c}} \right), (\forall d \in \Phi_D), \quad (4)$$

where n is the noise power which equals to $B \cdot \rho$, and ρ is the density of noise.

Based on (4), it is easy to find that the integer variable $x_{c,d,k}$ can be taken out of the \log function and therefore becomes a multiplier. Thus the achievable communication rate of d can be transformed as follows:

$$r_{d,k} = \sum_c x_{c,d,k} \cdot B \log \left(1 + \frac{p_{d,k} h_d}{n + p_c h_{d,c}} \right), \quad (5a)$$

$$r_d = \sum_k r_{d,k}, (\forall d \in \Phi_D), \quad (5b)$$

where $r_{d,k}$ is the achievable communication rate of the k -th sublink of DP d , and it will be zero when $\sum_c x_{c,d,k} = 0$, which means the k -th sublink of DP d is not activated to transmit data. Recall the beginning of this section, the above results are calculated with random variables, thus it is obvious that the achievable communication rate of DP d is also a random variable. Similarly, the communication rate of CU c in (3) is also a random variable when CU c suffers from interference from any DP, while it will be an exact value when the interference term values 0.

C. Problem Formulation

In this paper, we aim to obtain an energy-efficient spectrum and power allocation result while guaranteeing the QoS requirements of CUs and DPs. The total power consumption of mobile devices is used to reflect the energy efficiency of the system.

Based on statistical CSI, the QoS requirements are represented as outage probability constraints on communication links that transmit with certain rates. For DP d , the required transmission rate is denoted by r_d^R , thus the outage probability is the probability that the achievable D2D communication rate is lower than the required transmission rate. Therefore, if DP d transmits with a required transmission rate of r_d^R , its QoS requirement can be expressed as

$$\Pr \{O_d\} \triangleq \Pr \{r_d \leq r_d^R\} \leq \eta_d, (\forall d \in \Phi_D), \quad (6)$$

where η_d is the required outage probability threshold. The complicated data stream allocation issue, which decides how much data to be allocated on each sublink inside DP's transmitter, is out of the scope of the resource allocation issue here and is simplified. Similar to [32], we allocate the required data transmission rate evenly on the activated sublinks in a DP. Since DP d requires a transmission rate of r_d^R , with M_d activated sublinks, the data transmission rate allocated on each sublink is $r_{d,sub}^R$, obtained by

$$r_{d,sub}^R = \frac{r_d^R}{M_d}, (\forall d \in \Phi_D). \quad (7)$$

Similarly, the QoS requirements on cellular links can be expressed as

$$\Pr \{O_c\} \triangleq \Pr \{r_c \leq r_c^R\} \leq \eta_c, (\forall c \in \Phi_C), \quad (8)$$

where r_c^R is the required cellular transmission rate and η_c is the outage probability threshold.

Therefore, with the objective of obtaining an energy-efficient spectrum and power allocation result, the mathematical model can be formulated as follows:

$$\mathbf{P1}: \min_{P_C, P_D, X} \sum_c \sum_d \sum_k x_{c,d,k} \cdot (p_{d,k} + p_0^{sub}) + \sum_c (p_c + p_0^c), \quad (9a)$$

$$\text{s.t. (1a), (1b), (1c),} \quad (9b)$$

$$(6), (8), \quad (9c)$$

$$0 \leq p_c \leq p_c^{\max} (\forall c \in \Phi_C), \quad (9d)$$

$$0 \leq p_{d,k} \leq p_{sub}^{\max}, (\forall c \in \Phi_C, \forall d \in \Phi_D), \quad (9e)$$

$$\sum_k \sum_c x_{c,d,k} \cdot r_{d,sub}^R = r_d^R, (\forall d \in \Phi_D), \quad (9f)$$

$$r_{d,sub}^R \geq r_0^{th}, (\forall d \in \Phi_D), \quad (9g)$$

where p_c^c, p_0^{sub} are the static power of a CU and an activated D2D sublink respectively, and they are generally constant values [17]. $p_c^{\max}, p_{sub}^{\max}$ are the maximum transmit power of CU c and DP's each sublink respectively. P_C, P_D and X stand for the multiplex indicator parameter set of $p_c, p_{d,k}$ and $x_{c,d,k}$ respectively, for example, $X = \{x_{c,d,k}, (c \in \Phi_C, d \in \Phi_D, k = 1, \dots, M)\}$.

Similarly, the uppercase form of variables in the rest of this paper follows the same rule. Moreover, (9f) makes sure that, in a DP, the sum data transmission rate of all activated sublinks is equal to the DP's required transmission rate. Besides, as (9g) shows, the allocated transmission rate on each activated sublink in DP d should not be lower than the threshold.

As shown above, the mathematical model is formulated with the objective of minimizing the total power consumption of CUs and DPs, it is obvious that the objective function is in linear form and is linear with respect to the integer variable $x_{c,d,k}$. Besides, the constraint (9c) is apparently non-concave. As a result, the problem **P1** is a typical non-convex MINLP problem which has been proven to be NP-hard [33].

IV. PROBLEM ANALYSIS AND TRANSFORMATION

To analyze the problem more explicitly, the expanded outage probability expressions of the cellular and D2D links are derived in this section. Moreover, due to the difficulty of solving the original problem **P1**, transformation operations are employed on it, finally, an equivalent problem in a more tractable form is obtained.

A. Outage Analysis and Expression

In Section III, the outage probability expressions of the cellular and D2D links are formulated only according to the definitions. However, those expressions are intuitively hard to understand, and not convenient for problem solving either. Thus, we will first derive elaborated outage probability expressions in the following.

1) *Outage Analysis of Cellular Links*: Firstly, analysis on the outage probability of cellular links is introduced. For a cellular user, whether its uplink spectrum is reused by a DP will lead to different outage expressions of the cellular uplink. Let $z_c = e^{\frac{r_c}{B}} - 1$ and $z_c^{\min} = e^{\frac{r_c^R}{B}} - 1$, thus (3) can be transformed into:

$$\frac{p_c h_c}{n + \sum_k \sum_d x_{c,d,k} p_{d,k} h_{c,d}} = z_c. \quad (10)$$

For variable $x_{c,d,k}$, assume that $\exists x_{c,d,k} = 1$, i.e., the uplink spectrum of CU c is reused up a DP's sublink, then (10) can be simplified as

$$\frac{p_c h_c}{n + p_{d,k} h_{c,d}} = z_c, (x_{c,d,k} = 1), \quad (11)$$

based on which the outage probability can be formulated as

$$\begin{aligned} \Pr\{O_c\} &= \Pr\{z_c \leq z_c^{\min}\} \\ &= \Pr\left\{\frac{p_c h_c}{n + p_{d,k} h_{c,d}} \leq z_c^{\min}\right\} \\ &= \Pr\left\{h_{c,d} \geq \frac{\frac{p_c h_c}{z_c^{\min}} - n}{p_{d,k}}\right\}, (x_{c,d,k} = 1). \end{aligned} \quad (12)$$

Thus, based on the PDF of $h_{c,d}$, the outage probability can be calculated through the integral operation,

which gives

$$\begin{aligned} \Pr\{O_c\} &= \int_{\left(\frac{p_c h_c}{z_c^{\min}} - n\right)/p_{d,k}}^{+\infty} \lambda_{c,d} e^{-\lambda_{c,d} x} dx \\ &= e^{-\frac{\lambda_{c,d}}{p_{d,k}} \left(\frac{p_c h_c}{z_c^{\min}} - n\right)}, (x_{c,d,k} = 1). \end{aligned} \quad (13)$$

However, we notice that the above outage probability expression only covers the scenario where the uplink spectrum of CU c is reused. Considering another circumstance, where there is no interference caused onto the cellular link of CU c , i.e., $\sum_d \sum_k x_{c,d,k} = 0$, the outage probability can be formulated in a simpler form:

$$\begin{aligned} \Pr\{O_c\} &= \Pr\{z_c \leq z_c^{\min}\} \\ &= \Pr\left\{\frac{p_c h_c}{n} \leq z_c^{\min}\right\} \\ &= \Pr\left\{p_c \leq \frac{n z_c^{\min}}{h_c}\right\}, \left(\sum_d \sum_k x_{c,d,k} = 0\right). \end{aligned} \quad (14)$$

Based on (13) and (14), the outage probability of CU c can be jointly formulated as

$$\Pr\{O_c\} = \begin{cases} e^{-\frac{\lambda_{c,d}}{p_{d,k}} \left(\frac{p_c \cdot h_c}{z_c^{\min}} - n\right)}, (\exists x_{c,d,k} = 1) \\ u\left(p_c < \frac{n z_c^{\min}}{h_c}\right), (\sum_d \sum_k x_{c,d,k} = 0), \end{cases} \quad (15)$$

where the step function $u(\cdot)$ takes boolean operation on the input, and we omit recognizing the step point (i.e., $p_c = \frac{n z_c^{\min}}{h_c}$) as outage.

2) *Outage Analysis of D2D Links*: With respect to the outage probability of DP d , it can be formulated according to the following theorem:

Theorem 1: Based on (6) and the not outage probability of each activated sublink, here is the expanded form of the outage probability expression of DP d :

$$\Pr\{O_d\} = 1 - \prod_{c,k:\forall x_{c,d,k}=1} \Pr\{r_{d,k} \geq r_{d,sub}^R\}. \quad (16)$$

Proof: Based on the definition in (6), the outage probability of DP d can be calculated based on the not outage probability, shown as:

$$\begin{aligned} \Pr\{O_d\} &= 1 - \Pr\{r_d \geq r_d^R, r_{d,k} \geq r_{d,sub}^R, \dots, (\forall x_{c,d,k} = 1)\}. \\ \text{For DP } d, \text{ the activated sublinks separately transmit with a data rate of } r_{d,sub}^R. \text{ However, from the DP's perspective, if outage happens on any of the activated sublinks, data will not be completely or successfully transmitted, thus leading to the outage of DP } d. \text{ And based on Bayes formula, we have} \\ \Pr\{r_d \geq r_d^R, r_{d,k} \geq r_{d,sub}^R, \dots, (\forall x_{c,d,k} = 1)\} \\ &= \Pr\{r_{d,k_1} \geq r_{d,sub}^R\} \cdot \Pr\{r_{d,k_2} \geq r_{d,sub}^R | r_{d,k_1} \geq r_{d,sub}^R\} \\ &\quad \cdot \dots \cdot \Pr\{r_d \geq r_d^R | r_{d,k_1} \geq r_{d,sub}^R, \dots, r_{d,k_{M_d}} \geq r_{d,sub}^R\}, \end{aligned}$$

where $r_{d,k_1}, \dots, r_{d,k_{M_d}}$ are the achievable rates of DP d 's sublinks. In the above equation, each condition in the conditional probability term is independent, thus (16) is obtained. ■

With Theorem 1, it is obvious that only if any sublink in DP d does not experience an outage, the DP will not experience an outage. Therefore, the outage probability of DP d can be obtained by calculating the product terms in (16). It is easy to notice that each product term in (16) corresponds to the not outage probability of each sublink, thus we denote each product term by $\Pr\{\bar{O}_{d,k}\} \triangleq \Pr\{r_{d,k} \geq r_{d,sub}^R\}$. Then, for a certain $x_{c,d,k} = 1$, let $z_{d,k} = e^{\frac{r_{d,k}}{B}} - 1$ and $z_{d,k}^{\min} = e^{\frac{r_{d,sub}^R}{B}} - 1$, thus the not outage probability of the k -th sublink of DP d is

$$\Pr\{\bar{O}_{d,k}\} = \Pr\{z_{d,k} \geq z_{d,k}^{\min}\} = \Pr\left\{\frac{p_{d,k}h_d}{n + p_c h_{d,c}} \geq z_{d,k}^{\min}\right\}. \quad (17)$$

Let us denote $U = p_{d,k}h_d$ and $V = n + p_c h_{d,c}$, thus the not outage probability in (17) can be obtained through the following integral operation:

$$\begin{aligned} \Pr\{\bar{O}_{d,k}\} &= 1 - \Pr\{O_{d,k}\} \\ &= 1 - \int_n^{+\infty} \int_0^{v \cdot z_{d,k}^{\min}} \left[\frac{\lambda_d}{p_{d,k}} e^{-\frac{\lambda_d}{p_{d,k}} u} \right] \\ &\quad \cdot \left[\frac{\lambda_{d,c}}{p_c} e^{\frac{\lambda_{d,c}}{p_c} (n-v)} \right] dudv. \end{aligned} \quad (18)$$

Thus the integral result gives

$$\begin{aligned} \Pr\{\bar{O}_{d,k}\} &= \psi_{d,k}(p_c, p_{d,k}, r_{d,sub}^R(X)) \\ &= \frac{T_{d,k}}{T_{d,k} + T_d^c \cdot z_{d,k}^{\min}}, \end{aligned} \quad (19)$$

where $T_{d,k} = \frac{1}{\lambda_d} \frac{p_{d,k}}{n} = \frac{1}{\lambda_d} SNR_{d,k}$, $T_d^c = \frac{1}{\lambda_{d,c}} \frac{p_c}{n} = \frac{1}{\lambda_{d,c}} SNR_c$, and $r_{d,sub}^R(X)$ means $r_{d,sub}^R$ is related to the value of X .

Therefore, the outage probability of DP d can be represented according to the following corollary.

Corollary 1: The outage probability of DP d can be expressed as

$$\Pr\{O_d\} = 1 - \prod_{c,k:\forall x_{c,d,k}=1} \psi_{d,k}(p_c, p_{d,k}, r_{d,sub}^R(X)). \quad (20)$$

B. Problem Transformation

Recall the previous section, the expressions in (15) and (20) are piecewise and non-convex respectively, which makes the original problem **P1** very difficult to solve. In this section, we implement some transformation operations on the original problem to obtain a more tractable equivalent problem.

As depicted in **P1**, we aim to obtain an energy-efficient spectrum and power allocation result to minimize the total power consumption of CUs and DPs. With this objective, here is a theorem:

Theorem 2: The constraints on the outage probability of cellular links are always binding in the process of searching for the optimal solution of **P1**, as well as when the solution is

obtained. And under this circumstance, the boundary value of p_c is always within feasible range and thus is reachable.

Proof: In **P1**, the goal is to consume as less power as possible while meeting the communication requirements within the feasible range of the problem. Assume that in the solving process, under any feasible value of the spectrum reusing variable X , which is denoted by X^\dagger here, the transmit power of CU c and the k -th sublink in DP d are p_c^\dagger and $p_{d,k}^\dagger$, respectively.

For any feasible p_c^\dagger and $p_{d,k}^\dagger$, the constraints (9b)~(9g) are all satisfied. If $\Pr\{O_c\} \leq \eta_c$, there must exist $p_c' \leq p_c^\dagger$ and $p_{d,k}' \leq p_{d,k}^\dagger$ making the objective power consumption become less or remain unchanged without breaking the constraints. Regarding to the above conclusion, we have to mention that $\Pr\{O_c\}$ monotonically decreases with the increase of p_c when we fix other variables. Similarly, $\Pr\{O_d\}$ is monotonically non-increasing when p_c decreases. These characteristics make sure that the constraints still hold when decreasing p_c . Thus, as long as we ensure that $\Pr\{O_c\} \leq \eta_c$ holds, a solution with lower power consumption can be obtained when the boundary value of p_c is reached. Therefore, the proof is completed. ■

Based on Theorem 2, let us consider (15) and (20). In (15), for CU c when $\exists x_{c,d,k} = 1$, i.e., the uplink spectrum of CU c is reused by the k -th sublink of DP d , the outage probability constraint $e^{-\frac{\lambda_{c,d}}{p_{d,k}} \left(\frac{p_c h_c}{z_c^{\min}} - n\right)} \leq \eta_c$ holds. Thus it can be transformed into a constraint on p_c as

$$p_c \geq \left(\frac{-\log \eta_c}{n \lambda_{c,d}} p_{d,k} + 1 \right) \frac{n z_c^{\min}}{h_c}. \quad (21)$$

Besides, assume that for a CU c , $\sum_d \sum_k x_{c,d,k} = 0$ holds, i.e., the uplink spectrum (a CC) is not reused by any DP. Similarly, to ensure that $u(p_c < \frac{n z_c^{\min}}{h_c}) \leq \eta_c$ holds, we have to make sure

$$p_c \geq \frac{n z_c^{\min}}{h_c}. \quad (22)$$

Considering the binding characteristic of the outage probability constraints on cellular links referred in Theorem 2, here is a corollary.

Corollary 2: p_c can be jointly expressed as

$$p_c = \left(\sum_d \sum_k x_{c,d,k} \cdot \frac{-\log \eta_c}{n \lambda_{c,d}} p_{d,k} + 1 \right) \frac{n z_c^{\min}}{h_c}, \quad (23)$$

Proof: According to Theorem 2, (21) and (22) are binding, thus the above equation can be obtained. ■

Therefore, the outage expression of cellular links can be tightened as (23), by taking (23) into **P1** to replace p_c , the piecewise cellular outage constraints are well handled.

Then, by introducing variable substitution on $p_{d,k}$ by $p_{d,k} = e^{-\hat{p}_{d,k}}$, the objective function of **P1** becomes convex, shown as below:

$$\begin{aligned} &f_0(\hat{P}_D, X) \\ &= \sum_c \sum_d \sum_k x_{c,d,k} \left[\left(1 + \frac{-\ln \eta_c}{\lambda_{c,d}} \frac{\left(e^{\frac{r_c^R}{B}} - 1 \right)}{h_c} \right) e^{-\hat{p}_{d,k}} + p_0^{sub} \right] \end{aligned}$$

$$\begin{aligned}
& + \sum_c \left(\frac{n \left(e^{\frac{r_c^R}{B}} - 1 \right)}{h_c} + p_0^c \right) \\
& = f(\hat{P}_D, X) + \sum_c \left(\frac{n \left(e^{\frac{r_c^R}{B}} - 1 \right)}{h_c} + p_0^c \right), \quad (24)
\end{aligned}$$

where the summation term at the end is independent from the variables, thus it can be omitted in the solving process. For brevity, we refer to $f(\hat{P}_D, X)$ as the objective function in the rest of this paper.

For the outage probability of D2D links, after substituting the variables in (20) with the same substitution approach above, we exchange the product term with the right side in (20) and take the logarithm of both sides. The expression of the outage probability of DP d is finally obtained, as shown in (25) at the bottom of this page.

Based on the above analysis and transformation results, the transformed problem can be formulated as follows:

$$\mathbf{P1}' : \max_{\hat{P}_D, X} -f(\hat{P}_D, X) \quad (26a)$$

$$\text{s.t. (9b), (9e), (9f), (9g),} \quad (26b)$$

$$(25), \quad (26c)$$

$$-\log(\min\{p_{sub}^{\max}, x_{c,d,k} \cdot \phi_{c,d}(p_c^{\max})\}) \leq \hat{p}_{d,k}, \quad (26d)$$

where the function $\phi_{c,d}(p_c^{\max}) = \frac{n\lambda_{c,d}}{-\ln \eta_c} \left(\frac{p_c^{\max} h_c}{n(e^{\frac{r_c^R}{B}} - 1)} - 1 \right)$ is similar to the inverse function of (23), it makes sure that the transmit power constraints in $\mathbf{P1}$ are still effective in $\mathbf{P1}'$.

Through the above transformations, it is obvious that the objective function of problem $\mathbf{P1}'$ is concave, constraint (26c) is concave when we fix M_d , and the other constraints are linear. Thus, based on the structure of $\mathbf{P1}'$, the solving method will be put forward in the following section.

V. A TWO-LAYER GREEDY-BASED OUTER APPROXIMATION METHOD AND SOME SUPPLEMENTS

Several main issues that remain to be solved in the first place can be listed as follows: Which CU's uplink spectrum should the DPs reuse; How much power should UEs transmit with. To solve the transformed problem, we first propose a two-layer iterative algorithm IPGOA in the first subsection. Furthermore, to

eliminate unnecessary computations in spectrum allocation, we propose a supplemental method for compressing the spectrum allocation space. And at the end of this section, we propose the UPGOA algorithm for the scenario where uniform power is allocated on the activated sublinks in a DP.

A. A Two-Layer Greedy-Based Outer Approximation Method

Before introducing the solving method, we have to mention that as described in (7), the allocated data transmission rate requirement on each activated sublink $r_{d,sub}^R$ is related to the reusing number of the uplink spectrum of CUs, which makes $r_{d,sub}^R$ a variable rather than a constant. Thus, to solve this issue, we develop a two-layer algorithm:

- In the outer layer, by greedily searching the reusing number of the uplink spectrum of CUs for each DP, the near-optimal reusing number can be obtained.
- In the inner layer, with the fixed reusing number passed from the outer layer, problem $\mathbf{P1}'$ becomes a concave MINLP problem which can be solved by employing the outer approximation (OA) method.

1) *The Outer-Layer Greedy Searching Method:* In this layer, we aim at searching for near-optimal reusing numbers in iterations.

Firstly, initialize by setting the reusing number $M_d = \min\{M, r_d^R / r_0^{th}\}$ for each DP $d \in \Phi_D$ and then

- Sequentially choose one DP d ($d \in \Phi_D$) and continue to the next step.
- For DP d , monotonically decrease M_d by 1 (i.e., $M'_d = M_d - 1$) each time and calculate the objective power consumption under $(M'_d, \mathbf{M}_{\Phi_D \setminus d})$, where $\mathbf{M}_{\Phi_D \setminus d}$ stands for the value vector of $M_{d'}$ ($d' \in \Phi_D \setminus d$), the calculation method will be discussed in Section V-A2. In addition, if the problem becomes infeasible, refer to operations in (d1) and (d2) until the problem becomes feasible.
- Compare the objective power consumption under reusing number $(M'_d, \mathbf{M}_{\Phi_D \setminus d})$ with the previous one with $(M_d, \mathbf{M}_{\Phi_D \setminus d})$. If the total power decreases, let $M_d = M'_d$, otherwise, set DP d 's reusing number as M_d^* . If there are left DPs to be traversed, return to (a), otherwise continue to the next step.
- Traverse DPs in Φ_D one by one to slightly adjust M_d . For each $d \in \Phi_D$, keep traversing according the following steps until the objective power consumption stop decreasing.
 - Increase M_d^* by 1, compare the objective power consumption with the previous one. If it decreases,

$$\begin{aligned}
\hat{\psi}_d(\hat{P}_D, X) & \triangleq \ln \prod_{c,k:\forall x_{c,d,k}=1} \psi_{d,k}(p_c, p_{d,k}, r_{d,sub}^R(X)) \\
& = \sum_k \sum_c -x_{c,d,k} \left[\ln \left(1 + \frac{\lambda_d n \left(e^{\frac{r_c^R}{B}} - 1 \right)}{\lambda_{d,c} h_c \left(\frac{-\ln \eta_c}{n \lambda_{c,d}} + e^{\hat{p}_{d,k}} \right)} \left(e^{\frac{r_{d,sub}^R(X)}{B}} - 1 \right) \right) + e^{\hat{p}_{d,k}} \lambda_d n \left(e^{\frac{r_{d,sub}^R(X)}{B}} - 1 \right) \right] \\
& \geq \ln(1 - \eta_d) \quad (25)
\end{aligned}$$

set $M_d^* = M_d^* + 1$ and continue increasing M_d^* until the objective power consumption stops decreasing, else go to next step.

- (d2) Decrease M_d^* by 1, compare the objective power consumption with the previous one. If it decreases, set $M_d^* = M_d^* - 1$ and continue decreasing M_d^* until the objective power consumption stops decreasing. Then, start from another d and repeat the above operation. If the total power does not decrease in a full traversal, quit the loop.

Therefore, based on the above descriptions, the outer-layer algorithm is described in Algorithm 1. Through the analysis below, we can prove that the outer-layer algorithm can find near-optimal reusing numbers.

Theorem 3: For a DP d in DP set Φ_D , there must exist a unique optimal reusing number of M_d with which the minimum objective power consumption under $\mathbf{M}_{\Phi_D \setminus d}$ is obtained.

Proof: Let us omit the solving procedures in the inner layer, within the finite value range of M_d , it is obvious that there exists a value of M_d that outputs the minimum objective power consumption under $\mathbf{M}_{\Phi_D \setminus d}$. ■

Proposition 1: The above greedy searching method can find near-optimal allocation of reusing numbers for DPs.

Proof: Let us omit the solving procedures in the inner layer. With the decrease of M_d , less sublinks are activated for transmission, thus the required data transmission rate on each sublink (i.e., $r_{d,sub}^R$) increases, while the total static power consumption of sublinks decreases. For each sublink, they must transmit with higher power to meet the increasing transmission rate requirement. However, if the transmission rate on each sublink keeps increasing, the transmit power increases faster and faster. Once the M_d reaches a certain value, the objective power consumption no more decreases.

Due to the traversing characteristic on each DP where the reusing number of only one DP is chosen to change in one iteration. The circumstance that multiple DPs' reusing numbers are simultaneously changed is not considered here. However, the difference between changing multiple reusing numbers one time and changing one M_d in an iteration for multiple times is generally small. Firstly, Algorithm 1 makes sure that, for DP d , any $M_d > M_d^*$ or $M_d < M_d^*$ will lead to an increase of the objective power consumption under the value of $\mathbf{M}_{\Phi_D \setminus d}$. Secondly, in our model, the number of CUs is much more than DPs, DPs can make spectrum reusing choices from numerous CUs. Thus even under an optimal $\mathbf{M}_{\Phi_D \setminus d}$, a DP's reusing number usually stays the same, and the objective power consumption may not or only slightly change. Thus the gap between the above algorithm and the global searching will be pretty small, which is also reflected in the simulation results. ■

2) *The Inner-Layer Outer Approximation Algorithm:* With respect to the inner-layer algorithm, it aims to calculate the objective power consumption with a certain \mathbf{M}_{Φ_D} referred in the previous section, and the following discussions are all based on the precondition that \mathbf{M}_{Φ_D} is a constant passed from the outer layer. And based on the formulated problem **P1'** in Section IV-B, some propositions are proposed.

Algorithm 1: Greedy-based Outer-layer Iterative Method.

```

1 Initialization: Set  $M_d$  for each DP  $d \in \Phi_D$  by
    $M_d = \min\{M, r_d^R/r_0^{th}\} (d \in \Phi_D)$ ,  $f_c = \infty$ ,  $\delta = 10^{-3}$  is
   the computational error tolerance,  $f|_{(M_d, \mathbf{M}_{\Phi_D \setminus d})}$  stands
   for the objective power consumption under  $(M_d, \mathbf{M}_{\Phi_D \setminus d})$ ;
2 for each  $d \in \Phi_D$  do
3   while  $f|_{(M_d, \mathbf{M}_{\Phi_D \setminus d})} \leq f_c$  do
4     Let  $M'_d = M_d - 1$ , calculate  $f|_{(M'_d, \mathbf{M}_{\Phi_D \setminus d})}$ ;
5     if  $f_c - f|_{(M'_d, \mathbf{M}_{\Phi_D \setminus d})} \geq \delta$  and  $M'_d \geq 1$  then
6       |  $M_d = M'_d$ ,  $f_c = f|_{(M'_d, \mathbf{M}_{\Phi_D \setminus d})}$ ;
7     else
8       |  $M_d^* = M_d$ ; Break;
9     end
10  end
11 end
12 do
13   for  $d \in \Phi_D$  do
14     if  $f_c - f|_{(M_d^*-1, \mathbf{M}_{\Phi_D \setminus d})} \geq \delta$  and  $M_d^* > 1$  then
15       |  $M_d^* = M_d^* - 1$ ,  $f_c = f|_{(M_d^*, \mathbf{M}_{\Phi_D \setminus d})}$ ;
16     else if  $f_c - f|_{(M_d^*+1, \mathbf{M}_{\Phi_D \setminus d})} \geq \delta$  and
17        $M_d^* < \min\{M, r_d^R/r_0^{th}\}$  then
18       |  $M_d^* = M_d^* + 1$ ,  $f_c = f|_{(M_d^*, \mathbf{M}_{\Phi_D \setminus d})}$ ;
19     else
20       | Proceed to another DP;
21     end
22   end
23 while Any  $M_d$  is changed in a loop;

```

Under a certain \mathbf{M}_{Φ_D} determined in the outer-layer iteration, problem **P1'** has the properties described as below:

Proposition 2: In **P1'**, \hat{P}_D is a non-empty and convex set; the objective function of (26a) is obviously concave; constraint (25) is obviously concave due to the form of *log-exp-sum* function.

Proposition 3: The objective function (26a) and constraint (26c) are first order continuous differentiable.

Proposition 4: A constraint qualification holds at the solution of each concave nonlinear programming (NLP) problem obtained by fixing the values of X ; the concave NLP problem obtained by fixing X can be solved by convex programming algorithms exactly.

Based on the above propositions, the inner-layer joint spectrum and power allocation problem **P1'** under certain \mathbf{M}_{Φ_D} becomes a concave MINLP problem, which can be decomposed into two subproblems, an NLP primal problem and a mixed integer linear (MILP) master problem [34]. By fixing the integer variable X in **P1'**, a concave NLP problem is obtained. After solving the continuous variable \hat{P}_D , the solution to the NLP problem provides a lower bound of the solution to the concave MINLP problem **P1'**. And based on the solution of the NLP problem, the MILP master problem predicts a new upper bound of the MINLP problem as well as a new value of the integer variable in each iteration. By iteratively solving the sequence of the NLP primal problem and the MILP master problem to obtain the non-increasing upper bound and non-decreasing

lower bound, the algorithm finally reaches an ε -convergence capacity.

Detailedly, in order to obtain the NLP primal problem, the integer variable is fixed with X^\dagger , thus the NLP problem can be formulated as the following:

$$\mathbf{P2.1} : \max_{\hat{P}_D} -f(\hat{P}_D, X^\dagger), \quad (27a)$$

$$\text{s.t.} \quad (25), \quad (27b)$$

$$-\log\left(\min\left\{p_{sub}^{\max}, x_{c,d,k}^\dagger \cdot \phi_{c,d}(p_c^{\max})\right\}\right) \leq \hat{p}_{d,k}. \quad (27c)$$

It is obvious that **P2.1** is a concave maximization problem that can be rapidly solved by using optimization tools, like CVX [35]. We denote \hat{P}_D^\dagger as the solution to problem **P2.1**, and the objective function value is f_{NLP}^{low} .

The solution of the above NLP primal problem will be used for the master problem shown as follows:

$$\mathbf{P2.2} : \max_{X^\dagger} \left(\max_{\hat{P}_D} -f(\hat{P}_D, X^\dagger) \right), \quad (28a)$$

$$\text{s.t.} \quad (26b) \sim (27c), \quad (28b)$$

which is the projection of problem **P1'** on X . Besides, we note that constraint (27c) can be decomposed into $\hat{p}_{d,k} \geq -\log(p_{sub}^{\max})$ and $\log(\phi_{c,d}(p_c^{\max}/p_{sub}^{\max}))x_{c,d,k} + \log(p_{sub}^{\max}) + \hat{p}_{d,k} \geq 0$, where the second equation is denoted by $\varphi_{c,d,k}(\hat{p}_{d,k}, x_{c,d,k}) \geq 0$ for brevity.

Based on Proposition 4 and the solution \hat{P}_D^\dagger of the primal problem, the projection problem has the same solution as the one shown as below [36]:

$$\mathbf{P2.2}' : \max_{\xi, \hat{P}_D, X} \xi, \quad (29a)$$

$$\text{s.t.} \quad -f(\hat{P}_D^\dagger, X^\dagger) - \left(\nabla f(\hat{P}_D, X)\right)^T \begin{pmatrix} \hat{P}_D - \hat{P}_D^\dagger \\ X - X^\dagger \end{pmatrix} \\ -\xi \geq 0, \quad (29b)$$

$$\hat{\psi}_d(\hat{P}_D^\dagger, X^\dagger) + \left(\nabla \hat{\psi}_d(\hat{P}_D, X)\right)^T \\ \begin{pmatrix} \hat{P}_D - \hat{P}_D^\dagger \\ X - X^\dagger \end{pmatrix} - \ln(1 - \eta_d) \geq 0, \quad (29c)$$

$$\varphi_{c,d,k}(\hat{P}_D^\dagger, X^\dagger) + \left(\nabla \varphi_{c,d,k}(\hat{P}_D, X)\right)^T \\ \begin{pmatrix} \hat{P}_D - \hat{P}_D^\dagger \\ X - X^\dagger \end{pmatrix} + \log(p_{sub}^{\max}) \geq 0, \quad (29d)$$

$$\hat{p}_{d,k} \geq -\log(p_{sub}^{\max}), \quad (29e)$$

$$(1a) \sim (1c), \quad (29f)$$

where the product term with Hamiltonian (∇) completes the operation of summing the multiplication results of two parts, including the derivation result on each variable and the corresponding subtraction result. Through solving the master problem **P2.2'**, an upper bound of the original problem is obtained, which

Algorithm 2: Inner-layer Outer Approximation Algorithm.

```

1 initialize: for a given  $\mathbf{M}_{\Phi_D}$  in Algorithm 1, randomly
  choose a feasible  $X^\dagger$ ,  $\varepsilon = 10^{-3}$ ,  $\Delta f = \infty$ ;
2 while  $\Delta f \geq \varepsilon$  do
3   Solving the NLP problem (27a), get the solution  $\hat{P}_D^\dagger$ ,
  thus the objective function value of (27a) is
   $f_{NLP}^{low} = -f(\hat{P}_D^\dagger, X^\dagger)$ ;
4   Solving the MILP problem (29a), get the solution
   $\hat{P}_D^*, X^*$ , the objective function value of (29a) is
   $f_{MILP}^{up} = -f(\hat{P}_D^*, X^*)$ ;
   $\Delta f = f_{MILP}^{up} - f_{NLP}^{low}$ ;
5   if  $\Delta f \geq \varepsilon$  then
6      $X^\dagger = X^*$ ;
7   else
8     Solution  $(\hat{P}_D^\dagger, X^\dagger)$  is obtained, and the value of
   $f|_{\mathbf{M}_{\Phi_D}}$  can be calculated;
  Break;
9   end
10  end
11  end
12 end

```

is denoted by f_{MILP}^{up} , and the solution to **P2.2'** is denoted by \hat{P}_D^* and X^* . As iterations proceed, the upper bound and lower bound gradually approach to each other, an ε -convergence is reached when the gap between two bounds is within ε . The algorithm is shown in Algorithm 2.

B. A Method for Compressing Spectrum Allocation Space

In our model, the outage probability of communication links should be ensured to be under a certain level, thus some of the potential matching pairs of DP and CU can be efficiently excluded before solving the inner-layer problem in Section V-A2. Based on (20), we have the following proposition:

Proposition 5: For a DP d satisfying (20), for each activated sublink of DP d , the DP-CU matching pair must satisfy

$$1 - \eta_d < \psi_{d,k}(p_c, p_{d,k}, r_{d,sub}^R(X)), (\forall x_{c,d,k} = 1). \quad (30)$$

Based on the above proposition, here is an efficient compression method for excluding some impossible DP-CU matching case:

- Calculate the required transmit power p_c^r when CU c is not interfered.
- For DP d , take the required power p_c^r into the place of p_c in (30) and determine if the inequality can be true within feasible range. If the equation does not hold, exclude the case that DP d reuses the uplink spectrum of CU c under the current and bigger M_d .

By using the above method before solving the inner-layer problem in Section V-A2, the feasible range of the variable X can be greatly compressed.

C. A Uniform-Power Greedy-Based Outer Approximation

In CA technology, uniform power can be allocated on the activated sublinks of a DP for aggregating continuous CCs. If the BS allocates continuous CCs to the CUs whose spectrum are chosen to be reused by a DP, aggregating continuous CCs

becomes feasible in the DP's side. When the aggregated CCs are continuous, the physical layer can be simplified and it is easier to implement resource allocation and management algorithms [18], where the transmit power on a DP's sublinks are equal. Thus, the spectrum and power allocation problem, where uniform transmit power is allocated on each sublink in a DP, can be regarded as a simplified version of the problem **P1**, here, the $p_{d,k}$ are equal for the same DP d . Thus, UPGOA is naturally obtained based on IPGOA.

VI. NUMERICAL SIMULATIONS

In this section, we present the numerical simulation results of our proposed algorithms in terms of the objective power consumption $f(\hat{P}_D, X)$, the reusing number of CUs of the DPs, etc. For comparison, the traditional one-to-one reusing method and two other methods are introduced here. One is the optimal algorithm which is realized by using exhaustive searching method, the other algorithm is based on the bipartite graph method which is widely involved in literatures [20], [37], [38]. However, due to the difference in system model and target problem, the bipartite graph algorithm should be modified and the details will be described in the following.

In the modified bipartite graph method, the weight of the links between each DP d and CUs is set as the required transmit power when the DP reuses the uplink spectrum of the CU, with the constraint that the not outage probability be no less than $M_d \sqrt{1 - \eta_d}$, where M_d has the same meaning with the one in our methods. Similarly, the value of M_d is also determined in the outer layer of the bipartite graph method through exhaustive enumeration.

A. Simulation Settings

As depicted in Fig. 1, the BS is in the center of the round cellular area, the CUs and DPs are randomly and uniformly distributed in the area. The radius of cell is set as 300 meters, and the distance between D2D transceiver is between 20 to 50 meters. With respect to the available CSI to the BS, it is assumed to be able to timely obtain cellular uplink channel gain by estimation, which is mentioned in Section III-B. And the BS can also obtain statistical CSI of D2D links as well as interference links. In order to study the effect of the scale of CUs on the performance of different algorithms, the number of DPs is set as 5, and the number of CUs ranges from 40 to 110. To eliminate the randomness in simulations, the network is generated 100 times and the results are obtained by computing the average. Detailed simulation parameters and the description of each are demonstrated by Table I.

B. Numerical Results

To investigate the relationship between the objective power consumption and the ratio of the CU and DP numbers, we set the D2D transmission rate requirement as 50 Mbps. This is an eclectic value that makes sure that even if when the ratio of the number of CUs and DPs is relatively small (i.e., the number of CUs are not that many), like 8 indicated on the x-axis, the DPs are still able to reuse the uplink spectrum of some CUs to

TABLE I
SIMULATION PARAMETERS

Parameter	Description	Value
R	Cell radius	300 m
B	Bandwidth of a CC	2 MHz
N_C	Number of CUs	[40:110]
N_D	Number of DPs	5
α	Path-loss exponent	4
ρ	Noise density	-174 dBm/Hz
M	Maximum number of aggregated CCs	8
r_c^R	Cellular transmission rate requirement	2 Mbps
r_d^R	D2D transmission rate requirement	[10:110] Mbps
r_0^{th}	D2D sublink transmission rate threshold	2 Mbps
p_c^{\max}	Maximum cellular transmit power	26 dBm
p_{sub}^{\max}	Maximum D2D sublink transmit power	23 dBm
p_0	Static power of a D2D sublink	50 mW
$dist_{d2d}$	D2D communication distance	[20:50] m
η_c	Cellular outage probability threshold	0.1
η_d	D2D outage probability threshold	0.1

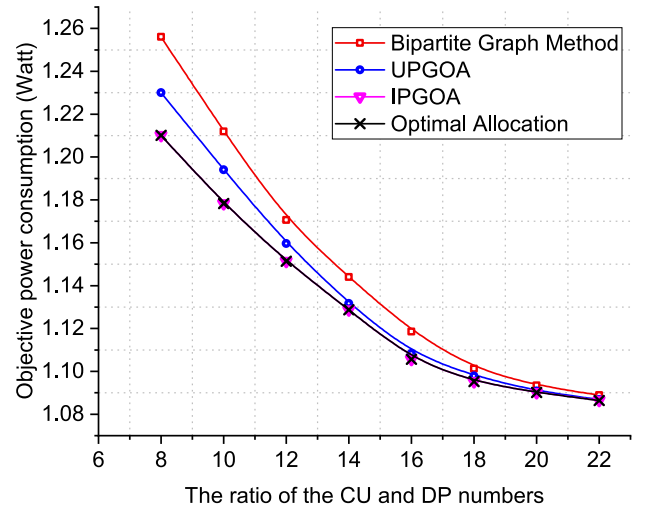


Fig. 2. The objective power consumption versus the ratio of the CU and DP numbers.

meet their communication requirements. As shown in Fig. 2, the objective power consumption decreases with the increase of the ratio of the CU and DP numbers, and so does the rate of descent. It is obvious that the proposed IPGOA is pretty close to the optimal allocation result, while the objective power consumption of UPGOA is between IPGOA and the bipartite graph method. Because when the ratio of the CU and DP numbers is small, the bipartite graph method must make sure that the not outage probability of each activated sublink in DP d is no less than $M_d \sqrt{1 - \eta_d}$. Thus the DPs must transmit with higher power, and some CUs not satisfying the above constraint are excluded from the feasible matching candidate, which makes the competition between DPs for suitable CUs more intense. However, IPGOA can handle the above situation well. Besides, we notice that the performance of UPGOA is pretty close to IPGOA when the ratio of the CUs and DPs numbers is more than about 14, while UPGOA costs less computation.

In Fig. 3, we introduce the traditional one-to-one reusing method and compare its objective power consumption with the another four schemes by increasing the D2D transmission rate requirement r_d^R . With the increase of r_d^R , the objective

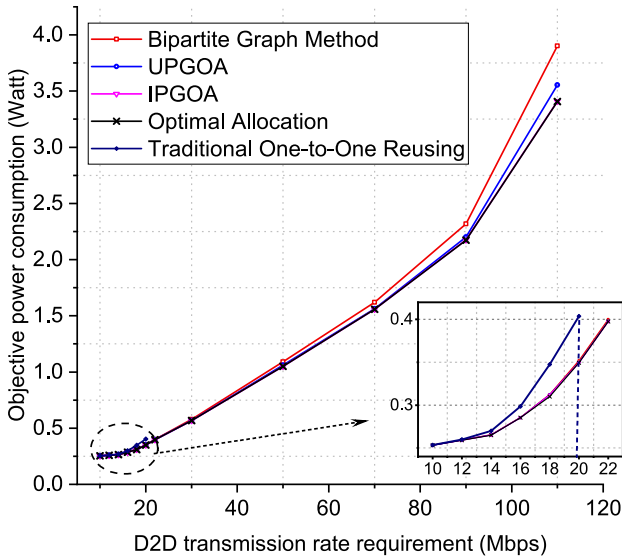


Fig. 3. The objective power consumption versus the D2D transmission rate requirement.

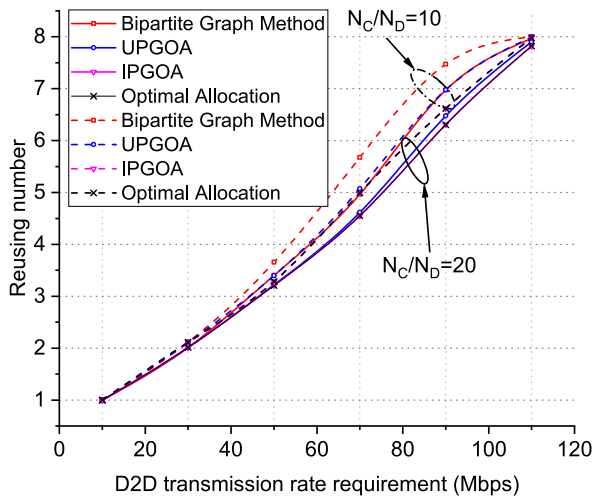


Fig. 4. The average reusing number of CUs of a DP versus D2D transmission rate requirement.

power consumption grows faster in all schemes. As we can see in the subgraph, the top line shows how the objective power consumption grows with r_d^R in one-to-one reusing method, and the power gap between it and the other schemes becomes bigger until it cannot meet the transmission requirement around the dash line. Not to mention the many-to-one circumstance, where additional interference will degrade the performance more seriously. Therefore, the results have clearly shown that the traditional one-to-one reusing method has non-negligible drawbacks in meeting the requirement of high-rate D2D communications. As r_d^R increases to much higher value, the gap between the bipartite graph method and our proposed algorithms become bigger, however, the proposed IPGOA is always close to the optimal allocation result.

As we can see from Fig. 4, with the increase of r_d^R , the reusing number reveals an increasing trend. It grows faster

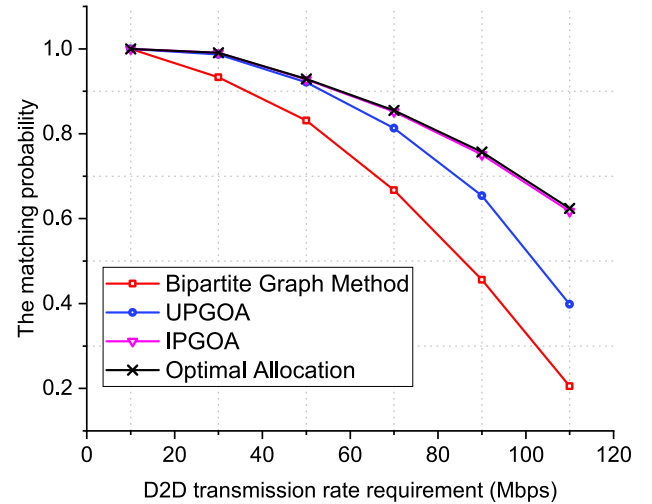


Fig. 5. The matching probability versus D2D transmission rate requirement.

before approaching around the upper limit M , which is set as 8, while when the reusing number is near M , the growth begins to slow down and the reusing number gradually approaches the upper limit M . Besides, it is obvious that our proposed methods interfere with less CUs compared with the bipartite graph method, regardless of how much the ratio of the CU and DP numbers is. We can also notice that the performance gap of IPGOA and the bipartite graph method is much bigger when the ratio of the CU and DP numbers is smaller, which has shown that IPGOA can averagely perform better even though the amount of CUs is relatively small.

And Fig. 5 shows the performance of different methods in the aspect of the statistical matching probability vs. D2D transmission rate requirement r_d^R . Here, the statistical matching probability is calculated by averaging the ratio of the number of successfully matched DPs and all the DPs. For the infeasible circumstances, we simply exclude the infeasible DPs and then solve the problem with the remaining DPs. As r_d^R grows, the statistical matching probability decreases and the rate of descent becomes faster. As shown in the figure, the proposed IPGOA is always pretty close to the optimal allocation result, while UPGOA and the bipartite graph method are inferior to the above two methods. This is because the bipartite graph method tries to ensure that the not outage probability of each sublink equals to the threshold $M_c\sqrt{1-\eta_d}$ and UPGOA demands that the transmit power of each sublink in a DP be uniform, both of which lead to the reduction of the scale of the available uplink spectrum for reusing.

In Fig. 6, the average sum D2D transmission rate is used to indicate the statistical average of the sum rate of the successful transmissions in DPs, and the transmission rate requirement of a DP is set as 50 Mbps. As the ratio of the CU and DP numbers increases, the average sum D2D transmission rate increases, while the growth rate slows down. It is obvious that the proposed IPGOA is superior to the bipartite graph method and pretty close to the optimal result. This is because with certain ratio of the CU and DP numbers, especially when the ratio is low, the bipartite graph method will exclude many CUs from the feasible

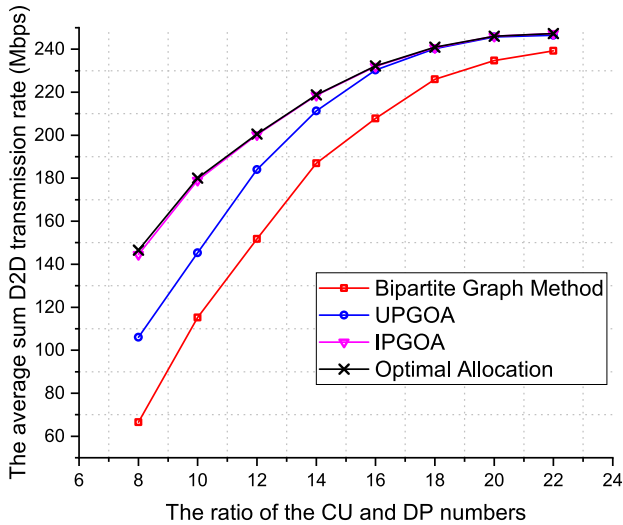


Fig. 6. The average sum D2D transmission rate versus the ratio of the CU and DP numbers.

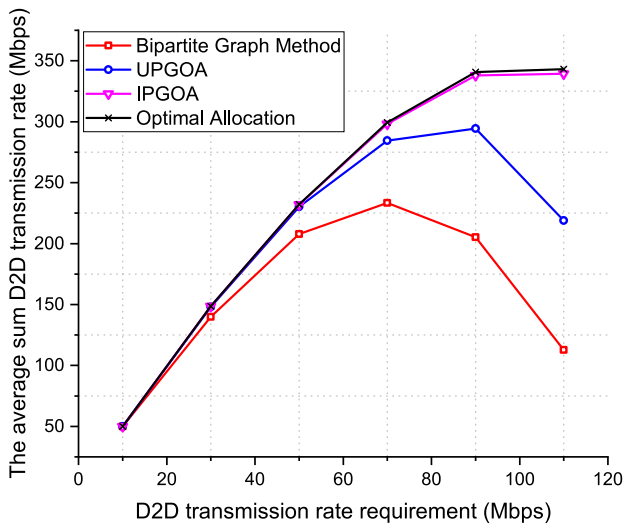


Fig. 7. The average sum D2D transmission rate versus D2D transmission rate requirement.

CU set for not satisfying the outage probability constraints of sublinks, thus some DPs are not allowed to transmit with the required transmission rate. Obviously, UPGOA is inferior to IPGOA, because it may also exclude some CUs from the matching candidate set due to the uniform power allocation strategy on the sublinks in a DP. Some CUs may not be able to match with the sublinks if those sublinks transmit with the same power. And similarly, the average sum D2D transmission rate is also investigated with respect to the D2D transmission rate requirement in Fig. 7. In the beginning, the average rate increases with the increase of D2D communication transmission requirement, but when the D2D transmission rate requirement reaches certain values, the average rate begins to decrease in the bipartite graph method and UPGOA, while IPGOA can always approach the optimal allocation result and still keeps a relatively high average rate.

VII. CONCLUSION

In this paper, we studied the spectrum and power allocation problem of high-rate D2D underlaid cellular networks under the condition of only statistical (partial) CSI. We proposed to use the CA technology to enable the DPs to aggregate multiple CCs, however, this makes ensuring the QoS of D2D communications more complicated from DP's perspective. To accomplish the resource allocation problem, we aimed to obtain an energy-efficient result to minimize the total power consumption while ensuring the QoS requirements of communication links. Due to the difficulty of directly solving the original problem, we conducted transformations and variable substitutions on the original problem to convert it into a more tractable form. In the following, we proposed an iterative algorithm IPGOA to solve it. Furthermore, we also considered the scenario where uniform power is allocated for each sublink in a DP, which can be regarded as a simplified version of the original problem, thus UPGOA is proposed. In the simulation part, the numerical results showed that our proposed methods outperform the existing algorithm and IPGOA is pretty close to the optimal allocation result.

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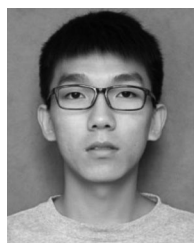
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