Resource allocation for device-to-device communications underlaying uplink cellular networks

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ABSTRACT

Underlying cellular networks, device-to-device (D2D) communications are a practical network technology that can increase power efficiency and spectrum usage for close-proximity wireless services and applications. However, D2D link interference, when sharing resources with cellular users (CUs), poses a major challenge in such distribution situations. In this research, we primarily utilize wireless channel data that exhibits slowly shifting large-scale fading to conduct spectrum sharing and power allocation. The overall ergodic capacity of all cellular user equipment (CUE) links is initially considered as the optimization target in order to maximize the overall throughput of CUE links while ensuring the reliability of each D2D link. Then, the expansion of the minimum ergodic capacity is measured to ensure a more consistent capacity performance across all CUE links. We utilized algorithms that are resilient to channel fluctuations and produce optimal resource allocation. We use MATLAB, and the computer simulation validates its intended performance.

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1. INTRODUCTION

One of the technological components of the third generation partnership projects (3GPPs) long term evolution advanced (LTE-A) is device-to-device (D2D) communication [1]. When it comes to D2D communication, nearby cellular users (CUs) can communicate with each other directly through a direct link instead of sending and receiving signals via a cellular base station (BS). D2D users remain under BS control while engaging in direct communication. When interacting directly with one another, CUs in close proximity can save energy and resources compared to routing through a BS. Furthermore, because direct contact occurs over short distances, D2D users can benefit from fast data rates and minimal transmission delays [1]. Another benefit of D2D communication is that it reduces stress on the network by bypassing the BS and other network components, allowing cellular traffic to be directly transmitted between users. This helps to increase the network's effective capacity. Additional advantages and applications are covered in [2].

In this paper, we utilize a random D2D underlaid cellular network model to analyze the performance of an improved power control approach and channel allocation. The study focuses on a diverse scenario where the distance between D2D pairs is randomly modeled. Each D2D transmitter chooses the power level for transmission based on the channel conditions, particularly the distance-dependent path-loss between D2D pairs, with the aim of maximizing its own D2D link rate. We also take into account the fact that one cellular user may share resources with the D2D links.

The rest of the paper is structured as follows. Section 2 description related work. The proposed concept for D2D underlaid cellular networks is outlined in section 3. Section 4 covers the design of resource and power allocation. Findings and debates are presented in section 5, and our conclusions are presented in section 6.

2. RELATED WORK

Techniques for controlling power in D2D underlaid cellular networks have attracted a lot of interest. A straightforward power control technique that limits D2D transmit power to safeguard the current cellular links was presented in [3] for a deterministic network model and a single-cell scenario. A D2D transmit power allocation strategy was presented in [4] for the stochastic network model in order to maximise the network's sum rate, [5] presented a dynamic power control system for a single D2D link communication with the goal of improving cellular system performance by minimising interference produced by D2D communication. The basic idea was to safeguard CUs by using BS to modify D2D transmit power. To ensure that both D2D and CUs receive the quality-of-service (QoS) they require, a power minimization solution was proposed in [6]. This solution combines joint subcarrier allocation, adaptive modulation, and mode selection. Yu *et al*. [4] investigated resource allocation and power control among D2Dand CUs, proposing an optimization strategy to enhance system capacity. The network capacity was examined by considering bidirectional data transmission and accounting for network complexity [7]. Additionally, an optimal D2D transmission capacity was proposed in [8]. Further research on cooperative communication in D2D, where CUs within the networks can assist in D2D transmission, was conducted in [9]–[12]. This enhancement satisfied the QoS standards for both downlink user equipments (DUEs) and uplink user equipments (UUEs) and enhanced the total system data rate. Li *et al.* [13] concentrated on minimising the data rate for each unique cellular user equipment (CUE) and optimising the data rate of the weighted system while maintaining D2Duser equipment (DUE) fairness. Research by Kai *et al*. [14], their goal was to minimise the total power consumption of the CUEs and DUEs in the system while satisfying each user's fundamental rate needs.

Intended to minimize the disturbance from users [15]. D2D downlink resource allocations are the other kind [16]–[21]. For example, DUEs exclusively reuse CUEs downlink subcarriers. Hu *et al.* [19] examined the impact of reusing downlink subcarrier resources of DUEs on D2D communication. The system's overall data rate can be improved by utilizing a number of mathematical techniques in [17], [18]. To achieve green communication, researchers [19]–[21] examined the problem of maximizing energy efficiency (EE), [19] only examined the problem of maximizing EE for all DUEs, [20] focused on maximizing the EE of the entire system, and [21] aimed to balance the system's EE and spectral efficiency (SE). Concurrent research on the reuse of uplink and downlink subcarriers in cellular networks was done in [22]–[24]. The goal of [25], [26] in particular was to maximise the total rate of all DUEs. Gain aware uplink-downlink (GAUD) is a unique resource allocation technique that was presented by [22]. On the other hand, [23] looked at the channel assignment, power allocation, and access control-based interference management algorithms.

When a D2D transmitter reuses cellular resources, it reduces its broadcast power in [25] to reduce interference with cellular receivers. Suggests using an area management system for interference limiting to stop cellular interference from getting to D2D receivers. With this strategy, it is not permitted for D2D users to share spectrum with CUsif the D2D receiver's interference-to-noise ratio is higher than a certain level. When multiple antennas are positioned at the BS, interference nulling is used [26] to mitigate interference from the cellular link to D2D communications BS. Yu *et al*. [4] maximized the aggregate rate of both D2D and CUs in the network with a single D2D pair and a single cellular user, while also ensuring a minimum rate for the cellular user. Many cellular and D2D users under more practical conditions have prompted research on the design of power distribution and spectrum in [9], [27]. In order to maintain a reasonable level of cellular link interference while optimizing the signal-to-interference-plus-noise ratio (SINR) of D2D connections, the BS in [27] regulates the transmit power of D2D devices. Furthermore, [9] proposes a three-step process for designing power control and spectrum allocation to maintain a minimum SINR for D2D links and increase system throughput.

3. SYSTEM MODEL

Figure 1 illustrates the presentation of the system model and the network metrics that will be utilized in this section of the article. This section outlines the network metrics that will be utilized in the study and presents the system model. Our consideration is a D2D underlay cellular network.

In this model, the coverage region of a BS centered at the origin is represented by the circular disk C with a radius of R. The number of cellular uplink users evenly distributed throughout this area is denoted by M={1, … ,m}. Furthermore, we assume that K={11, ... ,k}, the number of D2D users, is distributed according to a homogeneous Poisson point process (PPP) Φ with a density of λ throughout the entire R2 plane. A D2D transmitter's corresponding receiver is located in an isotropic direction at a configurable distance. Every node is assumed to have a single antenna.

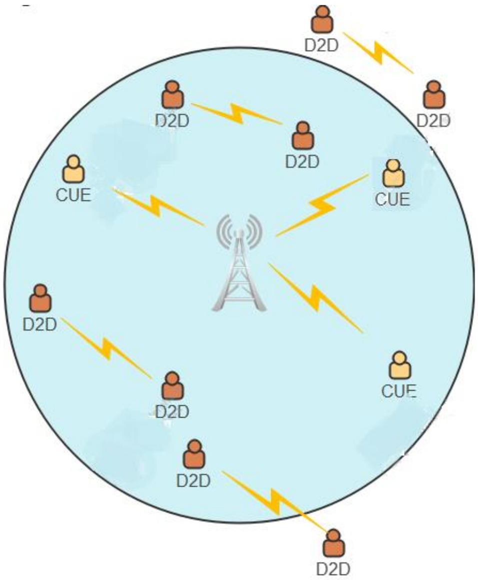


Figure 1. A single-cell D2D underlaid cellular system

The number of D2D transmitters in C is a Poisson random variable with a mean of E [K]=λπR2 based on the assumptions made. It is anticipated that the channel power gain between CUE m and the BS will follow a specific realization of the PPP.

$$h_{m,B} = g_{m,B}\beta_{m,B}Ad_{m,B}^{-\alpha} \quad (1)$$

Where ξ is the standard deviation of $\beta_{m,B}$ is a log-normal shadow fading random variable, $d_{m,B}^{-\alpha}$ is the distance between the m-th CUE and the BS, α is the decay exponent, and A is the pathloss constant. Additionally, there is the small-scale fast fading power component, which is assumed to be exponentially distributed with a mean of one unit. Similar definitions apply to the interfering channels $h_{k,B}$ from the k-th DUE to the BS, $h_{m,k}$ from the m-th CUE to the k-th DUE, and the channel $h_k$between the k-th D2D pair. The received SINRs for the m-th CUE and the k-th DUE at BS can be written as (2):

$$\gamma_m^c = \frac{p_m^c h_{m,B}}{\sigma^2 + \sum_{k\in K} x_{m,k} p_k^d h_{k,B}} \quad (2)$$

Where the transmit powers of the m-th CUE and the k-th DUE are denoted, respectively, by p_m^c and p_k^d. The noise power is represented by σ^2, and the spectrum allocation is indicated by $x_{m,k}$, where $x_{m,k} = 1$ indicates that the k-th DUE reuses the m-th CUE's spectrum and $x_{m,k} = 0$ otherwise. Next, assuming Gaussian inputs, the ergodic capacity of the m-th CUE is given by:

$$C_m = \mathbb{E}[\log_2(1 + \gamma_m^c)] \quad (3)$$

where the fast fading distribution is taken up by the expectation E[.].

4. RESOURCE AND POWER ALLOCATION DESIGN

4.1. Resource allocation

In this study, we examine the design of resource allocation under previous limitations. Our solution for resource allocation aims to provide the best level of dependability for each DUE while maximising the aggregate ergodic capacity of M CUEs. In order to ensure a minimum level of service quality for every CUE, we have established a minimum capacity requirement for each. By managing the likelihood of outage occurrences when a device's received SINR falls below a certain threshold, the dependability of the device is ensured. Because the codeword length is determined by using the long-term average of the rapid fading, it is assumed that the ergodic capacity of CUEs covers multiple coherence periods over the slow fading time scale [28]. Note that the allowable latency and the temporal variation of the user channels ultimately determine the system's performance in approximating the ergodic capacity. In order to mitigate the impact of fading and improve the system's performance in achieving the predicted ergodic capacity, faster variation introduces a greater number of channel states within a given time period. This ensures that the code word passes through most, if not all, of the channel states [29]. The problem of radio resource allocation is stated as (4a)-(4f).

$$\max_{\substack{\{x_{m,k}\}\\ \{p_m^c\},\{p_k^d\}}} \sum_{m\in M} \mathbb{E}[\log_2(1+\gamma_m^c)] \tag{4}$$

$$\mathbb{E}[\log_2(1+\gamma_m^c)] \geq r_0^c, \forall m \in M \tag{4a}$$

$$\Pr\{\gamma_k^d \leq \gamma_0^d\} \leq p_0 \tag{4b}$$

$$0 \leq p_m^c \leq p_{max}^c, \forall m \in M \tag{4c}$$

$$0 \leq p_k^d \leq p_{max}^d, \forall k \in K \tag{4d}$$

$$\sum_{m\in M} x_{m,k} \leq 1, x_{m,k} \in \{0,1\}, \forall k \in K \tag{4e}$$

$$\sum_{k\in K} x_{m,k} \leq 1, x_{m,k} \in \{0,1\}, \forall m \in M \tag{4f}$$

Where γ_0^d is the minimum SINR required by the DUEs to create a reliable link, and r_0^c is the minimum capacity required by the data rate-intensive CUEs. The permissible outage probability at the physical layer of the D2D connections is indicated by p_0, whereas $\Pr\{\cdot\}$ assesses the input probability. The maximum transmit powers of the CUE and DUE are p_{max}^c and p_{max}^d, respectively. For each CUE and DUE, the related minimum capacity and reliability needs are represented by constraints (4a) and (4b).

The minimum capacity and reliability requirements for each CUE and DUE are outlined in constraints (4a) and (4b), respectively. The transmit powers of CUEs and DUEs are prevented from exceeding their maximum limitations by (4c) and (4d), respectively. We mathematically represent our assumptions that only one DUE can access a single CUE's spectrum and that only one CUE can share a spectrum with another in (4e) and (4f). This premise simplifies the intricacy that intricate interference scenarios in networks-assisted D2D bring, and it offers a strong basis for examining the difficult issue of resource allocation in D2D networks.

From the network operator's point of view, a high overall throughput may be guaranteed by the resource allocation scheme previously discussed. However, from each CUE's perspective, it often appears unfair, especially for users experiencing channel difficulties. In this scenario, the overall performance improvement will be achieved at the expense of the CUEs with poor channel conditions. To address this issue and ensure consistent performance across all CUEs, we will maximize the minimum capacity among all CUEs in this section. The suggested optimization issue is:

$$\max_{\substack{\{x_{m,k}\}\\ \{p_m^c\},\{p_k^d\}}} \min_{m\in M} \mathbb{E}[\log_2(1+\gamma_m^c)] \tag{5}$$

With the same equations: (4a)-(4f) as conditions.

4.2. Power allocation

In this section, we will discuss the optimal method for distributing power among all possible combinations of DUE and CUE reuse. The power allocation problem reduces to finding an arbitrary spectrum reuse pattern where the k-th DUE shares the band with the m-th CUE for a single CUE-DUE pair.

$$\max_{p_m^c p_k^d} \mathbb{E}[log_2(1+\gamma_{\boldsymbol{m}}^{\boldsymbol{c}})] \tag{6}$$

$$Pr\{\gamma_{\boldsymbol{k}}^{\boldsymbol{d}} \leq \gamma_{\boldsymbol{0}}^{\boldsymbol{d}}\} \leq p_0 \tag{6a}$$

$$0 \leq p_m^c \leq p_{max}^c \tag{6b}$$

$$0 \leq p_k^d \leq p_{max}^d \tag{6c}$$

In the following lemma, we assess the k-th DUE (6a) reliability constraint and show the feasible areas of the D2D power optimisation problem, which is simplified.

Lemma 1: to maximise its own D2D link rate, the D2D transmitter chooses its broadcast power depending on the channel circumstances, i.e., the distance-based path-loss $d_{k,k}^{-\alpha}$. The use of transmit power p_k^d with transmit probability $\mathcal{P}_{tx}$ by the k-th D2D TX depends on the good channel quality of the k-th D2D link. One can determine the transmission probability by:

$$\mathcal{P}_{tx} \triangleq \mathbb{P}\left[\left|h_{k,k}\right|^2 d_{k,k}^{-\alpha} \geq \gamma_{min}^d\right] \approx exp\left(-\gamma_{min}^d \mathbb{E}\left[d_{k,k}^{\alpha}\right]\right) \tag{7}$$

Furthermore, to compensate for estimation errors in the D2D pair distances, an error margin ε is introduced. As a result, the channel inversion technique described in [30] is used to guide the power allocation for the D2D link.

$$\wp_k^d = \begin{cases} \mathfrak{p}_{rx} d_{k,k}^{\alpha}(1+\varepsilon) \text{with } \mathcal{P}_{tx} \\ 0 \qquad\qquad \text{with } 1-\mathcal{P}_{tx} \end{cases} \tag{8}$$

where $d_{k,k}$ is the distance between the k-th D2D pairings, ε is the estimate error margin of $d_{k,k}^{\alpha}$, and α is the path-loss exponent, with $0 \leq \varepsilon < 1$.

Theorem 1: for optimization problem (6), the optimal power allocation solution is provided by (9):

$$\begin{cases} p_m^c = \min\left(p_{max}^c, p_{d,max}^c\right) \\ \qquad and \\ p_k^d = \min\left(\wp_{max}^d, p_{c,max}^d\right) \end{cases} \tag{9}$$

Theorem 1 offers the best power distribution for a single CUE-DUE pair, maximising the ergodic capacity of the CUE under consideration and guaranteeing the dependability of the reused DUE. Because the initial resource allocation challenge in (4) to optimize the sum ergodic capacity of all CUEs has been split into two main sections, there is only interference within each reuse pair. The optimal power distribution for each individual pair, as shown in Theorem 1, is discussed in the first part. Optimal spectrum reuse pair matching should be used to raise the cumulative ergodic capacity of CUEs while adhering to all QoS constraints.

The appropriate power distribution for each CUE-DUE combination. The next step is to exclude any CUE-DUE pairings that do not meet the CUE's lowest QoS criterion, as defined in (4a) [8]. This is done by using the optimal allocation approach identified in step (9) as a reference. When sharing spectrum with the k-th DUE, the m-th CUE's ergodic capacity has a closed form that is:

$$C_{m,k}\left(p_m^c, p_k^d\right) \triangleq \left[log_2(1+\gamma_{sm}^c)\right] \tag{10}$$

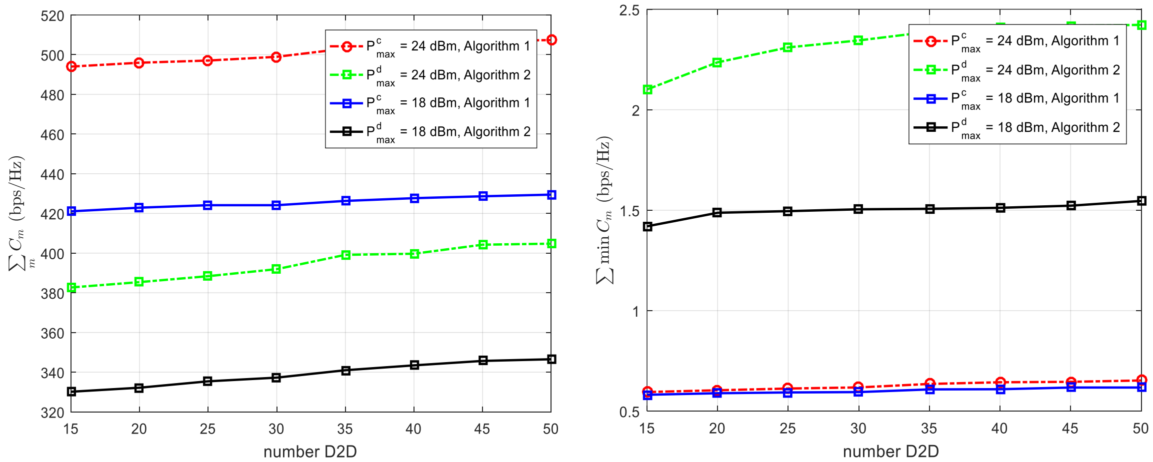
5. RESULTS AND DISCUSSION

We used the parameters listed in Table 1 to configure the system. Furthermore, we modified those parameters for the results to test the performance of our suggested algorithm. Our simulation takes into account a single cell with a radius of 500 meters. The D2D transmitter and receiver could only be separated by a maximum of 15 meters due to any distance beyond that would nullify the advantages of using D2D communication. Although the ergodic capacity can be adjusted by the network operator, it was calculated using 10. D2D users ranged in number from 15 to 50, increasing by 5 points. The outcome is the average of multiple iterations for each scenario. There was a limit of 50 users for each cellular device. Nonetheless, we discovered that our algorithm produced consistent results as the number of mobile users increased.

As the number of D2D pairings increases, Figures 2(a) and (b) display the total and minimum ergodic capacities of all D2Ds. The findings indicate that the minimum and total capacities of D2D increase with the number of D2D pairings. This is because efficient resource reuse for CUs would increase capacities and result in durable D2D links with optimal received power. As a result, DUEs may tolerate less interference from CUEs due to the maximum transmit power constraints. This would result in a decrease in the power allocated to CUEs, thereby increasing both their minimum and sum ergodic capabilities. Additionally, the results of using Algorithms 1 and 2 are displayed in each figure. Algorithms 1 and 2 represent the optimal resource allocation for (4) and (5), respectively. When considering the lowest ergodic capacity, Algorithm 2 performs better than Algorithm 1 in terms of cumulative ergodic capacity. This is understandable because Algorithm 2 aims to decrease ergodic capacity, while Algorithm 1 aims to increase the sum ergodic capacity. Notably, the cumulative D2D capacity performance of both Algorithms 1 and 2 stays steady when the maximum transmit power is increased as the number of D2D pairs rises (Figure 2(a)). When examining the minimum D2D capacity, as shown in Figure 2(b), this is not the case. Couples with a potent D2D.

Table 1. Simulation parameters

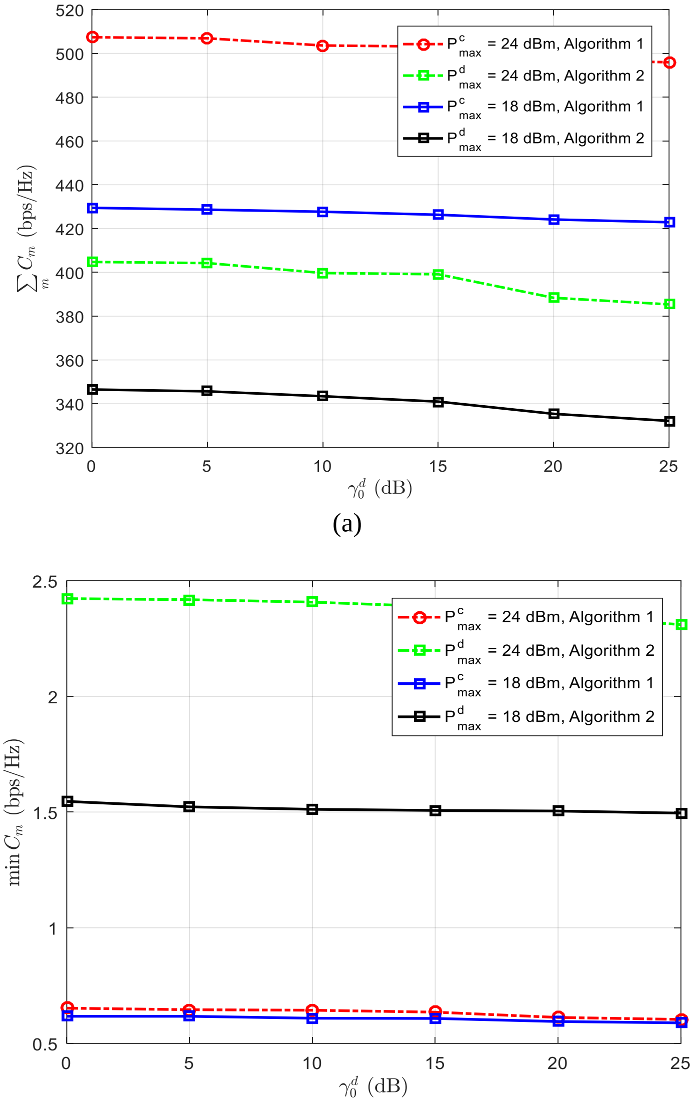
Variable	Value
Carrier frequency	2 GHz
Bandwidth	10 MHz
Cell radius	500 m
BS antenna height	25 m
BS antenna gain	8 dBi
BS receiver noise figure	5 dB
Distance between BS and users	35 m
Number of sup channel	6
Minimum capacity of DUEr_0^c	0.5 bps/Hz
SINR threshold for DUE γ_0^d	5 dB
Reliability for DUE p_0	0.001
Number of DUEs K	50
Number of CUEs M	50
Maximum CUE transmit power p_{max}^c	18, 24 dBm
Maximum DUE transmit power p_{max}^d	18, 24 dBm
Noise power σ^2	-114 dBm
Bisection search accuracy ε	10^{-5}



(a) (b)

Figure 2. Capacity performance of D2Ds with varying number D2D pairs; (a) sum ergodic capacity of D2Ds and (b) minimum ergodic capacity of D2Ds

The minimum and total ergodic capacities of D2D communications at higher SINR thresholds for DUEs are illustrated in Figure 3. As depicted in Figures 3(a) and (b), it can be observed that the analyzed ergodic capacity decreases in both cases as the minimum QoS requirement for DUEs increases. The cumulative ergodic capacity of D2Ds is depicted in Figure 3(a), while the minimum ergodic capacity of D2Ds is illustrated in Figure 3(b). The permitted transmit power of the paired CUEs is further limited due to the reduced capacity of the DUEs to tolerate interference caused by an increase in their required SINR threshold. Lower sums and minimum ergodic capacities that D2Ds can achieve while still meeting all QoS standards are correlated with lower transmit power.



(a)

(b)

Figure 3. Capacity performance of D2Ds with varying DUE SINR threshold; (a) sum ergodic capacity of D2Ds and (b) minimum ergodic capacity of D2Ds

6. CONCLUSION

We examined D2D network resource allocation techniques, such as spectrum sharing, in this article. Our optimization problems aim to develop a resource allocation strategy based solely on slowly changing large-scale fading data. We achieved this by considering the different requirements of device communications in terms of QoS. Robust techniques have made it possible to ensure dependable D2D links while improving the total and minimum ergodic capacity of CUE lines. This is achieved by utilizing the potential for energy allocation separation and by keeping in mind that, when generating the spectrum reuse pattern, the overlap is limited to each CUE-DUE reuse pair. Concentrating on every cue-due pair. We first determined the ideal spectrum sharing pattern between the CUE and DUE groups by comparing the feasibility of each CUE-DUE pair with the minimal capacity requirements for CUE. Next, we utilized the Hungarian algorithm to generate a bipartite histogram. Subsequently, unworkable pairs were excluded. The simulation results demonstrate that the suggested approach can identify the most effective configuration for CUEs and DUEs to share spectrum among all feasible possibilities. Additionally, it can generate the most optimal power control plan for each pair reuse, resulting in the most efficient utilization of resources.The current study excludes broader spectrum reuse and restricts spectrum sharing to only one CUE-DUE pair. These restrictions might be lifted in the future, allowing CUE and D2D linkages to share a significant number of resource blocks.

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