Joint Resource and Power Management for D2D Communication across Multiple Service Providers

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Abstract—*Device-to-device (D2D)* communication broadens the applicability of cellular networks, which permits *user equipments (UEs)* to converse with each other without the relay by a *base station (BS)*. D2D pairs can reuse the spectrum resources allocated to cellular UEs but they would cause interference. How to well manage resources and transmitted power for UEs is critical. This paper considers a RAN (radio access network) sharing scenario, where multiple *service providers (SPs)* collocate in the BS and have dedicated resources. To serve the maximum UEs, we propose a *joint resource allocation and power control with RAN sharing (JAPS)* scheme. Each SP allocates the dedicated resource to UEs and decides initial power to meet their SINR demands and restrain interference. Then, SPs can borrow resources from each other (i.e., inter-SP loan) to serve more UEs and better resource utilization. Lastly, the power of senders is carefully adjusted to improve signal quality. Simulation results show that JAPS can achieve a high service ratio, improve D2D throughput, and raise energy efficiency.

Index Terms—D2D communication, multiple service providers, power control, RAN sharing, resource allocation.

1 Introduction

Nowadays, more and more people use cellular networks for leisure entertainment and information inquiry. Many kinds of Internet-of-things (IoT) devices, which rely on cellular networks for communication, have increased substantially in number. According to [1], there will be 29 billion networked devices by 2023, up from 18 billion in 2018. Moreover, the share of machine-to-machine connections will raise from 33% in 2018 to 50% by 2023. Thus, it is a big challenge to allocate limited spectrum resources to a growing number of devices.

Device-to-device (D2D) communication is one promising solution. This technique lets two nearby devices talk with each other directly, without the relay by a *base station (BS)*. Such devices are called *D2D user equipments (DUEs)*. Using D2D communication has three advantages. First, DUEs can curtail transmitted power to conserve energy and reduce interference. Second, the spectral efficiency is improved, because DUEs and *cellular UEs* (*CUEs*, i.e., the devices in contact with the BS or with other devices via the BS) are able to share spectrum resources [2]. Third, D2D communication can extend the BS's service coverage in a cost-efficient way [3].

To support D2D communication, 3GPP (i.e., 3rd Generation Partnership Project) proposes *proximity-based services (ProSe)* and adds three components to a cellular system [4], as shown in Fig. 1. A *ProSe application* is installed in each UE for D2D discovery and communication. Two ProSe applications use the PC5 interface to build a D2D link. Then, the *ProSe function* handles D2D configuration, identifies D2D applications, and provides network-related functionalities (such as authorization and charging). It adopts a PC4 interface to get the subscriber information from the *evolved packet core (EPC)*. Finally, the *ProSe application server* is a third-party medium used to store information such as identifications and metadata. This server connects to each ProSe application and the ProSe function via the PC1 and PC2 interfaces, respectively.

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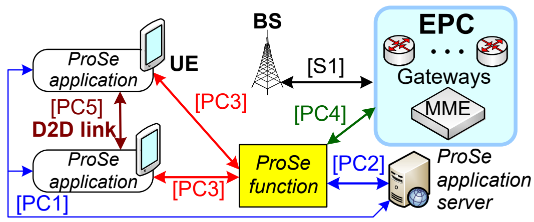


Fig. 1: 3GPP system architecture to support D2D communication.

D2D management can be in either *full* or *loose* control. Full control means that the network takes responsibility for everything, including authentication, resource allocation, and power control. In loose control, the network performs authentication and DUEs do other jobs. Thus, full control incurs three extra overheads. First, just like CUEs, DUEs also inform the BS of their *signal-to-interference-plus-noise ratios (SINRs)*. Second, the BS should allot its spectrum resources to DUEs. Third, the BS has to decide the transmitted power of D2D senders. In fact, the benefits of full control make these overheads seem insignificant, since the BS can allocate resources to UEs much more efficiently and flexibly. Moreover, the interference between CUEs and DUEs is greatly reduced. Consequently, like most studies in the literature (as discussed later in Section 2), we take the full-control strategy in this paper.

To promote the cooperation between *service providers (SPs)* and improve resource usage, the technique of network sharing is proposed [5], which has two models. For *passive network sharing*, SPs merely share sites (e.g., roofs or towers) to deploy their dedicated BSs. In *radio access network (RAN) sharing*, SPs share the spectrum resource and jointly use a BS, which connects to their EPCs by S1 interfaces. SPs can further share MMEs to offer better roaming for their customers (also known as *deeper sharing*). RAN sharing greatly extends services and coverage of 5G systems, and it facilitates network deployment for 5G standalone mode as well as non-standalone mode [6].

In this paper, we apply RAN sharing to D2D communication and consider a practical scenario where the subscribed CUEs and DUEs of different SPs reside in a cell. These SPs share the BS's spectrum resources, which are divided into *resource blocks (RBs)*. Each RB can be allocated to a CUE and may be shared by multiple D2D pairs, whose capacity is decided by the channel quality. When a receiver has a higher SINR on the RB, its sender can encode bits by a more complex modulation and coding scheme, thereby raising the RB's capacity [7].

The RAN sharing scenario poses challenges for resource management. Let us consider an example where two SPs s_a and s_b share a BS. The BS provides a set $\hat{\mathcal{R}}$ of RBs, which is equally divided into two disjoint subsets $\hat{\mathcal{R}}_a$ and $\hat{\mathcal{R}}_b$ dedicated to s_a and s_b, respectively. Conventional solutions make each SP use only its dedicated RBs to serve the subscribed UEs. Suppose that the cell contains many UEs (including CUEs and D2D pairs) of s_a but just a few UEs of s_b. In this case, even if a conventional solution can help s_a "fully" utilize all RBs in $\hat{\mathcal{R}}_a$, some of its UEs will not get RBs (i.e., starvation) as the number of RBs in $\hat{\mathcal{R}}_a$ is not enough to serve all of s_a's UEs. On the contrary, some RBs in $\hat{\mathcal{R}}_b$ may not be allocated because merely a few UEs request resources, which evidently causes a waste of resources. Since the number of UEs (and also demands) of each SP in the cell will dynamically change, it is difficult or even infeasible to let SPs adjust their dedicated RBs in $\hat{\mathcal{R}}$ based on the number of their UEs.

To address the above issue, this paper introduces the concept of *inter-SP loan* that allows SPs to borrow each other's RBs to enhance RAN sharing. Specifically, we formulate a *multi-SP D2D management problem* to assign RBs and decide power for UEs with RAN sharing such that the service ratio can be maximized. Here, the *service ratio* is defined by the ratio of the CUEs and D2D pairs whose minimum demands are sufficed to the total receivers in a cell. To solve this NP-hard problem efficiently, we propose a *joint resource allocation and power control with RAN sharing (JAPS)* scheme. Each SP gives its RBs to the subscribed UEs and finds suitable power, so as to meet their SINR demands. To do so, we build the interference relationship between UEs and separate them into groups, such that the CUE and D2D pairs in a group can share the RB with acceptable interference. If an SP still has UEs not served, it can borrow RBs from other SPs (i.e., inter-SP loan). In this way, not only more UEs are served but also the RB utilization is improved. Lastly, the power of senders is carefully amplified to improve signal quality. Simulation results show that JAPS greatly increases the service ratio, D2D throughput, and energy efficiency, as compared with existing methods.

Our contributions are threefold:

- We explicate a practical scenario for D2D communication with RAN sharing, where the UEs of multiple SPs coexist in a cell and share the BS's resources. This scenario is very useful for SPs to accelerate the deployment of 5G systems, yet it has not been well studied in the literature.
- JAPS is the first work that supports the inter-SP loan for RBs, where D2D pairs can reuse the RBs of CUEs served by different SPs. Thus, JAPS not only adds flexibility to RAN sharing but also greatly raises D2D performance in a multi-SP environment.
- The RB borrowing and lending method in JAPS ensures fairness among SPs. More concretely, JAPS prevents SPs from reserving their dedicated RBs but also borrowing RBs from others. Moreover, JAPS will preclude selfish SPs by giving them low priority on borrowing RBs.

2 Related Work

In the literature, there are four sharing cases proposed for D2D pairs to reuse the RBs allocated to CUEs:

- **S1.** A CUE shares its RBs with a D2D pair. Each D2D pair also chooses one CUE to reuse RBs.
- **S2.** Each CUE shares its RBs with at most one D2D pair, but a D2D pair can reuse RBs of multiple CUEs.
- **S3.** A CUE can share RBs with multiple D2D pairs, but each D2D pair picks just one CUE to reuse RBs.
- **S4.** It is a combination of cases S2 and S3 (i.e., RB sharing among multiple CUEs and multiple D2D pairs).

For case S1, the work [8] adopts the Hungarian method to match D2D pairs with CUEs for RB sharing. The study [9] builds a bipartite graph to describe the sharing relationship of CUEs and DUEs, and finds a maximum matching to improve the overall transmission capacity. In [10], an interference index is proposed to exclude the CUEs and DUEs that cause serious interference from RB-sharing candidates. The work [11] deals with subchannel assignment and power control to raise D2D throughput subject to the QoS constraints of CUEs.

For case S2, the study [12] lets a D2D pair reuse RBs from multiple CUEs if their SINRs can be above a given threshold. The work [13] schedules D2D links by time division multiple access. In each slot, some D2D pairs are enabled, and each of them can share the RBs of multiple CUEs to send data. Duong et al. [14] propose a distance-based scheme to mitigate CUE-to-DUE interference and reduce the outage probability of D2D links. The study [15] aims to serve more D2D pairs and reduce their transmitted power in a cloud RAN.

For case S3, Liu et al. [16] increase admitted D2D links and their data rates by a gradient-descent method. A greedy-based scheme is proposed in [17] to assign subchannels to D2D pairs to hold their interference below a negligible level, so as to suffice the demand of a CUE using the same subchannels.

Case S4 is the most flexible and widely used. The work [18] finds optimal power for DUEs and allots RBs to them by fractional programming. Li et al. [19] formulate a sum-rate maximization problem for partner assignment and power control, which is solved by a greedy approach. In [20], the Gale-Shapley method is applied to pick out matches between CUEs and D2D pairs for RB sharing, which achieves Pareto optimal [21]. Chen et al. [22] use the maximum independent set and Stackelberg game to handle RB allocation and power control. The work [23] allocates channels to D2D pairs and regulates their power to bring up energy efficiency. The study [24] calculates transmission periods and power allocation for DUEs to meet their demands and save energy. Zhou et al. [25] analyze the correlation of UEs by a game-theoretic method, and match D2D pairs with CUEs to improve energy efficiency. The work [26] proposes a graph-coloring solution to allocate RBs, so as to minimize interference between UEs. The *D2D resource allocation and power control (DRAPC)* method [27] groups UEs for reusing RBs. Each group is then reformed by exchanging members to improve signal quality and degree of RB sharing. However, the above studies assume a single SP environment (i.e., without RAN sharing).

The study [28] proposes a coordinated scheduling method to improve throughput in a two-tier network where femtocells are laid under macrocells. It reduces the power requirement of a femtocell by considering the interference from neighboring cells and balances a macrocell's load by changing femtocells'

TABLE 1: Comparison between the prior work and our JAPS scheme.

work	case	power control	RAN sharing	inter-SP loan	time complexity
[8]	S1	√			$O(\xi_D \log_2 \xi_D + \xi_C^3)$
[9]	S1				$O(\xi_D^3)$
[10]	S1	√			$O(\xi_D^2 \xi_C)$
[11]	S1	√			not mentioned
[12]	S2				not mentioned
[13]	S2				not mentioned
[14]	S2				not mentioned
[15]	S2	√			not mentioned
[16]	S3	√			not mentioned
[17]	S3	√			$O(\xi_D^2 \xi_C)$
[18]	S4	√			$O(\xi_D \xi_R)$
[19]	S4	√			not mentioned
[20]	S4				not mentioned
[22]	S4	√			not mentioned
[23]	S4	√			not mentioned
[24]	S4	√			not mentioned
[25]	S4	√			$O(\xi_D \xi_C \log_2(\xi_D \xi_C))$
[26]	S4	√			$O(t \xi_R \xi_D^2)$
[27]	S4	√			$O(\xi_U \xi_R (\xi_U - \xi_R)^3)$
[29]	S1	√			not mentioned
[30]	S4				$O(\xi_D \xi_R^2)$
[31]	S1		√		not mentioned
[32]	S2		√		$O(\xi_D \xi_C)$
JAPS	S4	√	√	√	$O(\xi_U^2)$

modes. However, the discussions in [28] are different from our RAN sharing issue. First, [28] considers a macrocell covering multiple femtocells, where cells have their "exclusive" RBs. In RAN sharing, multiple SPs cooperate on a BS and "share" its RBs. Second, [28] aims to control the power of femtocell BSs to reduce intercell interference, whereas RAN sharing focuses on assigning RBs to UEs of different SPs. Third, [28] assumes only CUEs while our work considers both CUEs and DUEs.

Both [29] and [30] consider *intercell* D2D communication, where D2D senders and receivers reside in different cells, and propose repeated game-theoretic approaches for RB allocation. They are devised for passive network sharing, where multiple SPs each with an unshared BS are situated on the same site. Nevertheless, these approaches could not be applied to RAN sharing, where SPs jointly use a BS and share its resources.

Only few studies consider RAN sharing for D2D communication. In [31], the RB allocation problem is formulated as the binary integer programming that takes account of the cost of each SP. However, [31] adopts the simplest case S1, and DUEs can merely share the RBs of CUEs which belong to the same SP. The work [32] defines two subproblems for RAN sharing. One is to dispense RBs to CUEs of different SPs. The other is to let D2D pairs share the RBs of CUEs served by the same SP with the least interference. However, [32] assumes that the power of the BS and UEs is constant.

Table 1 compares JAPS with the prior work[1]. Many studies consider adjusting the transmitted power of DUEs (i.e., power control) but few of them (e.g., [31], [32]) handle RB allocation with RAN sharing, where multiple SPs collocate in the BS. Our JAPS scheme is the only work that supports inter-SP loan, which allows D2D pairs reusing the RBs of CUEs belonging to different SPs. Thus, JAPS can offer more flexibility to RAN sharing and improve D2D throughput. In Table 1, we also list the time complexity of each work, where ξ_D, ξ_C, ξ_U, and ξ_R denote the numbers of D2D pairs, CUEs, receivers, and RBs, respectively, where $\xi_U = \xi_D + \xi_C$. Besides, t is the number of iterations performed by the method proposed in [26].

1. We do not put the work [28] in Table 1 as it considers only CUEs.

3 MULTI-SP D2D MANAGEMENT PROBLEM

3.1 System Model

Let a set $\hat{\mathcal{S}}$ of SPs cooperate on one BS by RAN sharing. The BS provides a set $\hat{\mathcal{R}}$ of downlink RBs in a period (e.g., transmission time interval), where each SP $s_k \in \hat{\mathcal{S}}$ possesses a subset $\hat{\mathcal{R}}_k$ of RBs in $\hat{\mathcal{R}}$ subject to three conditions: 1) $|\hat{\mathcal{R}}_k| \in \mathbb{Z}^+, \forall s_k \in \hat{\mathcal{S}}$ (i.e., every SP must own a part of RBs in $\hat{\mathcal{R}}$), 2) $\hat{\mathcal{R}}_k \cap \hat{\mathcal{R}}_{k'} = \emptyset$ for $s_k \neq s_{k'}$ (i.e., any two SPs have no common RBs), and 3) $\bigcup_{s_k \in \hat{\mathcal{S}}} \hat{\mathcal{R}}_k = \hat{\mathcal{R}}$ (i.e., all RBs in $\hat{\mathcal{R}}$ are distributed among the SPs in $\hat{\mathcal{S}}$).

3GPP proposes *capacity brokers* [33] to manage the requests and leases of resources for multiple SPs with RAN sharing. The work [34] further extends the capacity broker to a more powerful *network slice broker*. Using brokers substantiates the BS's entire frequency spectrum accessible to each SP in $\hat{\mathcal{S}}$, which facilitates borrowing and lending of RBs among SPs.

Each UE chooses either cellular or D2D communication in a period (i.e., a CUE will not be also a DUE, and vice versa). We consider both *in-band D2D communication* and *underlay-mode D2D communication*. For in-band D2D communication, D2D communication takes place within the licensed band used by CUEs. For underlay-mode D2D communication, D2D pairs can reuse the RBs allocated to CUEs. A D2D pair contains a D2D sender and a D2D receiver, where we use the receiver to represent that D2D pair. Each DUE belongs to only one D2D pair. For convenience, we defined the following sets of UEs: 1) $\hat{\mathcal{C}}_k$ and $\hat{\mathcal{D}}_k$ are the sets of subscribed CUEs and D2D receivers of SP s_k, respectively, where $\hat{\mathcal{C}}_k \cap \hat{\mathcal{D}}_k = \emptyset$ for each $s_k \in \hat{\mathcal{S}}$. 2) $\hat{\mathcal{C}}$ and $\hat{\mathcal{D}}$ denote the sets of all CUEs and all D2D receivers in the cell, respectively, where $\hat{\mathcal{C}} = \bigcup_{\forall s_k \in \hat{\mathcal{S}}} \hat{\mathcal{C}}_k$ and $\hat{\mathcal{D}} = \bigcup_{\forall s_k \in \hat{\mathcal{S}}} \hat{\mathcal{D}}_k$. 3) $\hat{\mathcal{U}}$ is the union of $\hat{\mathcal{C}}$ and $\hat{\mathcal{D}}$. Then, RBs are allocated to UEs based on four rules:

- **R1.** Two CUEs cannot use the same RB.
- **R2.** Multiple D2D pairs can reuse a CUE's RBs or mutually share the RBs not allocated to any CUE.
- **R3.** Each SP s_k first allocates the RBs in $\hat{\mathcal{R}}_k$ to its subscribed UEs (including RB sharing for DUEs).
- **R4.** After s_k allocates RBs by rule R3, it can lend other SPs the available RBs in $\hat{\mathcal{R}}_k$ (i.e., inter-SP loan).

When the members of a D2D pair belong to different SPs, the receiver's SP takes charge of RB allocation. Suppose that u_i and u_j are the sender and the receiver of a D2D pair, which belong to SPs s_a and s_b, respectively. By rule R3, s_b allots an RB r_x from $\hat{\mathcal{R}}_b$ for this pair. On the other hand, the CUEs attached to the D2D sender's SP s_a (i.e., $\hat{\mathcal{C}}_a$) use the RBs in $\hat{\mathcal{R}}_a$. Since $\hat{\mathcal{R}}_a \cap \hat{\mathcal{R}}_b = \emptyset$, we ascertain that $r_x \notin \hat{\mathcal{R}}_a$. Thus, even though s_a does not know what RB is used by u_i, u_i will not incur much interference on the CUEs in $\hat{\mathcal{C}}_a$ (as u_i sends data to u_j on r_x instead of on an RB in $\hat{\mathcal{R}}_a$). Moreover, if RB r_x is obtained by rule R4 (i.e., borrowing from another SP), u_i's power will be checked and carefully adjusted to avoid interfering with other UEs that also use r_x. Therefore, it is feasible to let the receiver's SP assign RBs for the D2D pair.

3.2 Estimation of Channel Quality

The capacity of each RB depends on the receiver's channel quality, which can be estimated by SINR. Consider that a UE u_i gets data from its sender $\tau(i)$ by using RB r_x. The strength of $\tau(i)$'s signal received by u_i is $\tilde{g}^x_{\tau(i),i} \times \tilde{p}^x_{\tau(i),i}$, where $\tilde{g}^x_{\tau(i),i}$ is

TABLE 2: The amount of interference from u_j's sender $\tau(j)$ to u_i.

$\tau(j)$	u_j	u_i	the amount of interference $\tilde{n}^x_{\tau(j),i}$ on RB r_x
BS	CUE	CUE	0 (as u_i and u_j cannot share r_x by rule R1)
BS	CUE	DUE	$\tilde{g}^x_{\text{BS},i} \times \tilde{p}^x_{\text{BS},j}$
DUE	DUE	UE	$\tilde{g}^x_{\tau(j),i} \times \tilde{p}^x_{\tau(j),j}$

$\tau(i)$'s channel gain to u_i on r_x and $\tilde{p}^x_{\tau(i),i}$ is $\tau(i)$'s transmitted power on r_x for sending data to u_i.

When two UEs u_i and u_j share RB r_x, u_i will be interfered by u_j's sender $\tau(j)$, and vice versa. The amount of interference $\tilde{n}^x_{\tau(j),i}$ is determined by the roles of $\tau(j)$, u_j, and u_i, as shown in Table 2. Then, u_i's SINR on r_x is computed by

$$\sigma^x_i = \frac{\alpha^x_i(\tilde{g}^x_{\text{BS},i} \times \tilde{p}^x_{\text{BS},i})}{\sum_{u_j \in \hat{\mathcal{D}}} \alpha^x_j \tilde{n}^x_{\tau(j),i} + \varepsilon} \quad \text{if } u_i \in \hat{\mathcal{C}}, \tag{1}$$

$$\sigma^x_i = \frac{\alpha^x_i(\tilde{g}^x_{\tau(i),i} \times \tilde{p}^x_{\tau(i),i})}{\sum_{u_j \in \hat{\mathcal{C}}} \alpha^x_j \tilde{n}^x_{\text{BS},i} + \sum_{u_{j'} \in \hat{\mathcal{D}} \setminus \{u_i\}} \alpha^x_{j'} \tilde{n}^x_{\tau(j'),i} + \varepsilon} \quad \text{if } u_i \in \hat{\mathcal{D}}, \tag{2}$$

where $\alpha^x_j = 1$ if u_j uses r_x, or $\alpha^x_j = 0$ otherwise. Moreover, ε denotes the environmental interference, including the thermal noise and interference from nearby cells. By using the inter-cell interference coordination technique [35], the latter can be ignored. Thus, we consider only the thermal noise in ε.

3.3 Problem Formulation

Let β^x_i be an indicator to reveal whether the channel quality of UE u_i on RB r_x meets its minimum required SINR $\sigma^{\min}_i$, where $\beta^x_i = 1$ if $\sigma^x_i \geq \sigma^{\min}_i$, or $\beta^x_i = 0$ otherwise. Then, the multi-SP D2D management problem is formulated as follows:

$$\text{maximize} \sum\nolimits_{s_k \in \hat{\mathcal{S}}} \sum\nolimits_{r_x \in \hat{\mathcal{R}}_k} \sum\nolimits_{u_i \in \hat{\mathcal{C}}_k \cup \hat{\mathcal{D}}_k} \alpha^x_i \beta^x_i, \tag{3}$$

subject to the following constraints:

$$\sum\nolimits_{s_k \in \hat{\mathcal{S}}} \sum\nolimits_{u_i \in \hat{\mathcal{C}}_k} \alpha^x_i \leq 1 \qquad \forall r_x \in \hat{\mathcal{R}}, \tag{4}$$

$$\alpha^x_i \in \{0,1\}, \beta^x_i \in \{0,1\} \qquad \forall u_i \in \hat{\mathcal{U}}, \forall r_x \in \hat{\mathcal{R}}, \tag{5}$$

$$\tilde{p}^x_{\tau(i),i} \in [\tilde{p}^{\min}_i, \tilde{p}^{\max}_i] \qquad \forall u_i \in \hat{\mathcal{U}}, \forall r_x \in \hat{\mathcal{R}}, \tag{6}$$

The objective function in Eq. (3) is to maximize the number of CUEs and D2D pairs served by all SPs, where $u_i \in \hat{\mathcal{C}}_k \cup \hat{\mathcal{D}}_k$ is regarded as a *served* UE if it can acquire RBs that fulfill the SINR demand $\sigma^{\min}_i$. The control parameters include α^x_i (i.e., RB allocation) and β^x_i (i.e., power control, as the transmitted power decides the UE's SINR). For constraints, Eq. (4) means that each RB cannot be used by multiple CUEs. In Eq. (5), both α^x_i and β^x_i are indicators whose values are 0 or 1. Then, Eq. (6) gives the minimum and maximum values (i.e., $\tilde{p}^{\min}_i$ and $\tilde{p}^{\max}_i$) of the power of u_i's sender. Here, the calculation of SINR σ^x_i in Eqs. (1) and (2) has taken account of interference, so we need not add extra constraints for interference.

The multi-SP D2D management problem is NP-hard, since its formulation can be expressed as a mixed integer nonlinear programming problem. Table 3 summarizes our notations and Table 4 lists all abbreviations.

TABLE 3: Summary of notations.

notation	definition
$\hat{\mathcal{S}}$	the set of SPs that cooperate on the BS
$\hat{\mathcal{R}}_k$	the set of RBs owned by SP s_k ($\hat{\mathcal{R}}$: union of all $\hat{\mathcal{R}}_k$)
$\hat{\mathcal{C}}_k$, $\hat{\mathcal{D}}_k$	the sets of subscribed CUEs and D2D receivers of s_k ($\hat{\mathcal{C}}$, $\hat{\mathcal{D}}$: union of all $\hat{\mathcal{C}}_k$ and $\hat{\mathcal{D}}_k$; $\hat{\mathcal{C}} \cup \hat{\mathcal{D}} = \hat{\mathcal{U}}$)
$\hat{\mathcal{C}}'_k$, $\hat{\mathcal{D}}'_k$	the sets of s_k's CUEs and D2D receivers not served yet
$\hat{\mathcal{I}}_i$	the set of UEs whose senders cause interference to UE u_i
$\hat{\mathcal{G}}_x$	the group of UEs that share RB r_x ($\lvert\hat{\mathcal{G}}_x\rvert \leq \delta$, where δ is the maximum group size)
$\tau(i)$	u_i's sender
$\tilde{g}^x_{\tau(i),i}$	$\tau(i)$'s channel gain to u_i on r_x
$\tilde{p}^x_{\tau(i),i}$	$\tau(i)$'s power to u_i on r_x ($\tilde{p}^{\min}_i \leq \tilde{p}^x_{\tau(i),i} \leq \tilde{p}^{\max}_i$)
$\tilde{n}^x_{\tau(j),i}$	$\tau(j)$'s interference to u_i on r_x ($\tilde{n}_{\text{th}}$: threshold)
σ^x_i	u_i's SINR on r_x ($\sigma^{\min}_i$: minimum required SINR)
λ_i	u_i's throughput
α^x_i	an indicator to check if u_i uses r_x
β^x_i	an indicator to check if $\sigma^x_i \geq \sigma^{\min}_i$
ξ_U, ξ_R	the number of UEs in $\hat{\mathcal{U}}$ and the number of RBs in $\hat{\mathcal{R}}$
ξ^C_k, ξ^D_k	the numbers of CUEs and D2D receivers attached to s_k
ξ^R_k	the number of RBs owned by s_k

TABLE 4: List of abbreviations.

abbrev.	full name
3GPP	3rd Generation Partnership Project
APC	adaptive power control
BS	base station
CRB	cross-SP RB borrowing
D2D	device-to-device
DRAPC	D2D resource allocation and power control
EPC	evolved packet core
IRA	intra-SP RB allocation
JAPS	joint resource allocation & power control with RAN sharing
MME	mobility management entity
ProSe	proximity-based services
RAN	radio access network
RB	resource block
RLB	RB lending and borrowing
SINR	signal-to-interference-plus-noise ratio
SP	service provider
UE	user equipment (CUE/DUE: cellular/D2D UE)
UTI	UE throughput improvement
WRVD	wireless resource virtualization with D2D communication

4 The Proposed JAPS Scheme

Each SP s_k keeps an *RB lending and borrowing (RLB)* table Γ_k to record the debtor-creditor relationship with other SPs, so as to carry out the inter-SP loan. The format of each entry is $\langle s_m, L_m, B_m \rangle$, which indicates that s_k has lent L_m RBs to s_m and borrowed B_m RBs from s_m. The RLB table helps figure out the charges among SPs for lending RBs. Moreover, s_k's *credit* is defined by

$$\gamma_k = \sum\nolimits_{s_m \in \hat{\mathcal{S}} \setminus \{s_k\}} L_m - B_m. \tag{7}$$

If the credit is positive (or negative), s_k lends more (or fewer) RBs than it borrows. Since $\hat{\mathcal{R}}_k$ is fixed for each SP, we have $\sum_{s_k \in \hat{\mathcal{S}}} \gamma_k = 0$. The credit will be used to determine the order for SPs to borrow RBs (as discussed in Section 4.2).

Let $\hat{\mathcal{I}}_i$ be the set of UEs whose senders will interfere with a UE u_i. Suppose that a UE u_j shares an RB r_x with u_i and u_j's sender $\tau(j)$ adopts the minimum power $\tilde{p}^{\min}_j$ to transmit data. If $\tilde{n}^x_{\tau(j),i}$ overtakes a threshold $\tilde{n}_{\text{th}}$, $\tau(j)$ imposes non-neglected interference on u_i. Thus, u_j belongs to $\hat{\mathcal{I}}_i$, and u_i and u_j should not share RBs due to significant interference.

Algo. 1 gives JAPS's pseudocode. In lines 1–4, we find $\hat{\mathcal{I}}_i$ for each UE u_i in $\hat{\mathcal{U}}$, whose interference $\tilde{n}^x_{\tau(j),i}$ (in line 3) is reckoned by $\tilde{g}^x_{\tau(j),i} \times \tilde{p}^{\min}_j$. To save the computational cost, we pick just one RB to check[2]. Then, each SP $s_k \in \hat{\mathcal{S}}$ allocates the

2. If $\tau(j)$ interferes with u_i on an RB significantly by using the minimum transmitted power, we infer that it would also cause non-neglected interference to u_i on other RBs (which are shared by both u_i and u_j).

Algorithm 1: The JAPS Scheme

Input: SPs in $\hat{\mathcal{S}}$, UEs in $\hat{\mathcal{U}}$, and RBs in $\hat{\mathcal{R}}$
Output: RB and power allocation for UEs in $\hat{\mathcal{U}}$
1 **foreach** $u_i \in \hat{\mathcal{U}}$ **do**
2   **foreach** $u_j \in \hat{\mathcal{U}} \setminus \{u_i\}$ *and the combination of u_i and u_j has not been checked yet* **do**
3   **if** $\tilde{n}^x_{\tau(j),i} > \tilde{n}_{\text{th}}$ *for any* $r_x \in \hat{\mathcal{R}}$ **then**
4       $\hat{\mathcal{I}}_i \leftarrow \hat{\mathcal{I}}_i \cup \{u_j\}$ and $\hat{\mathcal{I}}_j \leftarrow \hat{\mathcal{I}}_j \cup \{u_i\}$;
5 **foreach** $s_k \in \hat{\mathcal{S}}$ **do**
6   Allot RBs in $\hat{\mathcal{R}}_k$ to UEs in $\hat{\mathcal{C}}_k \cup \hat{\mathcal{D}}_k$ by Algo. 2;
7 SPs with unserved UEs borrow RBs by Algo. 3;
8 **foreach** $r_x \in \hat{\mathcal{R}}$ **do**
9   Improve throughput of UEs in $\hat{\mathcal{G}}_x$ by Algo. 4;

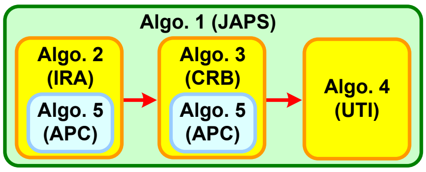


Fig. 2: The relationship between each algorithm.

TABLE 5: Comparison on the proposed algorithms.

algorithm	set of UEs	RB allocation	power control
Algo. 1 (JAPS)	$\hat{\mathcal{U}}$	√	√
Algo. 2 (IRA)	$\hat{\mathcal{C}}_k$ and $\hat{\mathcal{D}}_k$	√	√
Algo. 3 (CRB)	$\hat{\mathcal{C}}'_k$, $\hat{\mathcal{D}}'_k$, $\forall s_k \in \hat{\mathcal{S}}$	√	√
Algo. 4 (UTI)	$\hat{\mathcal{G}}_x$		√
Algo. 5 (APC)	$\hat{\mathcal{G}}_x$		√

RBs in $\hat{\mathcal{R}}_k$ to its subscribed UEs (i.e., $\hat{\mathcal{C}}_k \cup \hat{\mathcal{D}}_k$) by the *intra-SP RB allocation (IRA) algorithm* in Algo. 2. After that, if an SP still has some UEs not served (due to insufficient RBs in $\hat{\mathcal{R}}_k$), it borrows RBs from other SPs and uses these RBs to serve the unsatisfied UEs, which is done by the *cross-SP RB borrowing (CRB) algorithm* in Algo. 3. Lastly, for each group $\hat{\mathcal{G}}_x$ of UEs sharing RB r_x, we use the *UE throughput improvement (UTI) algorithm* in Algo. 4 to raise their throughput.

Fig. 2 depicts the relationship between each algorithm. Both IRA and CRB will involve the *adaptive power control (APC) algorithm* in Algo. 5 to compute transmitted power for UEs to facilitate RB allocation. Table 5 compares these algorithms. Algo. 1 (JAPS) deals with all UEs in $\hat{\mathcal{U}}$. Algo. 2 (IRA) copes with the subscribed CUEs and D2D receivers of an SP s_k (i.e., $\hat{\mathcal{C}}_k$ and $\hat{\mathcal{D}}_k$). Algo. 3 (CRB) handles non-served UEs (i.e., $\hat{\mathcal{C}}'_k$ and $\hat{\mathcal{D}}'_k$ for each SP s_k in $\hat{\mathcal{S}}$). Algorithms 1–3 consider both RB allocation and power control. Algo. 4 (UTI) and Algo. 5 (APC) aim at a group $\hat{\mathcal{G}}_x$ of UEs that share RB r_x. Hence, Algorithms 4–5 only perform power control.

Below, we detail each algorithm, followed by a discussion on JAPS. Lemma 1 presents a preliminary analysis of JAPS's time complexity (Theorem 7 will give the complete analysis).

Lemma 1. *Let $T_2(s_k)$, T_3, $T_4(r_x)$ be the computation time of Algo. 2 (for an SP s_k), Algo. 3, and Algo. 4 (for an RB r_x), respectively. Given ξ_U UEs in $\hat{\mathcal{U}}$, the time complexity of JAPS is $O(\frac{\xi_U(\xi_U-1)}{2}) + \sum_{s_k\in\hat{\mathcal{S}}} T_2(s_k) + T_3 + \sum_{r_x\in\hat{\mathcal{R}}} T_4(r_x)$.*

Algorithm 2: Intra-SP RB Allocation (IRA)

Input: CUEs $\hat{\mathcal{C}}_k$ and DUEs $\hat{\mathcal{D}}_k$ attached to SP s_k
Output: RB assignment and initial power for each UE in $\hat{\mathcal{C}}_k \cup \hat{\mathcal{D}}_k$
1 $\hat{\mathcal{C}}'_k \leftarrow f^{\text{DEC}}_{\text{SORT}}(\hat{\mathcal{C}}_k, \tilde{g}^x_{\text{BS},i})$;
2 **foreach** $u_i \in \hat{\mathcal{C}}'_k$ **do**
3   **foreach** $r_x \in \hat{\mathcal{R}}_k$ **do**
4   **if** $\hat{\mathcal{G}}_x = \emptyset$ **then**
5   Add u_i to $\hat{\mathcal{G}}_x$ and remove it from $\hat{\mathcal{C}}'_k$;
6       $\tilde{p}^x_{\text{BS},i} \leftarrow (\sigma^{\min}_i \times \varepsilon)/\tilde{g}^x_{\text{BS},i}$;
7   break;
8 $\hat{\mathcal{D}}'_k \leftarrow f^{\text{DEC}}_{\text{SORT}}(\hat{\mathcal{D}}_k, \tilde{g}^x_{\text{BS},i})$;
9 **foreach** $u_i \in \hat{\mathcal{D}}'_k$ **do**
10   **foreach** $r_x \in \hat{\mathcal{R}}_k$ **do**
11   **if** $\hat{\mathcal{G}}_x \cap \hat{\mathcal{I}}_i = \emptyset$ *and* $|\hat{\mathcal{G}}_x| < \delta$ **then**
12   Find power for $\hat{\mathcal{G}}_x \cup \{u_i\}$ by Algo. 5;
13   **if** $\sigma^x_j \geq \sigma^{\min}_j$, $\forall u_j \in \hat{\mathcal{G}}_x \cup \{u_i\}$ **then**
14   Add u_i to $\hat{\mathcal{G}}_x$ and remove it from $\hat{\mathcal{D}}'_k$;
15   break;

Proof: In lines 1–4, we check the combination of any two UEs in $\hat{\mathcal{U}}$ to build $\hat{\mathcal{I}}_i$ for every UE, which takes $O(\frac{\xi_U(\xi_U-1)}{2})$ time. The rest of Algo. 1 spends time of $\sum_{s_k\in\hat{\mathcal{S}}} T_2(s_k) + T_3 + \sum_{r_x\in\hat{\mathcal{R}}} T_4(r_x)$, so this theorem is verified. □

4.1 Intra-SP RB Allocation (IRA) Algorithm

Each SP $s_k \in \hat{\mathcal{S}}$ uses the IRA algorithm to serve its UEs by allocating RBs and deciding initial power, whose pseudocode is given in Algo. 2. This algorithm is composed of two parts. Part 1 (lines 1–7) copes with the CUEs in $\hat{\mathcal{C}}_k$ and part 2 (lines 8–15) deals with the DUEs in $\hat{\mathcal{D}}_k$.

For part 1, if a CUE u_i has a larger gain $\tilde{g}^x_{\text{BS},i}$, the BS can use less transmitted power $\tilde{p}^x_{\text{BS},i}$ to fulfill its SINR demand (referring to Eq. (1)), which helps reduce interference to DUEs sharing the same RB. In view of this, line 1 sorts all CUEs in $\hat{\mathcal{C}}_k$ by their gains from the BS decreasingly, which is denoted by $f^{\text{DEC}}_{\text{SORT}}(\hat{\mathcal{C}}_k, \tilde{g}^x_{\text{BS},i})$, and stores the result in $\hat{\mathcal{C}}'_k$ (i.e., the set of s_k's unserved CUEs). Then, we repeatedly pick a CUE u_i with the maximum gain from $\hat{\mathcal{C}}'_k$ (in line 2) and check if there exists an RB r_x in $\hat{\mathcal{R}}_k$ not given to any UE (i.e., lines 3–4). If so, we add u_i to $\hat{\mathcal{G}}_x$ (i.e., a group of UEs that share r_x) and remove it from $\hat{\mathcal{C}}'_k$. After that, line 6 decides the initial power $\tilde{p}^x_{\text{BS},i}$ to satisfy u_i's demand $\sigma^{\min}_i$, which can be derived by

$$(\tilde{g}^x_{\text{BS},i} \times \tilde{p}^x_{\text{BS},i})/\varepsilon \geq \sigma^{\min}_i \Rightarrow \tilde{p}^x_{\text{BS},i} = (\sigma^{\min}_i \times \varepsilon)/\tilde{g}^x_{\text{BS},i}. \quad (8)$$

In part 2, we also sort all DUEs in $\hat{\mathcal{D}}_k$ based on their gains $\tilde{g}^x_{\text{BS},i}$ from the BS in descending order, whose result is stored in $\hat{\mathcal{D}}'_k$ (i.e., the set of s_k's D2D receivers not served yet), as shown in line 8. Specifically, when a DUE u_i has a larger gain $\tilde{g}^x_{\text{BS},i}$, there is a good possibility that u_i is closer to the BS (and gets larger interference). As compared with those DUEs far away from the BS, the DUEs with large gains have fewer candidate RBs for sharing, so they should be considered first. Then, we iteratively pick a DUE from $\hat{\mathcal{D}}'_k$ and find an RB r_x in $\hat{\mathcal{R}}_k$ for it based on two conditions in line 11. First, there is no member in $\hat{\mathcal{I}}_i$ that also uses r_x (i.e., $\hat{\mathcal{G}}_x \cap \hat{\mathcal{I}}_i = \emptyset$, as its sender will cause significant interference to u_i). Second, the number of UEs (including CUEs and D2D receivers) that share r_x is below a threshold δ. Evidently, δ limits the maximum group size, and using it can save the computational cost[3]. Afterward, we adopt the APC algorithm in Algo. 5 to find the transmitted power for all UEs in $\hat{\mathcal{G}}_x \cup \{u_i\}$. If the SINR demand of each UE can be still met (i.e., line 13), it is safe to add u_i to $\hat{\mathcal{G}}_x$ in line 14 (i.e., u_i can share r_x). Theorem 1 analyzes the time complexity of the IRA algorithm.

Theorem 1. *Suppose that an SP s_k has ξ_k^C CUEs, ξ_k^D D2D receivers, and ξ_k^R RBs. The time complexity of Algo. 2 for s_k is $T_2(s_k) = O(\xi_k^R(\xi_k^C + \xi_k^D T_5(\delta)))$, where $T_5(\delta)$ is the computation time of Algo. 5 with δ UEs.*

Proof: Line 1 takes $O(\xi_k^C \log_2 \xi_k^C)$ time to sort $\hat{\mathcal{C}}_k$. The first double for-loop in lines 2–7 spends $O(\xi_k^C \xi_k^R)$ time. Line 8 requires $O(\xi_k^D \log_2 \xi_k^D)$ time to sort $\hat{\mathcal{D}}_k$. The worst case of the second double for-loop in lines 9–15 occurs when $|\hat{\mathcal{G}}_x| = \delta - 1$. In this case, line 12 takes $T_5(\delta)$ time and lines 13–15 spend $O(\delta)$ time. Therefore, the overall time complexity is $T_2(s_k) = O(\xi_k^C \log_2 \xi_k^C) + O(\xi_k^C \xi_k^R) + O(\xi_k^D \log_2 \xi_k^D) + \xi_k^D \xi_k^R (T_5(\delta) + O(\delta))$. As $\xi_k^R > \log_2 \xi_k^C$, $T_5(\delta) > \delta$, and $\xi_k^R T_5(\delta) > \log_2 \xi_k^D$, T_2 can be simplified to $O(\xi_k^R(\xi_k^C + \xi_k^D T_5(\delta)))$. □

4.2 Cross-SP RB Borrowing (CRB) Algorithm

Let $\hat{\mathcal{S}}_{\mathrm{C}}$ and $\hat{\mathcal{S}}_{\mathrm{D}}$ be the sets of SPs that have unserved CUEs and DUEs (i.e., $\hat{\mathcal{C}}'_k \neq \emptyset$ and $\hat{\mathcal{D}}'_k \neq \emptyset$) after running Algo. 2, respectively. The CRB algorithm in Algo. 3 allows these SPs to borrow RBs from others for serving the UEs in $\hat{\mathcal{S}}_{\mathrm{C}}$ and $\hat{\mathcal{S}}_{\mathrm{D}}$, which realizes the concept of inter-SP loan.

CRB first handles the unserved CUEs of the SPs in $\hat{\mathcal{S}}_{\mathrm{C}}$ by lines 1–9. According to Eq. (7), if an SP s_k has lent more RBs to others, it will have higher credit γ_k. For the sake of fairness, s_k is given priority to borrowing RBs. Thus, line 1 sorts all SPs in $\hat{\mathcal{S}}_{\mathrm{C}}$ by their credit decreasingly. Then, for each unserved CUE u_i in $\hat{\mathcal{C}}'_k$ (by line 3), we pick an RB r_x owned by another SP, say, s_m (by line 4). If $\hat{\mathcal{G}}_x$ (i.e., the group of UEs that share r_x) contains neither CUEs nor members in $\hat{\mathcal{I}}_i$ (whose senders will cause significant interference to u_i), we use Algo. 5 to find transmitted power for the UEs in $(\hat{\mathcal{G}}_x \cup \{u_i\})$. The code is given in lines 5 and 6. After that, line 7 checks if the $\sigma_j^{\min}$ demand of every UE in $(\hat{\mathcal{G}}_x \cup \{u_i\})$ is met. If so, u_i can share r_x, and thus line 8 adds u_i to $\hat{\mathcal{G}}_x$ and removes it from $\hat{\mathcal{C}}'_k$ (as u_i is served). Because r_x is owned by s_m instead of s_k, their RLB tables should be updated accordingly. Specifically, in table Γ_k, we update the entry $\langle s_m, L_m, B_m \rangle$ by $\langle s_m, L_m, B_m + 1 \rangle$, because s_k borrows one RB from s_m. On the other hand, in table Γ_m, the entry $\langle s_k, L_k, B_k \rangle$ will be updated by $\langle s_k, L_k + 1, B_k \rangle$.

In lines 10–18, we deal with the unserved DUEs of the SPs in $\hat{\mathcal{S}}_{\mathrm{D}}$. The code is similar to that in lines 1–9, except that in line 14, we check if $\hat{\mathcal{G}}_x$ does not contain any member in $\hat{\mathcal{I}}_i$ (to avoid interference) and its size is below threshold δ. Theorem 2 analyzes the time complexity of the CRB algorithm.

3. When an RB r_x is used by many UEs, they will raise the interference on r_x, which decreases the possibility of finding more UEs to share r_x. Thus, we use δ to reduce unnecessary checks. This condition can be relaxed to some extent by selecting a larger δ or completely invalidated by setting $\delta \geq |\hat{\mathcal{U}}|$.

Algorithm 3: Cross-SP RB Borrowing (CRB)

Input: SPs which have unserved CUEs or DUEs (i.e., $\hat{\mathcal{S}}_{\mathrm{C}}$ and $\hat{\mathcal{S}}_{\mathrm{D}}$)
Output: Updated RLB table for each SP

1 $\hat{\mathcal{S}}_{\mathrm{C}} \leftarrow f_{\mathtt{SORT}}^{\mathtt{DEC}}(\hat{\mathcal{S}}_{\mathrm{C}}, \gamma_k)$;
2 **foreach** $s_k \in \hat{\mathcal{S}}_{\mathrm{C}}$ **do**
3   **foreach** $u_i \in \hat{\mathcal{C}}'_k$ **do**
4   **foreach** $r_x \in \hat{\mathcal{R}} \setminus \hat{\mathcal{R}}_k$ **do**
5   **if** $\hat{\mathcal{G}}_x \cap (\hat{\mathcal{C}} \cup \hat{\mathcal{I}}_i) = \emptyset$ **then**
6   Find power for $\hat{\mathcal{G}}_x \cup \{u_i\}$ by Algo. 5;
7   **if** $\sigma_j^x \geq \sigma_j^{\min}, \forall u_j \in \hat{\mathcal{G}}_x \cup \{u_i\}$ **then**
8   Add u_i to $\hat{\mathcal{G}}_x$, remove u_i from $\hat{\mathcal{C}}'_k$, and update RLB tables;
9   break;
10 $\hat{\mathcal{S}}_{\mathrm{D}} \leftarrow f_{\mathtt{SORT}}^{\mathtt{DEC}}(\hat{\mathcal{S}}_{\mathrm{D}}, \gamma_k)$;
11 **foreach** $s_k \in \hat{\mathcal{S}}_{\mathrm{D}}$ **do**
12   **foreach** $u_i \in \hat{\mathcal{D}}'_k$ **do**
13   **foreach** $r_x \in \hat{\mathcal{R}} \setminus \hat{\mathcal{R}}_k$ **do**
14   **if** $\hat{\mathcal{G}}_x \cap \hat{\mathcal{I}}_i = \emptyset$ *and* $|\hat{\mathcal{G}}_x| < \delta$ **then**
15   Find power for $\hat{\mathcal{G}}_x \cup \{u_i\}$ by Algo. 5;
16   **if** $\sigma_j^x \geq \sigma_j^{\min}, \forall u_j \in \hat{\mathcal{G}}_x \cup \{u_i\}$ **then**
17   Add u_i to $\hat{\mathcal{G}}_x$, remove u_i from $\hat{\mathcal{D}}'_k$, and update RLB tables;
18   break;

Theorem 2. *Given ξ_U UEs in $\hat{\mathcal{U}}$ and ξ_R RBs in $\hat{\mathcal{R}}$, the time complexity of Algo. 3 is $T_3 = T_5(\delta)O(\xi_R(\xi_U - \xi_R))$, where $T_5(\delta)$ is the computation time of Algo. 5 with δ UEs.*

Proof: Line 1 takes $O(\xi_S \log_2 \xi_S)$ time to sort $\hat{\mathcal{S}}_{\mathrm{C}}$, where ξ_S is the number of SPs. Let SP s_k have ξ_k^C CUEs, ξ_k^D D2D receivers, and ξ_k^R RBs. In line 3, the worst case occurs when $\xi_k^C > \xi_k^R$, where $|\hat{\mathcal{C}}'_k| = \xi_k^C - \xi_k^R$ as Algo. 2 served ξ_k^R CUEs by giving each of them an RB[4]. Thus, the first triple for-loop in lines 2–9 repeats at most $\xi_S(\xi_k^C - \xi_k^R)(\xi_R - \xi_k^R)$ times. Since line 6 spends $T_5(\delta)$ time and lines 7–9 take $O(\delta)$ time, this loop takes time of $\xi_S(\xi_k^C - \xi_k^R)(\xi_R - \xi_k^R)(T_5(\delta) + O(\delta))$. Then, line 10 sorts $\hat{\mathcal{S}}_{\mathrm{D}}$ and consumes $O(\xi_S \log_2 \xi_S)$ time. The second triple for-loop in lines 11–18 repeats no more than $\xi_S \xi_k^D (\xi_R - \xi_k^R)$ times. Similarly, each iteration of this loop takes $(T_5(\delta) + O(\delta))$ time. To sum up, the total time complexity is $T_3 = 2O(\xi_S \log_2 \xi_S) + \xi_S(\xi_k^C - \xi_k^R)(\xi_R - \xi_k^R)(T_5(\delta) + O(\delta)) + \xi_S \xi_k^D (\xi_R - \xi_k^R)(T_5(\delta) + O(\delta)) = \xi_S(\xi_R - \xi_k^R)(T_5(\delta) + O(\delta))(\xi_k^C + \xi_k^D - \xi_k^R)$. Since $\sum_{\forall s_k \in \hat{\mathcal{S}}} (\hat{\mathcal{C}}_k \cup \hat{\mathcal{D}}_k) = \hat{\mathcal{U}}$ and $\sum_{\forall s_k \in \hat{\mathcal{S}}} \hat{\mathcal{R}}_k = \hat{\mathcal{R}}$, we have $\xi_S(\xi_k^C + \xi_k^D - \xi_k^R) \approx \xi_U - \xi_R$. Thus, T_3 can be simplified to $T_5(\delta)O(\xi_R(\xi_U - \xi_R))$. □

4.3 UE Throughput Improvement (UTI) Algorithm

Given a group $\hat{\mathcal{G}}_x$ of UEs that share RB r_x, UTI improves their throughput by raising transmitted power. Algo. 4 gives UTI's pseudocode, where $\hat{\mathcal{G}}_x^{\mathrm{can}}$ is a subset of UEs in $\hat{\mathcal{G}}_x$ such

4. Otherwise, s_k has enough RBs in $\hat{\mathcal{R}}_k$ to serve all CUEs in $\hat{\mathcal{C}}_k$ by Algo. 2, which makes $\hat{\mathcal{C}}'_k = \emptyset$. Thus, the loop in line 3 for s_k will be skipped.

Algorithm 4: UE Throughput Improvement (UTI)

Input: Group $\hat{\mathcal{G}}_x$ of UEs sharing RB r_x
Output: Amplified power for UEs in $\hat{\mathcal{G}}_x$ with the maximum throughput gain

1 $\hat{\mathcal{G}}_x^{\mathtt{can}} \leftarrow \hat{\mathcal{G}}_x$;
2 **while** $\hat{\mathcal{G}}_x^{\mathtt{can}} \neq \emptyset$ **do**
3   **foreach** $u_i \in \hat{\mathcal{G}}_x^{\mathtt{can}}$ **do**
4         $\tilde{p}_i^{\mathtt{inc}} \leftarrow \tilde{p}_{\tau(i),i}^x + \epsilon$;
5         $\lambda_i^{\mathtt{TG}} \leftarrow \sum_{u_j \in \hat{\mathcal{G}}_x} (\lambda_j^{\mathtt{inc}} - \lambda_j)$;
6   **if** $(\tilde{p}_i^{\mathtt{inc}} > \tilde{p}_i^{\max})$ *or* $(\exists u_j \in \hat{\mathcal{G}}_x, \sigma_j^x < \sigma_j^{\min})$ *or* $(\lambda_i^{\mathtt{TG}} \leq 0)$ **then**
7   Remove u_i from $\hat{\mathcal{G}}_x^{\mathtt{can}}$;
8   **if** $\hat{\mathcal{G}}_x^{\mathtt{can}}$ *is not null* **then**
9         $u_i \leftarrow \arg\max_{u_i \in \hat{\mathcal{G}}_x^{\mathtt{can}}} \lambda_i^{\mathtt{TG}}$;
10         $\tilde{p}_{\tau(i),i}^x \leftarrow \tilde{p}_i^{\mathtt{inc}}$;

Algorithm 5: Adaptive Power Control (APC)

Input: Group $\hat{\mathcal{G}}_x$ of UEs sharing RB r_x
Output: Adjusted power for UEs in $\hat{\mathcal{G}}_x$

1 **foreach** $u_i \in \hat{\mathcal{G}}_x$ **do**
2     $\tilde{p}_{\tau(i),i}^x \leftarrow (\sigma_i^{\min} \times \varepsilon)/\tilde{g}_{\tau(i),i}^x$;
3   Do boundary check to let $\tilde{p}_i^{\min} \leq \tilde{p}_{\tau(i),i}^x \leq \tilde{p}_i^{\max}$;
4     $\Delta_p \leftarrow \tilde{p}_i^{\max}/\varphi$;
5   **while** $\Delta_p \geq \tilde{p}_i^{\max}/\varphi^v$ **do**
6   **if** $\sigma_i^x < \sigma_i^{\min}$ *and* $(\tilde{p}_{\tau(i),i}^x + \Delta_p) \leq \tilde{p}_i^{\max}$ **then**
7             $\tilde{p}_{\tau(i),i}^x \leftarrow \tilde{p}_{\tau(i),i}^x + \Delta_p$;
8   **else if** Eq. (10) holds *and* $(\tilde{p}_{\tau(i),i}^x - \Delta_p) \geq \tilde{p}_i^{\min}$ **then**
9             $\tilde{p}_{\tau(i),i}^x \leftarrow \tilde{p}_{\tau(i),i}^x - \Delta_p$;
10         $\Delta_p \leftarrow \Delta_p/\varphi$;

that their senders are candidates to be raised power. In line 1, $\hat{\mathcal{G}}_x^{\mathtt{can}}$ is set to $\hat{\mathcal{G}}_x$ initially. For the sender $\tau(i)$ of each UE u_i in $\hat{\mathcal{G}}_x^{\mathtt{can}}$, line 4 adds a small positive value ϵ to its power $\tilde{p}_{\tau(i),i}^x$, where the result is $\tilde{p}_i^{\mathtt{inc}}$. Line 5 estimates the amount of $\hat{\mathcal{G}}_x$'s *throughput gain* $\lambda_i^{\mathtt{TG}}$ after increasing $\tau(i)$'s power, where $\lambda_j^{\mathtt{inc}}$ and λ_j denote throughput of a UE $u_j \in \hat{\mathcal{G}}_x$ when $\tau(i)$'s power is $\tilde{p}_i^{\mathtt{inc}}$ and $\tilde{p}_{\tau(i),i}^x$, respectively. Then, line 6 checks if $\tau(i)$'s power cannot be increased based on three conditions: 1) $\tilde{p}_i^{\mathtt{inc}}$ exceeds the upper bound $\tilde{p}_i^{\max}$, 2) the SINR demands of some UEs are not satisfied, and 3) there is no throughput gain. When any condition is met, $\tau(i)$'s power cannot be raised and u_i is removed from $\hat{\mathcal{G}}_x^{\mathtt{can}}$ (since $\tau(i)$ is no longer a candidate). However, if there is no candidate left in $\hat{\mathcal{G}}_x^{\mathtt{can}}$ due to the check, the current power setting will be optimal, so the UTI algorithm ends by line 2. Otherwise, we select a UE u_i from $\hat{\mathcal{G}}_x^{\mathtt{can}}$ with the maximum $\lambda_i^{\mathtt{TG}}$ value and update power $\tilde{p}_{\tau(i),i}^x$ by $\tilde{p}_i^{\mathtt{inc}}$. The code is presented in lines 8–10. Theorem 3 proves that Algo. 4 must converge and Theorem 4 analyzes its time complexity.

Theorem 3. *Algo. 4 should converge within finite iterations.*

Proof: The while-loop's termination condition is $\hat{\mathcal{G}}_x^{\mathtt{can}} = \emptyset$, where $\hat{\mathcal{G}}_x^{\mathtt{can}}$ is set to $\hat{\mathcal{G}}_x$ by line 1. The for-loop repeatedly picks a UE u_i from $\hat{\mathcal{G}}_x^{\mathtt{can}}$ to raise the power of its sender $\tau(i)$. The if-statement in lines 6–7 may remove u_i from $\hat{\mathcal{G}}_x^{\mathtt{can}}$ but no statement adds new UEs to $\hat{\mathcal{G}}_x^{\mathtt{can}}$, so $|\hat{\mathcal{G}}_x^{\mathtt{can}}|$ will only shrink.

Let us prove this theorem by contradiction. Assume that a UE u_i is always left in $\hat{\mathcal{G}}_x^{\mathtt{can}}$, causing the while-loop to run forever. In this case, the statements in lines 4, 9, and 10 must keep increasing $\tau(i)$'s power, which after finite iterations will overtake $\tilde{p}_i^{\max}$ and force u_i to be removed from $\hat{\mathcal{G}}_x^{\mathtt{can}}$ by line 6. Obviously, a contradiction occurs. Thus, the while-loop must terminate due to $\hat{\mathcal{G}}_x^{\mathtt{can}} = \emptyset$, so this theorem is verified. □

Theorem 4. *Algo. 4 has time complexity of* $T_4(r_x) = O(\psi\xi_x^2)$*, where* $\psi = \max_{u_i \in \hat{\mathcal{G}}_x} (\tilde{p}_i^{\max} - \tilde{p}_i^{\min})/\epsilon$ *and* $\xi_x = |\hat{\mathcal{G}}_x|$.

Proof: Let us first analyze the time required to perform one iteration of the while-loop (i.e., lines 3–10). The for-loop repeats at most ξ_x times, where lines 5 and 6 take $O(\xi_x)$ time to check each UE in $\hat{\mathcal{G}}_x$ once. Line 9 spends $O(\xi_x)$ time. Thus, an iteration of the while-loop takes time of $\xi_x O(\xi_x) + O(\xi_x) = O(\xi_x^2)$. For the while-loop, the worst case occurs when $\tilde{p}_{\tau(i),i}^x$ is initially set to $\tilde{p}_i^{\min}$ and $\tilde{p}_i^{\mathtt{inc}}$ is eventually increased to $\tilde{p}_i^{\max}$. In this case, the while-loop is repeated ψ times. Thus, the total time complexity is $\psi O(\xi_x^2) = O(\psi\xi_x^2)$. □

4.4 Adaptive Power Control (APC) Algorithm

Given a group $\hat{\mathcal{G}}_x$ of UEs sharing RB r_x, APC computes the transmitted power of the sender of each UE $u_i \in \hat{\mathcal{G}}_x$ to meet its $\sigma_i^{\min}$ demand while minimizing the interference in $\hat{\mathcal{G}}_x$. Algo. 5 shows the pseudocode. By replacing $\tilde{g}_{\mathrm{BS},i}^x$ and $\tilde{p}_{\mathrm{BS},i}^x$ with $\tilde{g}_{\tau(i),i}^x$ and $\tilde{p}_{\tau(i),i}^x$, respectively in Eq. (8), we can obtain the initial power of u_i's sender, as shown in line 2. Then, line 3 does boundary check for $\tilde{p}_{\tau(i),i}^x$ by the power constraint in Eq. (6). Specifically, if $\tilde{p}_{\tau(i),i}^x < \tilde{p}_i^{\min}$, we set $\tilde{p}_{\tau(i),i}^x$ to $\tilde{p}_i^{\min}$. When $\tilde{p}_{\tau(i),i}^x > \tilde{p}_i^{\max}$, $\tilde{p}_{\tau(i),i}^x$ is set to $\tilde{p}_i^{\max}$.

The while-loop in lines 5–10 adjusts $\tilde{p}_{\tau(i),i}^x$ by a *shrinking variable* Δ_p. In line 4, Δ_p is initially set to $\tilde{p}_i^{\max}/\varphi$, where $\varphi \in \mathbb{Z}^+$ and $\varphi > 1$. At the end of the while-loop (i.e., line 10), Δ_p is divided by φ. In this way, power $\tilde{p}_{\tau(i),i}^x$ can be fine-tuned iteration by iteration. For instance, Δ_p will be exponentially decreased if we set $\varphi = 2$.

In the while-loop, line 5 implies that it will be executed v times. Line 6 means that if u_i's SINR σ_i^x is below its $\sigma_i^{\min}$ demand and adding Δ_p to $\tilde{p}_{\tau(i),i}^x$ does not exceed $\tilde{p}_i^{\max}$, $\tilde{p}_{\tau(i),i}^x$ can be increased by Δ_p. Line 8 handles the case when $\tilde{p}_{\tau(i),i}^x$ is too large. Let $\tilde{p}_{\tau(i),i}^{\mathrm{th}}$ be $\tau(i)$'s minimum power to make u_i's SINR be equal to $\sigma_i^{\min}$. Suppose that an amount Υ of interference is imposed on u_i. To satisfy the $\sigma_i^{\min}$ demand after decreasing $\tilde{p}_{\tau(i),i}^x$ by Δ_p, the condition should obtain:

$$\frac{\tilde{g}_{\tau(i),i}^x \times (\tilde{p}_{\tau(i),i}^x - \Delta_p)}{\Upsilon + \varepsilon} > \sigma_i^{\min} = \frac{\tilde{g}_{\tau(i),i}^x \times \tilde{p}_{\tau(i),i}^{\mathrm{th}}}{\Upsilon + \varepsilon}. \quad (9)$$

By doing some algebra, we can derive that

$$\sigma_i^x > \sigma_i^{\min} \times (1 + (\Delta_p/\tilde{p}_{\tau(i),i}^{\mathrm{th}})). \quad (10)$$

When Eq. (10) holds and $\tilde{p}_{\tau(i),i}^x$ is no smaller than $\tilde{p}_i^{\min}$ after power adjustment, we can decrease $\tilde{p}_{\tau(i),i}^x$ by Δ_p. Theorem 5 shows that Algo. 5 must converge and Theorem 6 analyzes its time complexity.

Theorem 5. *Given a finite number of UEs in group* $\hat{\mathcal{G}}_x$*, Algo. 5 must converge.*

Proof: Algo. 5 uses a for-loop to check each UE u_i in $\hat{\mathcal{G}}_x$. Evidently, the number of iterations performed by the for-loop will be equal to the number of UEs in $\hat{\mathcal{G}}_x$. Then, the inner while-loop iteratively adjusts power $\tilde{p}^x_{\tau(i),i}$, whose termination condition is $\Delta_p < \tilde{p}_i^{\max}/\varphi^v$. The variable Δ_p is initially set to $\tilde{p}_i^{\max}/\varphi$ by line 4, and it will be divided by φ whenever an iteration of the while-loop ends (i.e., line 10). Thus, the while-loop must be repeated no more than v times based on lines 4, 5, and 10. In other words, the while-loop has a finite number of iterations for each UE in $\hat{\mathcal{G}}_x$, so Algo. 5 must converge. □

Theorem 6. *Given a group $\hat{\mathcal{G}}_x$ with ξ_x UEs, Algo. 5 spends time of $T_5(\xi_x) = O(v\xi_x)$, where $v \in \mathbb{Z}^+$ decides the number of iterations used to adjust transmitted power.*

Proof: Algo. 5 uses a for-loop that repeats ξ_x times. Lines 2, 3, and 4 consume constant time. The while-loop repeats v times (by Theorem 5), where lines 6–10 all spend $O(1)$ time. Thus, the time complexity is $\xi_x(O(1) + vO(1)) = O(v\xi_x)$. □

4.5 Discussion

The JAPS scheme has three core algorithms: IRA (Algo. 2), CRB (Algo. 3), and UTI (Algo. 4), as shown in Fig. 2. IRA helps each SP allocate its dedicated RBs to the subscribed UEs. Since CUEs are usually user or monitoring devices while DUEs may be IoT devices [36], CUEs are given precedence over DUEs on getting RBs. Consequently, the BS first allocates a *clean* RB (i.e., it is not allocated to any UE yet) to each CUE. Each D2D pair then shares an RB based on two rules: 1) this RB is not used by a member in $\hat{\mathcal{I}}_i$ (i.e., whose sender imposes serious interference on the D2D receiver) and 2) the number of UEs sharing the RB is below the maximum group size δ (to reduce the computational cost). However, if the SP cannot serve all of its UEs (e.g., due to insufficient RBs), it can use the inter-SP loan to borrow RBs from other SPs by the CRB algorithm. To encourage SPs to lend their RBs, the SP that has the highest credit γ_k (i.e., this SP has lent the most RBs) can prioritize reusing the RBs of other SPs. Whenever a UE u_i is added to share an RB r_x, we have to make sure that the SINR demand $\sigma_i^{\min}$ of every member in $\hat{\mathcal{G}}_x$ (i.e., the group of UEs sharing r_x, including u_i) should be met. Both IRA and CRB use the APC algorithm in Algo. 5 to guardedly find the transmitted power for each sender on an RB r_x, so as to meet SINR demands and avoid interference. Then, among those UEs in a group $\hat{\mathcal{G}}_x$ whose senders are capable of raising power, the UTI algorithm iteratively picks a UE with the most throughput gain to adjust power. In this way, UTI can improve throughput of UEs in each group by bettering their signal quality.

In JAPS, there are four designs in RB borrowing and lending to guarantee fairness among SPs. First, based on the code in lines 5–7 in Algo. 1, each SP s_k should allot its dedicated RBs (i.e., $\hat{\mathcal{R}}_k$) to the subscribed UEs first by the IRA algorithm. Only after all RBs in $\hat{\mathcal{R}}_k$ are used up can s_k borrow RBs from other SPs by the CRB algorithm. Thus, no SP will ever reserve its RBs and also borrow RBs from others. Second, if an RB r_x is fully occupied, it must be excluded by line 5 or line 14 in Algo. 3. In other words, r_x cannot be lent in CRB. Thus, once the available RBs in $\hat{\mathcal{R}}_k$ are fully occupied by SP s_k, there is no way that s_k could lend its RBs to other SPs and thus degrade the performance of its subscribed UEs. Third, CRB prioritizes the SP with the highest credit γ_k (i.e., the SP has lent the most RBs so far) to borrow RBs first. This approach has been proven to achieve long-term fairness (among SPs) [37]. Moreover, if an SP is selfish (i.e., the SP prefers not to lend RBs to others), it would obtain pretty low credit. In this case, CRB punishes that SP by ranking it last in $\hat{\mathcal{S}}_{\mathrm{C}}$ or $\hat{\mathcal{S}}_{\mathrm{D}}$, so the selfish SP has very low priority on borrowing RBs. Fourth, JAPS uses an RLB table Γ_k for each SP to record the debtor-creditor relationship with other SPs. When an SP s_k borrows some RBs from others by CRB, a charging mechanism can be devised among s_k and lending SPs [38].

TABLE 6: Simulation parameters.

BS-related parameters:	
cell radius	0.5 km
transmitted power	min: -40 dBm, max: 46 dBm
number of SPs	3
spectrum resource	45 RBs/ms
UE-related parameters:	
number of UEs	CUEs: 45, D2D pairs: 15–135
transmitted power	min: -40 dBm, max: 23 dBm
minimum demand	1 Mbps (i.e., $\sigma_i^{\min} \approx 17$ dB)
modulation	QPSK, 16QAM, 64QAM
Channel model for wireless communication:	
propagation loss	urban macrocell model
path loss	BS to UE: $128.1 + 37.6 \log_{10} \mathrm{dist}(\mathrm{BS}, u_i)$
	UE to UE: $148 + 40 \log_{10} \mathrm{dist}(\tau(i), u_i)$
shadowing fading	log-normal distribution
thermal noise (ε)	-174 dBm/Hz

Theorem 7 and Corollary 1 give JAPS's time complexity.

Theorem 7. *Given ξ_U UEs in $\hat{\mathcal{U}}$ and ξ_R RBs in $\hat{\mathcal{R}}$, the time complexity of JAPS is $O(\xi_U^2 + \psi\xi_R^2 + v\delta\xi_R(\xi_U - \xi_R))$, where ψ and v are the parameters used in Algos. 4 and 5, respectively.*

Proof: By applying Theorems 1, 2, 4, and 6 to Lemma 1, the time complexity T is $O(\frac{\xi_U(\xi_U-1)}{2}) + \sum_{s_k\in\hat{\mathcal{S}}} O(\xi_k^R(\xi_k^C + v\delta\xi_k^D)) + v\delta O(\xi_R(\xi_U - \xi_R)) + \sum_{r_x\in\hat{\mathcal{R}}} O(\psi\xi_x^2)$. With some algebra, we obtain that $T = O(\xi_U^2) + O(\xi_R\xi_C) + O(v\delta\xi_R\xi_D) + O(v\delta\xi_R\xi_U) - O(v\delta\xi_R^2) + O(\psi\xi_R^2)$. Because $v\delta\xi_R\xi_U > \xi_R\xi_C$ and $v\delta\xi_R\xi_U > v\delta\xi_R\xi_D$, we can simplify T to $O(\xi_U^2 + \psi\xi_R^2 + v\delta\xi_R(\xi_U - \xi_R))$. □

Corollary 1. *Let ψ and v be constants. JAPS's time complexity in Theorem 7 can be simplified to $O(\xi_U^2)$ if $\xi_U > \delta\xi_R$.*

5 Performance Evaluation

Our simulation is built on MATLAB for performance evaluation, whose parameters are given in Table 6 [39], [40]. We consider a BS cooperated by three SPs. Each SP owns 15 RBs in one ms and has to serve 15 CUEs and 5–45 D2D pairs. The path-loss effect is decided by the distance between a UE u_i and its sender $\tau(i)$, which is measured in km. For a D2D pair, the distance between two DUEs is at most 30 m. The shadowing fading is modeled by a log-normal distribution with the mean and standard deviation of 0 dB and 8 dB, respectively.

We compare our JAPS scheme with four methods:

- *DRAPC* [27]: UEs are grouped to share RBs with the aim of maximizing the service ratio. Each SP uses only the dedicated RBs to serve UEs (i.e., without RAN sharing).
- *Wireless resource virtualization with D2D communication (WRVD)* [32]: WRVD allocates RBs to CUEs of different SPs and makes D2D pairs share the RBs of CUEs served by the same SP with the least interference. However, each RB is shared by at most a D2D pair (i.e., case S2).
- *Enhanced WRVD (E-WRVD)*: We apply the IRA algorithm (Algo. 2) to WRVD to check if the SINR demand

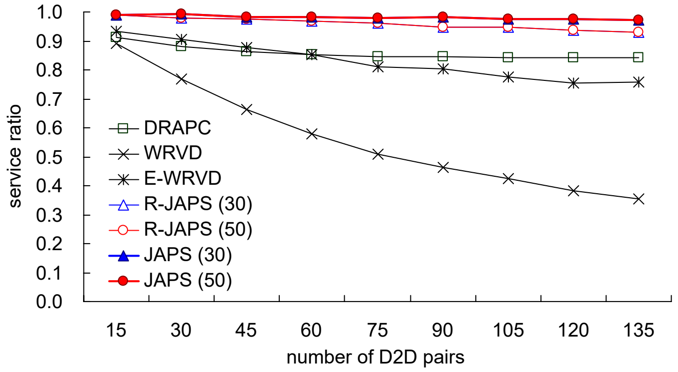


Fig. 3: Comparison on the service ratio.

of each UE sharing the same RB is met. In this way, E-WRVD can let an RB be shared by multiple D2D pairs.

- *Reduced JAPS (R-JAPS)*: This is a reduced version of JAPS by removing the CRB algorithm (Algo. 3). In other words, R-JAPS prohibits an SP from borrowing the RBs of other SPs. By comparing JAPS with R-JAPS, we can assess the influence of CRB on the JAPS scheme.

In JAPS and R-JAPS, the maximum group size (i.e., δ) is set to 30 and 50 for studying its effect.

5.1 Comparison on the Service Ratio

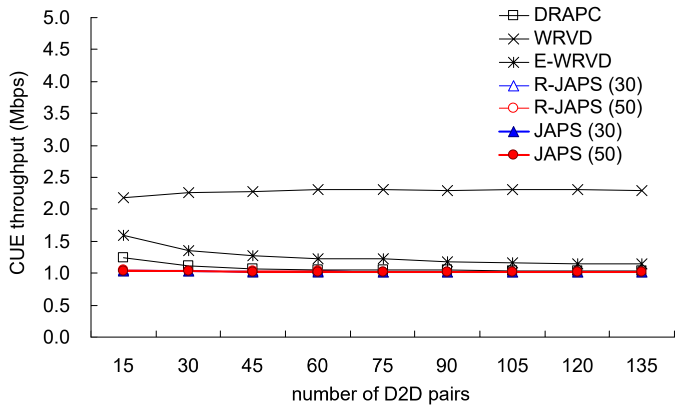
Let us first evaluate the service ratio, which is the ratio of the number of CUEs and D2D pairs whose minimum demands are met to the total number of UEs in $\hat{\mathcal{U}}$. According to Eq. (3), it can be calculated as follows:

$$\frac{\sum_{s_k\in\hat{\mathcal{S}}}\sum_{r_x\in\hat{\mathcal{R}}_k}\sum_{u_i\in\hat{\mathcal{C}}_k\cup\hat{\mathcal{D}}_k}\alpha_i^x\beta_i^x}{\sum_{s_k\in\hat{\mathcal{S}}}|\hat{\mathcal{C}}_k|+|\hat{\mathcal{D}}_k|}. \tag{11}$$

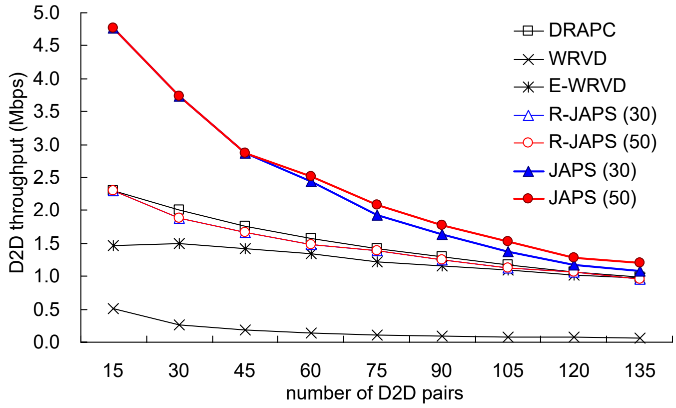
Fig. 3 shows the result. On the whole, the service ratio of each method decreases as the number of D2D pairs increases, since more UEs compete for the fixed resource. This phenomenon is particularly manifest in both WRVD and E-WRVD.

Since the WRVD method adopts case S2, where each CUE shares its RB with at most one D2D pair, many D2D receivers cannot be allocated with RBs when there are more D2D pairs. Thus, WRVD results in the lowest service ratio. By applying our IRA algorithm to WRVD to let multiple D2D pairs share the same RB, the E-WRVD method can advance the average service ratio from 0.56 to 0.83. The DRAPC method seeks to maximize the group of UEs (belonging to the same SP) to share each RB, which keeps its service ratio around 0.85. On the other hand, the R-JAPS method not only employs the IRA algorithm for RB allocation but also adopts the UTI algorithm for power control, so it can increase the average service ratio to 0.96. As each SP could make good use of its RBs (i.e., $\hat{\mathcal{R}}_k$) to satisfy the minimum demands of most subscribed UEs, the effect of δ on R-JAPS is not apparent.

As compared with R-JAPS, our JAPS scheme allows each SP that still has unserved UEs to borrow RBs from other SPs by the CRB algorithm. Thus, JAPS has the highest service ratio among all the methods. Specifically, its average service ratio is above 0.98. The result in Fig. 3 corroborates that JAPS can fulfill the objective in Eq. (3).



(a) average throughput of CUEs



(b) average throughput of D2D pairs

Fig. 4: Comparison on throughput.

5.2 Comparison on Throughput

Fig. 4(a) measures the average throughput of CUEs in $\hat{\mathcal{C}}$. Because each SP owns 15 RBs (per ms) and has 15 CUEs, a CUE will get one RB every 1 ms. In the WRVD method, at most one D2D pair can share the RB of each CUE, so there is less interference caused by the D2D sender on that RB. Therefore, each CUE has better channel quality and thereby higher throughput. By applying the IRA algorithm to WRVD, multiple D2D pairs will reuse the RB of each CUE, which adversely brings up interference. This explains why E-WRVD has lower throughput of CUEs than WRVD. The DRAPC, R-JAPS, and JAPS methods adopt case S4, which make more D2D pairs share the RBs of CUEs, subject to the constraint that the minimum demand of each CUE should be met. Thus, their average throughput of CUEs is close to 1 Mbps.

Then, Fig. 4(b) evaluates the average throughput of DUEs in $\hat{\mathcal{D}}$ (i.e., D2D throughput). In general, the D2D throughput decreases as the number of D2D pairs grows, since more UEs contend for resources. WRVD has the highest throughput of CUEs, but its D2D throughput is comparatively low. Thanks to the IRA algorithm, E-WRVD remarkably improves the D2D throughput, as compared with WRVD. R-JAPS not only uses the IRA algorithm for each SP to allocate the dedicated RBs to its CUEs and DUEs, but also carefully amplifies the power of senders. Thus, R-JAPS can have higher D2D throughput than E-WRVD. Besides, the effect of the maximum group size δ on R-JAPS is neglected. DRAPC attempts to find out more D2D pairs to share the RB of each CUE attached to the same SP, and it has slightly higher D2D throughput than R-JAPS. By carrying out the inter-SP loan, our JAPS scheme can flexibly

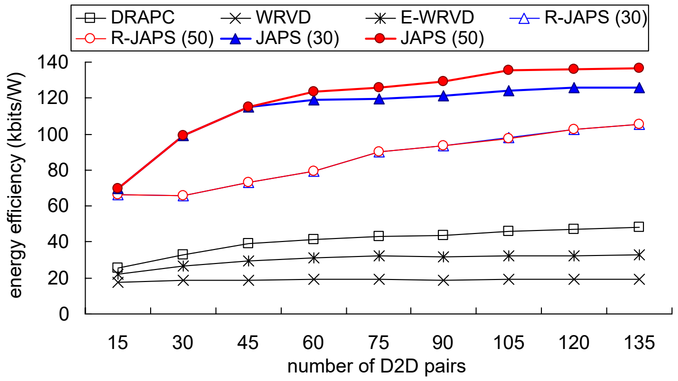


Fig. 5: Comparison on energy efficiency.

allow SPs to borrow RBs from other SPs, thereby achieving the highest D2D throughput. Moreover, when there are more than 45 D2D pairs, enlarging δ can improve D2D throughput in JAPS, because D2D pairs have more choices of RBs and each RB can also accommodate more UEs. The experimental result in Fig. 4(b) verifies that JAPS can efficiently increase the average D2D throughput.

5.3 Comparison on Energy Efficiency

Finally, we study the amount of *energy efficiency*, which is defined as follows:

$$\frac{\sum_{u_i \in \hat{\mathcal{U}}} \lambda_i}{\sum_{u_i \in \hat{\mathcal{U}}} \tilde{p}^x_{\tau(i),i}}. \tag{12}$$

In Eq. (12), the numerator indicates the amount of throughput of UEs (i.e., λ_i) in $\hat{\mathcal{U}}$ and the denominator is the amount of energy consumed by their senders (i.e., $\tilde{p}^x_{\tau(i),i}$). Thus, higher energy efficiency means that UEs have higher throughput or their senders can use lower transmitted power.

Fig. 5 presents the experimental result. Since WRVD has very low D2D throughput and it employs fixed power for the BS and D2D senders, WRVD inevitably results in the lowest energy efficiency. By adopting the IRA algorithm to improve throughput, E-WRVD can raise the average energy efficiency from 19.0 to 30.1 kbits/W, as compared with WRVD. DRAPC endeavors to maximize the D2D throughput by letting more D2D pairs share the RB of each CUE (attached to the same SP), and its average energy efficiency is around 40.8 kbits/W. Through the APC algorithm, R-JAPS can guardedly adjust the power of each sender, thereby increasing the average energy efficiency to 86.0 kbits/W. As discussed in Section 5.2, our JAPS scheme greatly advances the D2D throughput. Moreover, it also conducts power control by the APC algorithm. Thus, JAPS maintains the highest energy efficiency among all the methods. More concretely, the average energy efficiency of JAPS is 113.3 and 119.0 kbits/W when δ is set to 30 and 50, respectively. This experiment shows that JAPS performs well in terms of resource and power management.

6 Conclusion

In this paper, we propose the JAPS scheme to efficiently manage resources and transmitted power for D2D communication with RAN sharing. JAPS first uses the IRA algorithm to let each SP allocate the dedicated RBs and decide initial power for its UEs. Afterward, SPs can borrow RBs from others by the CRB algorithm to cope with unserved UEs, which carries out the inter-SP loan and betters the resource utilization. Finally, the UTI algorithm carefully amplifies the power of senders, so as to advance throughput while avoiding interference. Through simulations in MATLAB, we show that the JAPS scheme can attain a high service ratio, raise D2D throughput, and improve energy efficiency, as compared with the DRAPC, WRVD, E-WRVD, and R-JAPS methods.

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