Resource and Power Management for In-Band D2D Communications

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Abstract—*Device-to-device (D2D)* communications significantly increase the flexibility and capacity of a cellular network, where *user equipments (UEs)* are capable of directly conversing with each other without the relay by a *base station (BS)*. For in-band D2D communications, D2D pairs share the spectrum resources allocated to *cellular UEs (CUEs)*, which are the UEs in contact with the BS or with other devices through the BS. However, resource sharing would cause mutual signal interference between CUEs and D2D pairs. Consequently, how to efficiently allocate resources to CUEs and D2D pairs and also decide appropriate transmitted power for them is critical. In the chapter, we provide a comprehensive survey of resource and power management schemes for in-band D2D communications, and our discussion contains four parts. First, we give an overview of D2D communications, including their architecture, control policy, and communication mode. Then, we present the system model, which covers the network model, the estimation of channel quality, and the problem formulation for D2D resource and power management. After that, we elaborate on the existing management schemes, which are classified into matching-based, game-based, coloring-based, and other schemes. Finally, some research directions and challenges will be also addressed in this chapter.

Index Terms—in-band D2D communications, interference mitigation, power control, resource allocation, underlay mode.

1 Introduction

In traditional cellular networks, the communication of every *user equipment (UE)* has to pass through the *base station (BS)*. Even though two UEs reside within the communication range between each other, two-hop relay via the BS is mandatory. Such a communication paradigm is fit for the Third Generation (3G) or older cellular networks, where each user spends a small amount of the BS's spectrum resources for only voice calls or text messages. Nowadays, more and more people employ cellular networks for web browsing and video watching, which is bandwidth consuming. Moreover, IoT (Internet of Things) devices have increased substantially year by year, which usually rely on cellular networks for communications [1]. In this case, the traditional communication paradigm would not only cause a shortage of spectrum resources, but also increase the burden on a BS.

To tackle the above problem, the *device-to-device (D2D) communication* technique is proposed, which carries out the direct communication between a pair of neighboring UEs (called a *D2D pair*) without necessarily asking the BS to be a relay node. This technique also brings some benefits [2], [3]. First, the overall spectral efficiency is improved, because spectrum resources can be shared between D2D pairs and other devices, such as *cellular UEs* (*CUEs*, that is, the UEs communicating with the BS or with other UEs via the BS). Second, since the two UEs in a D2D pair are close to each other, a D2D sender can curtail its transmitted power to save energy and reduce interference. Third, using D2D communications is viewed as an economical way to extend the service coverage of a BS.

The communication of a D2D pair can be either *out-band* or *in-band* [4]. More concretely, out-band D2D pairs compete with Wi-Fi or Bluetooth devices for the unlicensed band, which could increase the available bandwidth. However, both service discovery and connection setup for out-band D2D pairs and Wi-Fi/Bluetooth devices must require user intervention. Even worse, these Wi-Fi/Bluetooth devices would impose uncontrolled interference on the out-band D2D pairs and thereby degrade their performance. On the other hand, in-band D2D communications will take place only within the licensed band used by CUEs. Thus, the aforementioned user intervention and uncontrolled interference problems can be conquered. In this chapter, our discussion aims at in-band D2D communications.

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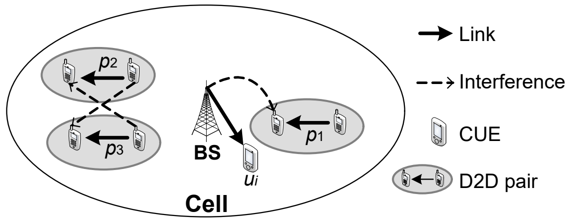

Fig. 1: An example of signal interference between CUEs and D2D pairs in a cell, where we consider the downlink case.

For in-band D2D communications, D2D pairs are able to share the spectrum resources allocated to CUEs to improve the resource utilization. Nevertheless, not every D2D pair is applicable to share a CUE's resource. Figure 1 illustrates an example, where we consider the downlink case and dotted lines indicate the interference relationship between CUEs and D2D pairs. Suppose that the BS transmits data to a CUE u_i. As the receiver of D2D pair p_1 is close to u_i, the BS will impose significant interference on that receiver. Thus, p_1 cannot share the resource allocated to u_i. On the other hand, the receivers of both D2D pairs p_2 and p_3 are far away from u_i, so they can reuse u_i's resource with quite little interference from the BS. However, since p_2's sender may interfere with p_3's receiver and vice versa (with their current transmitted power), as shown in Figure 1, only one of p_2 and p_3 can share u_i's resource. In fact, we could carefully lower the transmitted power of these D2D senders, so as to mitigate the interference while keeping the channel quality of their receivers above an

TABLE 1: Summary of notations.

notation	definition
$\hat{\mathcal{U}}_{\mathsf{UL}}$	the set of uplink CUEs in a cell, where N_{UL} denotes the number of uplink CUEs in $\hat{\mathcal{U}}_{\mathsf{UL}}$
$\hat{\mathcal{U}}_{\mathsf{DL}}$	the set of downlink CUEs in a cell, where N_{DL} denotes the number of downlink CUEs in $\hat{\mathcal{U}}_{\mathsf{DL}}$
$\hat{\mathcal{P}}$	the set of D2D pairs in a cell, where N_{DP} denotes the number of D2D pairs in $\hat{\mathcal{P}}$
$\hat{\mathcal{R}}$	the set of RBs provided by the BS, where N_{RB} denotes the number of RBs in $\hat{\mathcal{R}}$
τ	the BS
u_i	a CUE in $\hat{\mathcal{U}}_{\mathsf{UL}}$ or $\hat{\mathcal{U}}_{\mathsf{DL}}$
p_j	a D2D pair in $\hat{\mathcal{P}}$ (p_j^{S}: D2D sender, p_j^{R}: D2D receiver)
r_k	an RB in $\hat{\mathcal{R}}$
$\xi(x)$	the sender of node x
$\tilde{\mathbf{s}}(x,y)$	the strength of node x's signal gotten by node y
$\tilde{\mathbf{g}}(x,y)$	the channel gain from node x to node y
$\tilde{\mathbf{t}}(x)$	the transmitted power of node x, where x is an uplink CUE or a D2D sender
$\tilde{\mathbf{t}}(\tau[i])$	the BS's transmitted power to send data to a downlink CUE $u_i \in \hat{\mathcal{U}}_{\mathsf{DL}}$
λ_a^k	the current SINR of a CUE u_a or a D2D pair p_a on a specific RB r_k (k will be omitted if there is no RB specified)
$\lambda_a^{\min}$	the minimum required SINR of a CUE u_a or a D2D pair p_a
σ	the power of the thermal noise
z_a^k	an indicator to reveal whether RB r_k is allocated to a CUE u_a or a D2D pair p_a
B	total channel bandwidth
ε	the exponent for path loss
$L(x,y)$	the distance between two nodes x and y
$w(x,y)$	the weight of an edge (x,y) in a graph

acceptable threshold (i.e., to satisfy their traffic demands). In this way, both p_2 and p_3 are allowed to reuse u_i's resource, which further increases the resource utilization. As can be seen, how to select D2D pairs to share the resource of each CUE (namely *resource allocation*) and also adjust their transmitted power (namely *power control*) plays a key role in deciding the network performance.

In this chapter, we provide a comprehensive survey of recent researches on resource and power management for in-band D2D communications, which are classified into four categories. First, the *matching-based management schemes* build a weighted bipartite graph to describe the sharing relationship between CUEs and D2D pairs, and then find a maximum matching from the bipartite graph. Second, the *game-based management schemes* apply game-theoretic models to handle resource allocation and power control. Third, the *coloring-based management schemes* convert the management problem into a vertex coloring problem in the graph theory to mitigate interference between CUEs and D2D pairs when allotting resources to them. Lastly, we introduce different management schemes not in the above three categories.

The rest of this chapter is organized as follows: Section 2 gives a brief introduction to D2D communications and Section 3 presents the system model. After that, we discuss the resource and power management schemes developed for in-band D2D communications in Section 4, followed by research directions and challenges in Section 5. Finally, Section 6 concludes this chapter. We summarize the notations and abbreviations used in this chapter in Table 1 and Table 2, respectively.

TABLE 2: List of abbreviations.

abbreviation	full name
3GPP	3rd Generation Partnership Project
BnB	branch-and-bound
BS	base station
CoAP	constrained application protocol
CSG	coalition structure generation
CUE	cellular user equipment
D2D	device to device
DC	difference of convex
DNN	deep neural network
EPC	evolved packet core
ERP	equally reduced power
E-UTRAN	evolved universal terrestrial access network
HSS	home subscriber server
IoT	Internet of Things
MINP	mixed integer nonlinear programming
MIS	maximum independent set
MME	mobility management entity
mmWave	millimeter wave
P-GW	packet data network gateway
ProSe	proximity-based services
RAN	radio access network
RB	resource block
S-GW	serving gateway
SINR	signal-to-interference-plus-noise ratio
SLA	SINR limited area
UE	user equipment
WOA	whale optimization algorithm

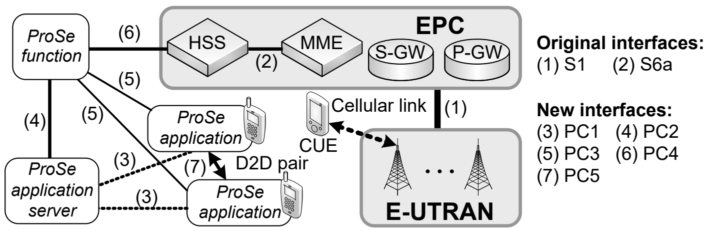

Fig. 2: 3GPP architecture to support D2D communications.

2 Overview of D2D Communications

In this section, we first introduce the system architecture proposed by the 3rd Generation Partnership Project (3GPP) to support D2D communications. Then, we discuss the control policy for D2D communications, followed their communication modes.

2.1 3GPP Architecture

A cellular network is typically split up into two parts: *evolved universal terrestrial access network (E-UTRAN)* and *evolved packet core (EPC)*, as illustrated in Figure 2. E-UTRAN comprises multiple cells, each coordinated by one BS. EPC is the core network responsible for management and control, which contains the following major components: 1) the *home subscriber server (HSS)* maintains a database for user authentication, 2) the *mobility* *management entity (MME)* processes signaling between UEs and EPC, 3) a *serving gateway (S-GW)* routes packets and serves as a mobility anchor when UEs move across cells, and 4) the *packet data network gateway (P-GW)* connects to the external network and performs policy enforcement such as flow control and user charging [5].

To support D2D communications, 3GPP proposes the *proximity-based services (ProSe)* [6] and adds three extra components to a cellular network (referring to Figure 2):

- *ProSe application:* This component is installed in a UE to perform the service discovery and D2D communications, whose authorization process is done by the PC3 protocol. Two ProSe applications can communicate with each other through the PC5 interface (i.e., D2D link). Moreover, a ProSe application can exchange the application-layer parameters with the ProSe application server by using the PC1 interface.
- *ProSe function:* This logical function takes charge of offering D2D parameters, identifying D2D applications, and supporting network-related functionalities (e.g., authorization and charging). The PC4 interface is used to connect the ProSe function and the HSS for managing the information about subscribers.
- *ProSe application server:* This server is regarded as one third-party medium (i.e., not subject to the 3GPP standard), which stores the information of available functions to be provided to the ProSe applications. The ProSe application server can communicate with the ProSe function through a PC2 interface.

The aforementioned interfaces are defined in [7]. Furthermore, the S6a interface between the HSS and the MME is also modified for these two components to exchange the information about the ProSe subscription.

2.2 Control Policy

The D2D control policy determines how deeply the network (including the BS and the EPC) is involved in the management of D2D communications, which is divided into two types: *full control* (i.e., entirely managed by the network) and *loose control* (i.e., partially managed by the network) [8].

In the full control policy, the network takes responsibility for most of the management work, for example, authentication, resource allocation, and power control. This policy facilitates the network to coordinate cellular and D2D communications, which mitigates the mutual interference between CUEs and D2D pairs. In addition, the BS can allocate resources to UEs more efficiently and flexibly (e.g., giving priorities to some UEs to fulfil their demands). However, the main cost of full control is the signaling overhead required to manage D2D communications. More concretely, CUEs as well as D2D pairs have to keep informing the BS of their channel conditions, such as the *signal-to-interference-plus-noise ratio (SINR)* or the *channel quality indicator (CQI)* [9], so the BS can allocate resources to them without significant interference. Despite the signaling overhead, most service providers prefer employing the full control policy for in-band D2D communications.

In the loose control policy, the network performs only authentication, while D2D pairs deal with the rest work. In other words, UEs carry out D2D communications on their own with limited intervention from the network's side. As compared with the full control policy, the signaling overhead can be substantially reduced. However, because D2D pairs handle resource allocation and power control by themselves, they may cause non-neglected or even uncontrolled interference to CUEs. In view of this, the loose control policy is usually applied to out-band D2D communications, where D2D pairs vie with Wi-Fi/Bluetooth devices for the unlicensed band instead of with CUEs for the licensed band.

2.3 Communication Mode

The communication mode decides how the UEs in a D2D pair communicate with each other and use spectrum resources. In the literature, there are three common modes proposed for in-band D2D communications [2]:

- *Cellular mode:* The UEs in a D2D pair still require the BS to relay their data. This mode is usually used in the scenarios where these UEs are far away from each other or the D2D communication cannot pay off. The BS can easily control the interference of each UE, and there is no need to implement D2D features. However, the cellular mode inevitably results in the lowest spectral efficiency.
- *Overlay mode:* Two neighboring UEs can directly talk to each other without the BS's intervention. D2D pairs and CUEs have their dedicated (and disjoint) resources for data transmissions. Consequently, they would not interfere with each other. However, since resources cannot be shared between CUEs and D2D pairs, the improvement in spectral efficiency may be limited. The overlay mode is also known as the *orthogonal* or *dedicated* mode.
- *Underlay mode:* Similar to the overlay mode, the BS need not act as the relay node for the two UEs in a D2D pair. In theory, the underlay mode will achieve the highest spectral efficiency, because cellular and D2D communications can be carried out by reusing resources. However, the BS has to cope with the mutual interference between CUEs and D2D pairs that share the same resource. The underlay mode is also called the *non-orthogonal* or *shared* mode.

As compared with both cellular and overlay modes, the underlay mode can significantly improve network throughput. In view of this, many research efforts address how to efficiently allocate resources to CUEs and D2D pairs by adopting the underlay mode.

3 System Model

In this section, we present the network model and then discuss how to estimate the channel quality. Afterward, we formulate the problem of resource and power management for in-band D2D communications.

3.1 Network Model

Let us consider one macro-cell that covers multiple UEs, which is coordinated by a BS (as denoted by τ). Without loss of generality, the BS is located at the cell's center, and all UEs are uniformly distributed inside the cell. Each UE operates in the half-duplex mode, which means that the communication of the UE is in only one direction (i.e., either transmitting or receiving data) at a time. On the other hand, the BS works in the full-duplex mode, so it can transmit data to some UEs while receiving data from some other UEs.

In every period (e.g., one transmission time interval), each UE can select only one of the following communication behaviors: 1) transmitting data to the BS (called an *uplink CUE*), 2) receiving data from the BS (called a *downlink CUE*), and 3) directly communicating with another UE (called a member of a *D2D pair*). For the sake of convenience, let us denote by $\hat{\mathcal{U}}_{\mathsf{UL}}$, $\hat{\mathcal{U}}_{\mathsf{DL}}$, and $\hat{\mathcal{P}}$ the set of all uplink CUEs, the set of all downlink CUEs, and the set of all D2D pairs in the cell, respectively. Any two of the above sets have no overlaps. In other words, the following condition is held:

$$(\hat{\mathcal{U}}_{\mathsf{UL}} \cap \hat{\mathcal{U}}_{\mathsf{DL}}) \cup (\hat{\mathcal{U}}_{\mathsf{UL}} \cap \hat{\mathcal{P}}) \cup (\hat{\mathcal{U}}_{\mathsf{DL}} \cap \hat{\mathcal{P}}) = \emptyset. \quad (1)$$

In addition, we denote by u_i a CUE in $\hat{\mathcal{U}}_{\mathsf{UL}}$ or $\hat{\mathcal{U}}_{\mathsf{DL}}$. For each D2D pair $p_j \in \hat{\mathcal{P}}$, p_j^{S} and p_j^{R} signify its sender and receiver, respectively. Note that both p_j^{S} and p_j^{R} have to be within the communication range of each other.

The spectrum resources are divided into a set $\hat{\mathcal{R}}$ of disjointed *resource blocks (RBs)*, and the BS is responsible for allocating these RBs to CUEs and D2D pairs. The amount of data that can be carried by an RB depends on its associated modulation and coding scheme, which is decided by the channel quality. In particular, when a receiver has a higher SINR on the RB, its sender can encode data bits by a more complex modulation and coding scheme, thereby increasing the RB's capacity [10]. Each RB occupies a fixed number of orthogonal subcarriers, and the channel fading on the RB is considered to be flat (e.g., following the Rayleigh distribution). Furthermore, we assume that the power of the thermal noise at each receiver on every RB is equal, which is denoted by σ. Note that some management schemes consider dividing the spectrum resources into disjointed *subchannels* rather than RBs. Since these subchannels have similar features with RBs (such as channel quality and fading), for the sake of consistency, we use the term "RB" in this chapter.

Generally speaking, CUEs should be given precedence over D2D pairs on allotting RBs, because CUEs are usually user or monitoring devices while D2D pairs could be IoT devices [11]. An uplink CUE and a downlink CUE might share an RB, and the couple of these two CUEs is called a *link couple* [12]. However, differen link couples cannot share the same RB, since they have the same downlink transmitter (i.e., the BS). Once different link couples use the same RB, the data for different receivers will be mixed at the BS, thereby making each receiver hard to distinguish its data from the overlapping signals. On the other hand, D2D pairs are allowed to reuse the RBs allocated to CUEs to improve the spectral efficiency.

3.2 Estimation of Channel Quality

Suppose that two nodes x and y are allocated with an RB $r_k \in \hat{\mathcal{R}}$ to receive their data. Moreover, let us denote by $\xi(y)$ the sender of node y. Here, x, y, and $\xi(y)$ can be a UE or the BS. Then, the strength of $\xi(y)$'s signal gotten by x can be calculated by

$$\tilde{\mathbf{s}}(\xi(y), x) = \tilde{\mathbf{g}}(\xi(y), x) \times \tilde{\mathbf{t}}(\xi(y)), \quad (2)$$

where $\tilde{\mathbf{g}}(\xi(y), x)$ signifies the channel gain from $\xi(y)$ to x, and $\tilde{\mathbf{t}}(\xi(y))$ is $\xi(y)$'s transmitted power (to send data to y). When $y = x$ (that is, they are the same node), a larger $\tilde{\mathbf{s}}(\xi(y), x)$ value means that x has a higher SINR (i.e., better channel quality) when receiving its data. Otherwise, $\xi(y)$ imposes interference on x, and a larger $\tilde{\mathbf{s}}(\xi(y), x)$ value implies that x has a lower SINR (i.e., worse channel quality). In Equation (2), the gain can be estimated by

$$\tilde{\mathbf{g}}(\xi(y), x) = \tilde{h} \times L(\xi(y), x)^{-\varepsilon}, \quad (3)$$

where $\tilde{h}$ is the normalized fading in small scale, $L(\xi(y), x)$ is the distance between $\xi(y)$ and x, and ε denotes the exponent for path loss. One exception is that a link couple of uplink CUE and downlink CUE share RB r_k. In this case, the BS plays the role of the sender for the downlink CUE and also the role of the receiver for the uplink CUE at the same time (i.e., $\xi(y) = x = \tau$). Consequently, the *self-interference* will occur at the BS, which can be evaluated as follows:

$$\tilde{\mathbf{s}}(\tau, \tau) = \bar{g}_\tau \times \tilde{\mathbf{t}}(\tau[i]), \quad (4)$$

where $\bar{g}_\tau$ is the cancelation factor of the BS's self-interference and $\tilde{\mathbf{t}}(\tau[i])$ is the transmitted power for the BS to send data to the downlink CUE u_i in that link couple. According to [13], the value of $\bar{g}_\tau$ can be decreased to 110 dB .

Let z_i^k be an indicator to reveal whether a CUE u_i or a D2D pair p_i uses an RB r_k for communication, where $z_i^k = 1$ if r_k is allocated to u_i (or p_i), and $z_i^k = 0$ otherwise. For each uplink CUE $u_a \in \hat{\mathcal{U}}_{\mathsf{UL}}$, the corresponding SINR on r_k (measured at the BS's side) is estimated by

$$\lambda_a^k = \frac{z_a^k \times \tilde{\mathbf{s}}(u_a, \tau)}{\sum_{u_i \in \hat{\mathcal{U}}_{\mathsf{DL}}} z_i^k \times \tilde{\mathbf{s}}(\tau, \tau) + \sum_{p_j \in \hat{\mathcal{P}}} z_j^k \times \tilde{\mathbf{s}}(p_j^{\mathsf{S}}, \tau) + \sigma}. \quad (5)$$

In particular, the three terms of the denominator in Equation (5) sequentially indicate the amount of self-interference at the BS (caused by the downlink communications), the amount of interference from the D2D pairs using the same RB, and the thermal noise (i.e., σ).

For each downlink CUE $u_b \in \hat{\mathcal{U}}_{\mathsf{DL}}$, its SINR on r_k is measured by

$$\lambda_b^k = \frac{z_b^k \times \tilde{\mathbf{s}}(\tau, u_b)}{\sum_{u_i \in \hat{\mathcal{U}}_{\mathsf{UL}}} z_i^k \times \tilde{\mathbf{s}}(u_i, u_b) + \sum_{p_j \in \hat{\mathcal{P}}} z_j^k \times \tilde{\mathbf{s}}(p_j^{\mathsf{S}}, u_b) + \sigma}. \quad (6)$$

The first two terms of the denominator in Equation (6) give the amount of interference from the uplink CUEs and the D2D pairs that also use r_k.

For each D2D pair $p_c \in \hat{\mathcal{P}}$, the SINR on r_k (measured at the side of p_c^{R}) is calculated by

$$\lambda_c^k = \frac{z_c^k \times \tilde{\mathbf{s}}(p_c^{\mathsf{S}}, p_c^{\mathsf{R}})}{\sum_{u_i \in \hat{\mathcal{U}}_{\mathsf{UL}}} z_i^k \times \tilde{\mathbf{s}}(u_i, p_c^{\mathsf{R}}) + \sum_{u_j \in \hat{\mathcal{U}}_{\mathsf{DL}}} z_j^k \times \tilde{\mathbf{s}}(\tau, p_c^{\mathsf{R}}) + \chi + \sigma}.$$
$$\chi = \sum_{p_l \in \hat{\mathcal{P}}, p_l \neq p_c} z_l^k \times \tilde{\mathbf{s}}(p_l^{\mathsf{S}}, p_c^{\mathsf{R}}) \quad (7)$$

Since a D2D pair can reuse the RBs allocated to a CUE, the interference sources will include (1) the uplink CUEs, (2) the BS (which sends data to the downlink CUEs), (3) the D2D senders not in the same D2D pair, and (4) the thermal noise. These four terms are reflected in the denominator in Equation (7).

3.3 Problem Formulation

Let B be the total channel bandwidth. According to the Shannon's capacity formula [14], we can estimate the amount of network throughput as follows:

$$\Phi = \sum_{r_k \in \hat{\mathcal{R}}} \frac{B}{|\hat{\mathcal{R}}|} \left(\Phi_a + \Phi_b + \Phi_c\right), \tag{8}$$
$$\Phi_a = \sum\nolimits_{u_a \in \hat{\mathcal{U}}_{\mathsf{UL}}} \log_2(1+\lambda_a^k),$$
$$\Phi_b = \sum\nolimits_{u_b \in \hat{\mathcal{U}}_{\mathsf{DL}}} \log_2(1+\lambda_b^k),$$
$$\Phi_c = \sum\nolimits_{p_c \in \hat{\mathcal{P}}} \log_2(1+\lambda_c^k),$$

where "$|\cdot|$" represents the number of elements in a set (that is, $|\hat{\mathcal{R}}|$ is the number of RBs in $\hat{\mathcal{R}}$). After that, an RB allocation solution can be described as a matrix $\mathbf{Z}$ whose dimension is $(N_{\mathsf{UL}} + N_{\mathsf{DL}} + N_{\mathsf{DP}}) \times N_{\mathsf{RB}}$, where $N_{\mathsf{UL}} = |\hat{\mathcal{U}}_{\mathsf{UL}}|$, $N_{\mathsf{DL}} = |\hat{\mathcal{U}}_{\mathsf{DL}}|$, $N_{\mathsf{DP}} = |\hat{\mathcal{P}}|$, and $N_{\mathsf{RB}} = |\hat{\mathcal{R}}|$:

$$\mathbf{Z} = \begin{bmatrix} \mathrm{Z}_{\mathsf{UL}} \\ \mathrm{Z}_{\mathsf{DL}} \\ \mathrm{Z}_{\mathsf{DP}} \end{bmatrix}, \tag{9}$$

where $\mathrm{Z}_{\mathsf{UL}} = \left[z_a^k\right]_{N_{\mathsf{UL}} \times N_{\mathsf{RB}}}$, $\mathrm{Z}_{\mathsf{DL}} = \left[z_b^k\right]_{N_{\mathsf{DL}} \times N_{\mathsf{RB}}}$, and $\mathrm{Z}_{\mathsf{DP}} = \left[z_c^k\right]_{N_{\mathsf{DP}} \times N_{\mathsf{RB}}}$ signify the matrices of RB allocation for uplink CUEs, downlink CUEs, and D2D pairs, respectively. On the other hand, a power allocation solution can be expressed by a matrix $\mathbf{T}$ of dimension $(N_{\mathsf{UL}} + N_{\mathsf{DL}} + N_{\mathsf{DP}})$ as follows:

$$\mathbf{T} = \begin{bmatrix} \mathrm{T}_{\mathsf{UL}} \\ \mathrm{T}_{\mathsf{DL}} \\ \mathrm{T}_{\mathsf{DP}} \end{bmatrix}, \tag{10}$$

where $\mathrm{T}_{\mathsf{UL}} = \left[\tilde{\mathbf{t}}(u_a)\right]_{N_{\mathsf{UL}}}$, $\mathrm{T}_{\mathsf{DL}} = \left[\tilde{\mathbf{t}}(\tau[b])\right]_{N_{\mathsf{DL}}}$, and $\mathrm{T}_{\mathsf{DP}} = \left[\tilde{\mathbf{t}}(p_c^{\mathsf{S}})\right]_{N_{\mathsf{DP}}}$ denote the matrices of power allocation for uplink CUEs, downlink CUEs, and D2D pairs, respectively.

After that, the problem of resource and power management for in-band D2D communications can be formulated as an optimization problem:

$$[\mathbf{Z}_{\text{opt}}, \mathbf{T}_{\text{opt}}] = \arg_{\mathbf{Z},\mathbf{T}} \max \Phi, \tag{11}$$

subject to the following constraints:

$$z_a^k, z_b^k, z_c^k \in \{0,1\}, \qquad \forall u_a \in \hat{\mathcal{U}}_{\mathsf{UL}}, \forall u_b \in \hat{\mathcal{U}}_{\mathsf{DL}}, \forall p_c \in \hat{\mathcal{P}}, \forall r_k \in \hat{\mathcal{R}}, \tag{12}$$
$$\sum\nolimits_{u_a \in \hat{\mathcal{U}}_{\mathsf{UL}}} z_a^k \le 1, \qquad \forall r_k \in \hat{\mathcal{R}}, \tag{13}$$
$$\sum\nolimits_{u_b \in \hat{\mathcal{U}}_{\mathsf{DL}}} z_b^k \le 1, \qquad \forall r_k \in \hat{\mathcal{R}}, \tag{14}$$
$$t_a^{\min} \le \tilde{\mathbf{t}}(u_a) \le t_a^{\max}, \qquad \forall u_a \in \hat{\mathcal{U}}_{\mathsf{UL}}, \tag{15}$$
$$t_\tau^{\min} \le \tilde{\mathbf{t}}(\tau[b]) \le t_\tau^{\max}, \qquad \forall u_b \in \hat{\mathcal{U}}_{\mathsf{DL}}, \tag{16}$$
$$t_c^{\min} \le \tilde{\mathbf{t}}(p_c^{\mathsf{S}}) \le t_c^{\max}, \qquad \forall p_c \in \hat{\mathcal{P}}. \tag{17}$$

The objective function in Equation (11) wants to find out the optimal solution to RB and power allocation (i.e., $\mathbf{Z}_{\text{opt}}$ and $\mathbf{T}_{\text{opt}}$), so as to maximize network throughput. Then, Equation (12) means that z_a^k, z_b^k, z_c^k are indicators whose values are either 0 or 1. Both constraints in Equations (13) and (14) indicate that every RB can be allocated to at most one uplink CUE and one downlink CUE, respectively. These two constraints together imply that at most one link couple can use the same RB for data transmissions. After that, Equation (15) gives the lower and upper bounds on the transmitted power of each uplink CUE $u_a \in \hat{\mathcal{U}}_{\mathsf{UL}}$, which are denoted by $t_a^{\min}$ and $t_a^{\max}$, respectively. Equation (16) indicates the lower and upper bounds on the BS's transmitted power to send data to a downlink CUE in $\hat{\mathcal{U}}_{\mathsf{DL}}$, as denoted by $t_\tau^{\min}$ and $t_\tau^{\max}$, respectively. Finally, Equation (17) puts the lower and upper bounds on the transmitted power of each D2D sender, which are denoted by $t_c^{\min}$ and $t_c^{\max}$ for a D2D pair $p_c \in \hat{\mathcal{P}}$, respectively.

The above formulation is in the form of *mixed integer nonlinear programming (MINP)* [15], which means that this problem is NP-hard. In addition, the optimal solution $\mathbf{Z}_{\text{opt}}$ to RB allocation and the optimal solution $\mathbf{T}_{\text{opt}}$ to power allocation cannot be obtained independently. That is because the power allocation determines the intensity of the receiving signals and also the interference relationship between different communication links. On the other hand, the interference relationship substantially affects network throughput. Consequently, it is a big challenge to efficiently manage resources and transmitted power for in-band D2D communications.

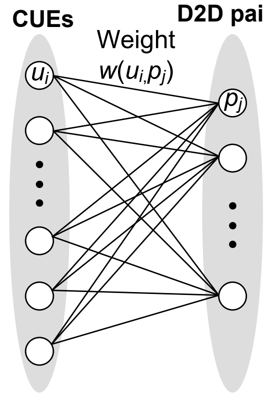

Fig. 3: A weighted bipartite graph to reveal the partnership of CUEs and D2D pairs.

4 Resource and Power Management Schemes

In this section, we discuss the existing resource and power management schemes proposed for in-band D2D communications, which are divided into four categories: matching-based, game-based, coloring-based, and other schemes. Then, we give a comparison between these management schemes. If not specified, the underlay mode is employed by a management scheme, as discussed in Section 2.3.

4.1 Matching-based Management Schemes

The matching-based management schemes construct a *weighted bipartite graph* to reveal the RB-sharing partnership of UEs, which comprises a vertex set $\hat{\mathcal{V}}$ and an edge set $\hat{\mathcal{E}}$, as shown in Figure 3. Specifically, the vertex set $\hat{\mathcal{V}}$ contains the involved UEs, which is further divided into two subsets composed of CUEs and D2D pairs. On the other hand, each edge in $\hat{\mathcal{E}}$ joins one CUE u_i to a D2D pair p_j, which indicates that p_j wants to reuse u_i's RB. Moreover, there is a weight $w(u_i, p_j)$ associated with every edge (u_i, p_j) in $\hat{\mathcal{E}}$.

Chen et al. [16] assume that there are more uplink CUEs than D2D pairs in a cell (that is, $\hat{\mathcal{V}} = \hat{\mathcal{U}}_{\mathsf{UL}} \cup \hat{\mathcal{P}}$ and $|\hat{\mathcal{U}}_{\mathsf{UL}}| > |\hat{\mathcal{P}}|$). Each uplink CUE $u_i \in \hat{\mathcal{U}}_{\mathsf{UL}}$ has a dedicated RB and its transmitted power $\tilde{\mathbf{t}}(u_i)$ is fixed to $\bar{t}_i$. On the other hand, the transmitted power of each D2D sender p_j^{S} is set to $\tilde{\mathbf{t}}(p_j^{\mathsf{S}}) = \bar{t}_j$

(i.e. also predefined). Then, the weight of each edge (u_i, p_j) in $\hat{\mathcal{E}}$ is defined as follows:

$$w(u_i,p_j) = \frac{B}{|\hat{\mathcal{R}}|}\log_2\left(1+\frac{\tilde{\mathbf{g}}(u_i,\tau)\times\bar{t}_i}{\tilde{\mathbf{g}}(p_j^{\mathsf{S}},\tau)\times\bar{t}_j+\sigma}\right)+ \frac{B}{|\hat{\mathcal{R}}|}\log_2\left(1+\frac{\tilde{\mathbf{g}}(p_j^{\mathsf{S}},p_j^{\mathsf{R}})\times\bar{t}_j}{\tilde{\mathbf{g}}(u_i,p_j^{\mathsf{R}})\times\bar{t}_i+\sigma}\right). \quad (18)$$

In Equation (18), the first term gives u_i's expected throughput and the second term indicates p_j's expected throughput when u_i and p_j share the same RB. However, since $|\hat{\mathcal{U}}_{\mathsf{UL}}|$ is larger than $|\hat{\mathcal{P}}|$, a number $(|\hat{\mathcal{U}}_{\mathsf{UL}}| - |\hat{\mathcal{P}}|)$ of *extended nodes* are added to the subset $\hat{\mathcal{P}}$ in the bipartite graph. The corresponding transmitted power $\bar{\mathbf{t}}(p_{j'}^{\mathsf{S}})$ of an extended node $p_{j'} \in \hat{\mathcal{P}}$ is zero (as it is virtual). Then, for each edge $(u_i, p_{j'})$ linked to an extend node, according to Equation (18), its weight can be simplified to

$$w(u_i,p_{j'}) = \frac{B}{|\hat{\mathcal{R}}|}\log_2\left(1+\frac{\tilde{\mathbf{g}}(u_i,\tau)\times\bar{t}_i}{\sigma}\right). \quad (19)$$

By using the Kuhn-Munkres algorithm [17], a matching in which the sum of edge weights is maximized (also known as a *maximum-weight matching*) can be found in $O(N_{\mathsf{UL}}^3)$ time, where N_{UL} is the number of uplink CUEs (i.e., $|\hat{\mathcal{U}}_{\mathsf{UL}}|$). After that, for each edge (u_i, p_j) in the maximum-weight matching, D2D pair p_j is allowed to share CUE u_i's RB. However, if p_j is an extended node (i.e., $p_j = p_{j'}$), it means that CUE u_i will use its RB solely.

Feng et al. [18] consider a similar scenario with the work [16] (i.e., $|\hat{\mathcal{U}}_{\mathsf{UL}}| > |\hat{\mathcal{P}}|$). For each uplink CUE $u_i \in \hat{\mathcal{U}}_{\mathsf{UL}}$ and each D2D pair $p_j \in \hat{\mathcal{P}}$, they find the best transmitted power for u_i and p_j^{S} (as denoted by t_i^* and t_j^*, respectively) to maximize their throughput:

$$(t_i^*, t_j^*) = \arg\max_{\tilde{\mathbf{t}}(u_i),\tilde{\mathbf{t}}(p_j^{\mathsf{S}})} \log_2(1+\lambda_i)+\log_2(1+\lambda_j), \quad (20)$$

subject to

$$\lambda_i = \frac{\tilde{\mathbf{g}}(u_i,\tau)\times\tilde{\mathbf{t}}(u_i)}{\tilde{\mathbf{g}}(p_j^{\mathsf{S}},\tau)\times\tilde{\mathbf{t}}(p_j^{\mathsf{S}})+\sigma} \geq \lambda_i^{\min}, \quad (21)$$

$$\lambda_j = \frac{\tilde{\mathbf{g}}(p_j^{\mathsf{S}},p_j^{\mathsf{R}})\times\tilde{\mathbf{t}}(p_j^{\mathsf{S}})}{\tilde{\mathbf{g}}(u_i,p_j^{\mathsf{R}})\times\tilde{\mathbf{t}}(u_i)+\sigma} \geq \lambda_j^{\min}, \quad (22)$$

$$\tilde{\mathbf{t}}(u_i) \leq t_{\max}^{\mathsf{CUE}} \text{ and } \tilde{\mathbf{t}}(p_j^{\mathsf{S}}) \leq t_{\max}^{\mathsf{D2D}}, \quad (23)$$

where $\lambda_i^{\min}$ and $\lambda_j^{\min}$ are the target SINRs for CUE u_i and D2D pair p_j, respectively. Moreover, $t_{\max}^{\mathsf{CUE}}$ and $t_{\max}^{\mathsf{D2D}}$ denote the maximum transmitted power of CUEs and D2D senders, respectively. In Equation (20), the bandwidth of each RB (i.e., $B/|\hat{\mathcal{R}}|$) is omitted for simplification (as the bandwidth is a constant). For CUE u_i, if there is no D2D pair to share its RB, the amount of u_i's maximum throughput will be

$$\phi_i = \log_2\left(1+\frac{\tilde{\mathbf{g}}(u_i,\tau)\times t_{\max}^{\mathsf{CUE}}}{\sigma}\right). \quad (24)$$

When D2D pair p_j shares u_i's RB, the aggregate throughput will be

$$\phi_{i,j}^{\text{sum}} = \log_2\left(1+\frac{\tilde{\mathbf{g}}(u_i,\tau)\times t_i^*}{\tilde{\mathbf{g}}(p_j^{\mathsf{S}},\tau)\times t_j^*+\sigma}\right)+ \log_2\left(1+\frac{\tilde{\mathbf{g}}(p_j^{\mathsf{S}},p_j^{\mathsf{R}})\times t_j^*}{\tilde{\mathbf{g}}(u_i,p_j^{\mathsf{R}})\times t_i^*+\sigma}\right). \quad (25)$$

Afterward, the weight of each edge (u_i, p_j) in the bipartite graph, where $u_i \in \hat{\mathcal{U}}_{\mathsf{UL}}$ and $p_j \in \hat{\mathcal{P}}$, is defined as the amount of *throughput gain* by D2D pair p_j, which is calculated by $\phi_{i,j}^{\text{sum}} - \phi_i$. Like [16], a maximum-weight matching is found by the Kuhn-Munkres algorithm, so the time complexity of the RB allocation method in [18] is $O(N_{\mathsf{UL}}^3)$. However, the time complexity of the power control method (i.e., Equation (20)) is not analyzed.

Chang et al. [19] let the D2D pairs share the RBs that have been allocated to the downlink CUEs (i.e., $\hat{\mathcal{V}} = \hat{\mathcal{U}}_{\mathsf{DL}} \cup \hat{\mathcal{P}}$). To do so, each CUE $u_i \in \hat{\mathcal{U}}_{\mathsf{DL}}$ maintains a *preference list* of the desired D2D pairs, which sorts each D2D pair $p_j \in \hat{\mathcal{P}}$ in decreasing order according to the ratio $\tilde{\mathbf{g}}(p_j^{\mathsf{S}}, p_j^{\mathsf{R}})/\tilde{\mathbf{g}}(u_i, p_j^{\mathsf{R}})$, where $\tilde{\mathbf{g}}(p_j^{\mathsf{S}}, p_j^{\mathsf{R}})$ denotes the channel gain from the sender p_j^{S} to the receiver p_j^{R} in D2D pair p_j, and $\tilde{\mathbf{g}}(u_i, p_j^{\mathsf{R}})$ represents the channel gain between CUE u_i and D2D receiver p_j^{R}. In particular, with a larger gain value $\tilde{\mathbf{g}}(p_j^{\mathsf{S}}, p_j^{\mathsf{R}})$, CUE u_i could experience less interference from D2D sender p_j^{S}, because p_j^{S} can transmit data to p_j^{R} by using less power to reach its target SINR. On the other hand, each D2D pair p_j in $\hat{\mathcal{P}}$ also adopts a preference list to prioritize each CUE u_i in $\hat{\mathcal{U}}_{\mathsf{DL}}$ according to the ratio $\tilde{\mathbf{g}}(\tau, u_i)/\tilde{\mathbf{g}}(u_i, p_j^{\mathsf{R}})$, where $\tilde{\mathbf{g}}(\tau, u_i)$ is the channel gain between the BS and u_i. More concretely, when a CUE has a larger gain value $\tilde{\mathbf{g}}(\tau, u_i)$, it can be more resistant to the intra-cell interference. Besides, the CUE will experience less interference from the D2D sender if the gain value $\tilde{\mathbf{g}}(u_i, p_j^{\mathsf{R}})$ is smaller. After that, the Gale-Shapley algorithm [20] is applied to match downlink CUEs and D2D pairs according to their preference lists. As to the time complexity, constructing the preference lists for all downlink CUEs and D2D pairs takes time of $O(N_{\mathsf{DL}}\log_2 N_{\mathsf{DL}}) + O(N_{\mathsf{DP}}\log_2 N_{\mathsf{DP}})$, where N_{DL} is the number of downlink CUEs in $\hat{\mathcal{U}}_{\mathsf{DL}}$, and N_{DP} is the number of D2D pairs in $\hat{\mathcal{P}}$. Then, running the Gale-Shapley algorithm requires $O(N_{\mathsf{DL}} \times N_{\mathsf{DP}})$ time. Supposing that $N_{\mathsf{DL}} > N_{\mathsf{DP}} > \log_2 N_{\mathsf{DL}}$ (i.e., there are more downlink CUEs than D2D pairs), the total time complexity will be $O(N_{\mathsf{DL}}\log_2 N_{\mathsf{DL}}) + O(N_{\mathsf{DP}}\log_2 N_{\mathsf{DP}}) + O(N_{\mathsf{DL}} \times N_{\mathsf{DP}}) = O(N_{\mathsf{DL}} \times N_{\mathsf{DP}})$.

Given a set $\hat{\mathcal{U}}_{\mathsf{UL}}$ of uplink CUEs and a set $\hat{\mathcal{P}}$ of D2D pairs, Zhou et al. [21] allocate one RB to each CUE and then make D2D pairs reuse their RBs, where each RB is allowed to be shared by at most one D2D pair, such that the overall *energy efficiency* can be maximized. Specifically, the energy efficiency (measured in bits/J/Hz) is defined as the amount of spectrum efficiency (measured in bits/s/Hz) divided by the total power consumption (measured in W) [22]. Then, a *partner selection matrix* $\mathbf{C}_{N_{\mathsf{UL}}\times N_{\mathsf{DP}}}$ for CUEs is built, where the (i,j)-th element $c_{i,j} \in \{0,1\}$ indicates the selection decision of the CUE-D2D partnership (u_i, p_j) for CUE $u_i \in \hat{\mathcal{U}}_{\mathsf{UL}}$ and D2D pair $p_j \in \hat{\mathcal{P}}$. If $c_{i,j} = 1$, u_i prefers to have a relationship with p_j. Otherwise, we have $c_{i,j} = 0$. Moreover, a partner selection matrix $\mathbf{D}_{N_{\mathsf{DP}}\times N_{\mathsf{UL}}}$ for D2D pairs is built, where the (j,i)-th element $d_{j,i} \in \{0,1\}$ indicates the selection decision of the D2D-CUE partnership (p_j, u_i) for D2D pair $p_j \in \hat{\mathcal{P}}$ and CUE $u_i \in \hat{\mathcal{U}}_{\mathsf{UL}}$. If $d_{j,i} = 1$, p_j prefers to form a relationship with u_i. Otherwise, $d_{j,i}$ is set to zero. Then, for each uplink CUE $u_i \in \hat{\mathcal{U}}_{\mathsf{UL}}$, its spectrum efficiency is calculated by

$$\vartheta_i = \log_2\left(1+\frac{\tilde{\mathbf{g}}(u_i,\tau)\times\tilde{\mathbf{t}}(u_i)}{\sigma+\sum_{p_j\in\hat{\mathcal{P}}} c_{i,j}\times d_{j,i}\times\tilde{\mathbf{g}}(p_j^{\mathsf{S}},\tau)\times\tilde{\mathbf{t}}(p_j^{\mathsf{S}})}\right). \quad (26)$$

Moreover, the power consumption for CUE u_i is estimated as follows:

$$e_i = \frac{\tilde{\mathbf{t}}(u_i)}{\eta} + e_{\mathsf{cir}}, \quad (27)$$

where η denotes the power amplifier efficiency ($0 < \eta < 1$) and e_{cir} is the total circuit power consumption (i.e., the amount of power consumed by the frequency synthesizer, mixer, analog-to-digital converter, digital-to-analog converter and so on).

On the other hand, for each D2D pair $p_j \in \hat{\mathcal{P}}$, its spectrum efficiency is estimated by

$$\vartheta_j = \sum_{u_i \in \hat{\mathcal{U}}_{\mathsf{UL}}} \log_2 \left(1 + \frac{c_{i,j} \times d_{j,i} \times \tilde{\mathbf{g}}(p_j^{\mathsf{S}}, p_j^{\mathsf{R}}) \times \tilde{\mathbf{t}}(p_j^{\mathsf{S}})}{\sigma + c_{i,j} \times d_{j,i} \times \tilde{\mathbf{g}}(u_i, p_j^{\mathsf{S}}) \times \tilde{\mathbf{t}}(u_i)}\right). \quad (28)$$

In addition, the power consumption for D2D pair p_j is measured by

$$e_j = \sum_{u_i \in \hat{\mathcal{U}}_{\mathsf{UL}}} \frac{c_{i,j} \times d_{j,i} \times \tilde{\mathbf{t}}(p_j^{\mathsf{S}})}{\eta} + 2e_{\mathsf{cir}}. \quad (29)$$

After that, each CUE is associated with a preference list, which sorts every D2D pair p_j in $\hat{\mathcal{P}}$ based on the value of ϑ_j/e_j decreasingly. On the other hand, each D2D pair is also associated with a preference list that sorts every CUE u_i in $\hat{\mathcal{U}}_{\mathsf{UL}}$ according to the value of ϑ_i/e_i in descending order. The Gale-Shapley algorithm is then adopted to match CUEs with D2D pairs. According to [21], the time complexity is shown to be $O(\alpha_1 N_{\mathsf{UL}} \times N_{\mathsf{DP}})$, where α_1 is the number of iterations used to find adequate transmitted power for UEs (including uplink CUEs and D2D senders) and construct the two partner selection matrices.

Mondal et al. [23] assume that there is a set $\hat{\mathcal{R}}$ of RBs allocated to a set $\hat{\mathcal{U}}_{\mathsf{UL}}$ of uplink CUEs. The objective is to schedule the D2D pairs in $\hat{\mathcal{P}}$ to reuse these RBs, where each D2D pair is allowed to reuse at most α_2 RBs in $\hat{\mathcal{R}}$ ($\alpha_2 \geq 1$), such that their data rates can achieve the proportional fairness. Suppose that an RB $r_k \in \hat{\mathcal{R}}$ is allocated to a CUE $u_i \in \hat{\mathcal{U}}_{\mathsf{UL}}$ whose minimum required SINR is $\lambda_i^{\min}$. If r_k is also allotted to a D2D pair $p_j \in \hat{\mathcal{P}}$, the transmitted power for its sender must satisfy the following condition:

$$\tilde{\mathbf{t}}(p_j^{\mathsf{S}}) \leq \frac{\tilde{\mathbf{g}}(u_i, \tau) \times \tilde{\mathbf{t}}(u_i)}{\lambda_i^{\min} \times \tilde{\mathbf{g}}(p_j^{\mathsf{S}}, \tau)} - \frac{\sigma}{\tilde{\mathbf{g}}(p_j^{\mathsf{S}}, \tau)}. \quad (30)$$

Then, the achievable data rate for D2D pair p_j can be estimated by

$$\phi_j = \frac{B}{|\hat{\mathcal{R}}|} \log_2 \left(1 + \frac{\tilde{\mathbf{g}}(p_j^{\mathsf{S}}, p_j^{\mathsf{R}}) \times \tilde{\mathbf{t}}(p_j^{\mathsf{S}})}{\tilde{\mathbf{g}}(u_i, p_j^{\mathsf{R}}) \times \tilde{\mathbf{t}}(u_i) + \sigma}\right). \quad (31)$$

To allocate the RBs in $\hat{\mathcal{R}}$ to the D2D pairs in $\hat{\mathcal{P}}$, a weighted bipartite graph is constructed, whose vertex set contains a special set $\hat{\mathcal{D}}'$ and the set $\hat{\mathcal{R}}$, where $\hat{\mathcal{D}}'$ is the set of D2D pairs in $\hat{\mathcal{P}}$ repeated α_2 times (since each D2D pair can reuse at most α_2 RBs). Moreover, for each edge (p_j, r_k) in the bipartite graph, where $p_j \in \hat{\mathcal{D}}'$ and $r_k \in \hat{\mathcal{R}}$, the associated weight is calculated by $\phi_j/\phi_j^{\text{avg}}$, where ϕ_j^{avg} denotes the average data rate of D2D pair p_j in the past. Here, the weight can be viewed as a metric to evaluate the degree of proportional fairness [24]. After that, the Blossom algorithm [25] is adopted to match the D2D pairs in $\hat{\mathcal{D}}'$ and the RBs in $\hat{\mathcal{R}}$. In [23], it consumes $O(\alpha_2^2 N_{\mathsf{DP}})$ time to calculate edge weights. Moreover, the Blossom algorithm takes $O(((\alpha_2+1)N_{\mathsf{DP}})^3)$ time. To sum up, the overall time complexity is $O(\alpha_2^2 N_{\mathsf{DP}}) + O(((\alpha_2+1)N_{\mathsf{DP}})^3) = O((\alpha_2 N_{\mathsf{DP}})^3)$.

4.2 Game-based Management Schemes

As the name suggests, the game-based management schemes formulate the resource allocation problem or the power control problem by using different strategic games. Then, various game-theoretic mechanisms are proposed to solve these problems.

Chen et al. [26] let the D2D pairs in $\hat{\mathcal{P}}$ reuse the RBs allocated to the uplink CUEs in $\hat{\mathcal{U}}_{\mathsf{UL}}$, where the Stackelberg game is used to find the transmitted power of each D2D sender (i.e., power control). In a general Stackelberg game with one leader and one follower [27], according to the price offered by the leader, the follower decides its best quantity such that the follower's utility can be maximized. Moreover, the leader knows the follower's quantity function of the price variable, and it charges a price for the follower in order to maximize the leader's utility. For power control, the leader is a CUE $u_i \in \hat{\mathcal{U}}_{\mathsf{UL}}$ and the follower is a D2D pair $p_j \in \hat{\mathcal{P}}$ that wants to share u_i's RB. The objective is to find the optimal price μ and the best transmitted power $\tilde{\mathbf{t}}(p_j^{\mathsf{S}})$ for D2D sender p_j^{S}, such that the utilities of both u_i and p_j can be maximized. For D2D pair p_j (i.e., the follower), the utility function is defined as its throughput subtracted by the payment that p_j should pay for sharing u_i's RB, which is expressed by

$$\mathbb{U}_{\mathbf{D}}(\mu, \tilde{\mathbf{t}}(p_j^{\mathsf{S}})) = \log_2 \left(1 + \frac{\tilde{\mathbf{g}}(p_j^{\mathsf{S}}, p_j^{\mathsf{R}}) \times \tilde{\mathbf{t}}(p_j^{\mathsf{S}})}{\tilde{\mathbf{g}}(u_i, p_j^{\mathsf{R}}) \times \tilde{\mathbf{t}}(u_i) + \Omega_{\mathbf{D}}}\right) - \mu \times \tilde{\mathbf{g}}(p_j^{\mathsf{S}}, \tau) \times \tilde{\mathbf{t}}(p_j^{\mathsf{S}}), \quad (32)$$

where

$$\Omega_{\mathbf{D}} = \sum\nolimits_{p_a \in \hat{\mathcal{P}}_i} \tilde{\mathbf{g}}(p_a^{\mathsf{S}}, p_j^{\mathsf{R}}) \times \tilde{\mathbf{t}}(p_a^{\mathsf{S}}) + \sigma, \quad (33)$$

where $\hat{\mathcal{P}}_i \subset \hat{\mathcal{P}}$ is the subset of D2D pairs that currently share u_i's RB. On the other hand, for CUE u_i (i.e., the leader), the utility function is defined as its throughput added by the revenue that u_i earns from D2D pair p_j, which can be expressed by

$$\mathbb{U}_{\mathbf{C}}(\mu, \tilde{\mathbf{t}}(p_j^{\mathsf{S}})) = \log_2 \left(1 + \frac{\tilde{\mathbf{g}}(u_i, \tau) \times \tilde{\mathbf{t}}(u_i)}{\tilde{\mathbf{g}}(p_j^{\mathsf{S}}, \tau) \times \tilde{\mathbf{t}}(p_j^{\mathsf{S}}) + \Omega_{\mathbf{C}}}\right) + \chi\mu \times \tilde{\mathbf{g}}(p_j^{\mathsf{S}}, \tau) \times \tilde{\mathbf{t}}(p_j^{\mathsf{S}}), \quad (34)$$

where

$$\Omega_{\mathbf{C}} = \sum\nolimits_{p_a \in \hat{\mathcal{P}}_i} \tilde{\mathbf{g}}(p_a^{\mathsf{S}}, \tau) \times \tilde{\mathbf{t}}(p_a^{\mathsf{S}}) + \sigma, \quad (35)$$

and χ is a constant ratio of the revenue that CUE u_i obtains to the payment that D2D pair p_j pays. The optimal price μ takes only on one of the six values derived in [26], and the best transmitted power can be calculated as follows:

$$\tilde{\mathbf{t}}(p_j^{\mathsf{S}}) = \frac{1}{\mu \ln 2 \times \tilde{\mathbf{g}}(p_j^{\mathsf{S}}, \tau)} - \frac{\tilde{\mathbf{g}}(u_i, p_j^{\mathsf{R}}) \times \tilde{\mathbf{t}}(u_i) + \Omega_{\mathbf{D}}}{\tilde{\mathbf{g}}(p_j^{\mathsf{S}}, p_j^{\mathsf{R}})}. \quad (36)$$

On the other hand, the resource allocation problem (for D2D pairs) is translated into a *maximum independent set (MIS)* problem. More concretely, a conflict graph is constructed for D2D pairs, where each vertex corresponds to a D2D pair not allocated any RB yet. For any two vertices p_a and p_b in the graph, there is an edge (p_a, p_b) to connect them if the distance between D2D pairs p_a and p_b is shorter than a given threshold (in other words, these two D2D pairs will impose significant interference on each other). Because the MIS problem is NP-hard, the heuristic algorithm in [28] is used to find an approximate solution. Let $\hat{\mathcal{P}}_{\mathsf{MIS}}$ be an MIS of D2D pairs found by the heuristic, where these D2D pairs will not interfere with each other. For each D2D pair $p_j \in \hat{\mathcal{P}}_{\mathsf{MIS}}$, the transmitted power of its sender is decided by Equation (36). Afterward, we check whether adding p_j to $\hat{\mathcal{P}}_i$ (i.e., sharing the RB of CUE u_i) can still satisfy the target SINRs of both u_i and p_j. If so, p_j is moved from $\hat{\mathcal{P}}_{\mathsf{MIS}}$ to $\hat{\mathcal{P}}_i$. Otherwise, p_j is kept in $\hat{\mathcal{P}}_{\mathsf{MIS}}$ for another trial. For the time complexity, since the optimal price μ is limited to the six values, it takes a constant time to find the transmitted power for each D2D sender by Equation (36) (i.e., the Stackelberg game). Moreover, the heuristic in [28] requires $O(N^3_{\mathsf{DP}})$ time to find the MIS solution. To sum up, the total time complexity is $N_{\mathsf{DP}} \times O(1) + O(N^3_{\mathsf{DP}}) = O(N^3_{\mathsf{DP}})$.

Given a set $\hat{\mathcal{R}}$ of RBs, each allocated to one uplink CUE whose transmitted power is fixed to $\bar{t}$, Yuan et al. [29] let a set $\hat{\mathcal{P}}$ of D2D pairs share the RBs in $\hat{\mathcal{R}}$ and decide their transmitted power, so as to maximize the throughput of D2D pairs while suppressing their interference to cellular links. An RB can be shared by multiple D2D pairs, but each D2D pair is given at most one RB. Let z^k_i be an indicator to reveal whether RB r_k is allocated to D2D pair p_i, where $z^k_i \in \{0, 1\}$. Then, the data rate of p_i on r_k is estimated by

$$\phi_{i,k} = \log_2\left(1 + \frac{z^k_i \times \tilde{\mathbf{g}}(p^{\mathsf{S}}_i, p^{\mathsf{R}}_i) \times \tilde{\mathbf{t}}(p^{\mathsf{S}}_i)}{\sigma + \phi_1 + \phi_2}\right), \tag{37}$$
$$\phi_1 = \tilde{\mathbf{g}}(u_k, p^{\mathsf{R}}_i) \times \bar{t},$$
$$\phi_2 = \sum\nolimits_{p_j \in \hat{\mathcal{P}} \setminus \{p_i\}} z^k_j \times \tilde{\mathbf{g}}(p^{\mathsf{S}}_j, p^{\mathsf{R}}_i) \times \tilde{\mathbf{t}}(p^{\mathsf{S}}_j),$$

where CUE u_k uses RB r_k. In Equation (37), the bandwidth is omitted for simplification. Given the transmitted power of each D2D sender (that is, $\tilde{\mathbf{t}}(p^{\mathsf{S}}_i)$ is predefined, $\forall p_i \in \hat{\mathcal{P}}$), the RB allocation problem for D2D pairs is formulated as a *many-to-one matching game*. More concretely, given two disjoint sets $\hat{\mathcal{P}}$ and $\hat{\mathcal{R}}$ of players, a many-to-one matching ζ is a subset of $\hat{\mathcal{P}} \otimes \hat{\mathcal{R}}$ such that (1) $|\zeta(p_i)| = 1$ and (2) $|\zeta(r_k)| \leq n_k, \forall r_k \in \hat{\mathcal{R}}$ and $\zeta(r_k) = \emptyset$ if RB r_k is not allocated to any D2D pair, where $\zeta(p_i) = \{r_k \in \hat{\mathcal{R}} \,|\, (p_i, r_k) \in \zeta\}$ and $\zeta(r_k) = \{p_i \in \hat{\mathcal{P}} \,|\, (p_i, r_k) \in \zeta\}$. Specifically, condition (1) indicates that each D2D pair is matched to an RB in any matching, and condition (2) means that at most n_k D2D pairs can reuse RB r_k.

In the many-to-one matching game, a utility function is used to describe the preference of each player. In particular, the utility of D2D pair p_i for RB r_k is defined by

$$f_i(r_k) = \phi_{i,k} - \sum\nolimits_{p_j \in \hat{\mathcal{P}} \setminus \{p_i\}} \mu^{\mathsf{IP}}_{j,k} \times \tilde{\mathbf{g}}(p^{\mathsf{S}}_i, p^{\mathsf{R}}_j) \times \tilde{\mathbf{t}}(p^{\mathsf{S}}_i) - \mu_{\mathsf{CH}}, \tag{38}$$

where $\mu^{\mathsf{IP}}_{j,k}$ denotes the *interference price* [30], which is the decrease of the data rate of D2D pair p_i with relation to one unit increment of the interference from other D2D pairs on RB r_k, and μ_{CH} is the price that p_i should pay to reuse r_k. On the other hand, to restrain the interference to cellular links, given a subset $\hat{\mathcal{P}}_k \subseteq \hat{\mathcal{P}}$ of D2D pairs, the utility function for RB r_k is defined as follows:

$$f_k(\hat{\mathcal{P}}_k) = \mu_{\mathsf{CH}} \times |\hat{\mathcal{P}}_k| - \mu_k \sum\nolimits_{p_i \in \hat{\mathcal{P}}_k} \tilde{\mathbf{g}}(p^{\mathsf{S}}_i, \tau) \times \tilde{\mathbf{t}}(p^{\mathsf{S}}_i), \tag{39}$$

where μ_k is the price of r_k. In Equation (39), despite the interference caused by D2D pairs to a cellular link, r_k can still get payoff from RB sharing, which encourages the CUE to share its RB with D2D pairs. Then, the swap-matching approach in [31] is employed to find the solution to the matching game according to the preferences of D2D pairs and RBs. After obtaining the result of RB allocation for D2D pairs, the transmitted power of D2D senders is decided by playing the Stackelberg game, just like that discussed in [26].

Given uplink CUEs (i.e., $\hat{\mathcal{U}}_{\mathsf{UL}}$) and D2D pairs (i.e, $\hat{\mathcal{P}}$), Sun et al. [32] formulate the resource allocation problem by a coalition formation game, where each D2D pair forms a coalition with multiple CUEs, whereas a CUE merely chooses one coalition to join. In other words, each D2D pair can reuse the RBs of multiple CUEs, but each CUE is allowed to share its RB with just one D2D pair. Supposing that a CUE $u_i \in \hat{\mathcal{U}}_{\mathsf{UL}}$ shares its RB with a D2D pair $p_j \in \hat{\mathcal{P}}$, their data rates (as denoted by $\phi^{\mathsf{CUE}}_{i,j}$ and $\phi^{\mathsf{D2D}}_{j,i}$, respectively) are estimated as follows:

$$\phi^{\mathsf{CUE}}_{i,j} = \log_2\left(1 + \frac{\tilde{\mathbf{g}}(u_i, \tau) \times \tilde{\mathbf{t}}(u_i)}{\tilde{\mathbf{g}}(p^{\mathsf{S}}_j, \tau) \times \tilde{\mathbf{t}}(p^{\mathsf{S}}_j) + \sigma}\right), \tag{40}$$
$$\phi^{\mathsf{D2D}}_{j,i} = \log_2\left(1 + \frac{\tilde{\mathbf{g}}(p^{\mathsf{S}}_j, p^{\mathsf{R}}_j) \times \tilde{\mathbf{t}}(p^{\mathsf{S}}_j)}{\tilde{\mathbf{g}}(u_i, p^{\mathsf{R}}_j) \times \tilde{\mathbf{t}}(u_i) + \sigma}\right), \tag{41}$$

where the bandwidth is also omitted for simplification. Let $\phi^{\mathsf{CUE}}_{\min}$ and $\phi^{\mathsf{D2D}}_{\min}$ denote the minimum required rates for CUEs and D2D pairs, respectively. Then, the coalition formation game will find a set of coalitions $\mathbf{\Theta} = \{\Theta_1, \Theta_2, \cdots, \Theta_{|\hat{\mathcal{P}}|}\}$. Each coalition Θ_j in $\mathbf{\Theta}$ contains D2D pair p_j and possibly multiple CUEs, which means that p_j will share the RBs of these CUEs, and its utility is defined by

$$f(\Theta_j) = \begin{cases} 0, & \text{if } \phi^{\mathsf{CUE}}_{i,j} < \phi^{\mathsf{CUE}}_{\min}, \exists u_i \in \Theta_j \\ 0, & \text{if } \phi^{\mathsf{D2D}}_{j,i} < \phi^{\mathsf{D2D}}_{\min}, \exists u_i \in \Theta_j \\ \sum_{u_i \in \Theta_j} \phi^{\mathsf{D2D}}_{j,i}, & \text{otherwise} \end{cases} \tag{42}$$

In other words, the utility will be the sum rate of p_j by reusing the RBs of the CUEs in Θ_j. To play the game, the set $\mathbf{\Theta}$ is initialized to be all singletons (for D2D pairs):

$$\begin{aligned} \mathbf{\Theta} &= \left\{\Theta_1, \Theta_2, \cdots, \Theta_{|\hat{\mathcal{P}}|}, \Theta_{|\hat{\mathcal{P}}|+1}\right\} \\ &= \left\{\{p_1\}, \{p_2\}, \cdots, \{p_{|\hat{\mathcal{P}}|}\}, \{\emptyset\}\right\}, \end{aligned} \tag{43}$$

where $\Theta_{|\hat{\mathcal{P}}|+1}$ is an empty coalition at beginning. Each CUE $u_i \in \hat{\mathcal{U}}_{\mathsf{UL}}$ chooses the coalition, say, Θ_j to join, such that u_i and p_j has the minimum mutual interference. However, if the joining of u_i leads to $f(\Theta_j) = 0$, it means that the data rates of some UEs in Θ_j cannot satisfy their requirements. Thus, u_i leaves the current coalition and joins $\Theta_{|\hat{\mathcal{P}}|+1}$. In other words, u_i will not share its RB with any D2D pair.

On the other hand, the power control problem is formulated as follows:

$$\arg\max\nolimits_{\tilde{\mathbf{t}}(u_i), \tilde{\mathbf{t}}(p^{\mathsf{S}}_j)} \sum\nolimits_{u_i \in \hat{\mathcal{U}}_{\mathsf{UL}}} \sum\nolimits_{p_j \in \hat{\mathcal{P}}} \mathsf{sign}(\phi^{\mathsf{D2D}}_{j,i} - \phi^{\mathsf{D2D}}_{\min}) \times \phi^{\mathsf{D2D}}_{j,i}, \tag{44}$$

subject to

$$\phi^{\mathsf{CUE}}_{i,j} \geq \phi^{\mathsf{CUE}}_{\min}, \qquad \forall u_i \in \hat{\mathcal{U}}_{\mathsf{UL}}, \tag{45}$$
$$\tilde{\mathbf{t}}(u_i) \leq t^{\mathsf{CUE}}_{\max}, \qquad \forall u_i \in \hat{\mathcal{U}}_{\mathsf{UL}}, \tag{46}$$
$$\tilde{\mathbf{t}}(p^{\mathsf{S}}_j) \leq t^{\mathsf{D2D}}_{\max}, \qquad \forall p_j \in \hat{\mathcal{P}}, \tag{47}$$

where

$$\mathsf{sign}(x) = \begin{cases} 1, & \text{if } x \geq 0 \\ -1, & \text{otherwise} \end{cases} \tag{48}$$

The objective function in Equation (44) is to maximize the throughput of D2D pairs. The constraint in Equation (45) is to ensure that each CUE can meet its rate requirement. Both Equations (46) and (47) put upper bounds $t^{\mathsf{CUE}}_{\max}$ and $t^{\mathsf{D2D}}_{\max}$ on the transmitted power of CUEs and D2D pairs, respectively. After that, the *whale optimization algorithm* (WOA) proposed in [33] is used to solve the power control problem, which is a meta-heuristic optimization algorithm mimicking the hunting behavior of humpback whales.

Najla et al. [34] adopt the overlay mode, where D2D pairs have dedicated RBs for communications, instead of sharing RBs with CUEs (and interfering with them). Specifically, there is a set $\hat{\mathcal{R}}$ of RBs dedicated to a set $\hat{\mathcal{P}}$ of D2D pairs ($|\hat{\mathcal{R}}| = |\hat{\mathcal{P}}|$), where each RB may be allocated to a D2D pair or shared by multiple D2D pairs. The objective is to maximize the sum rate of all D2D pairs in $\hat{\mathcal{P}}$, provided that the rate of each D2D pair is at least $\phi_{\min}$. This problem is formulated as a *coalition structure generation (CSG) problem* [35], which finds a set $\mathbf{\Theta} = \{\Theta_1, \Theta_2, \cdots, \Theta_M\}$ of coalitions of D2D pairs. Each coalition Θ_m contains a subset of D2D pairs in $\hat{\mathcal{P}}$ that can mutually reuse all RBs assigned to these D2D pairs in Θ_m. Besides, each D2D pair joins at most one coalition. Mathematically, the CSG problem can be expressed as follows:

$$\mathbf{\Theta} = \arg\max \sum\nolimits_{p_i \in \hat{\mathcal{P}}} \sum\nolimits_{r_k \in \hat{\mathcal{R}}} \frac{B}{|\hat{\mathcal{R}}|} \log_2(1 + \lambda_i^k), \tag{49}$$

subject to

$$\sum\nolimits_{r_k \in \hat{\mathcal{R}}} \frac{B}{|\hat{\mathcal{R}}|} \log_2(1 + \lambda_i^k) \geq \phi_{\min}, \forall p_i \in \hat{\mathcal{P}}. \tag{50}$$

The objective function in Equation (49) is to maximize the overall data rate of D2D pairs, where B is the channel bandwidth, and λ_i^k is the SINR of D2D pair p_i on RB r_k, which is calculated by

$$\lambda_i^k = \frac{\tilde{\mathbf{g}}(p_i^{\mathsf{S}}, p_i^{\mathsf{R}}) \times \tilde{\mathbf{t}}(p_i^{\mathsf{S}})}{\sigma + \sum_{p_a \in \hat{\mathcal{P}}_k, p_a \neq p_i} \tilde{\mathbf{g}}(p_a^{\mathsf{S}}, p_i^{\mathsf{R}}) \times \tilde{\mathbf{t}}(p_a^{\mathsf{S}})}, \tag{51}$$

where $\hat{\mathcal{P}}_k$ is a set of D2D pairs using RB r_k. On the other hand, Equation (50) gives the $\phi_{\min}$ constraint for each D2D pair.

Then, the sequential bargaining game is applied to solve the CSG problem, which defines a utility function for any two D2D pairs p_i and p_j in $\hat{\mathcal{P}}$ as follows:

$$f_{i,j} = \begin{cases} -1 & \text{if } \phi_{i,i} + \phi_{i,j} < \phi_{\min} \\ -1 & \text{if } \phi_{j,i} + \phi_{j,j} < \phi_{\min} \\ \phi_{i,j}^{\mathsf{gain}} & \text{otherwise,} \end{cases} \tag{52}$$

where $\phi_{x,y}$ denotes the data rate of D2D pair x on RB r_y, where $x, y \in \{i, j\}$. Here, D2D pairs p_i and p_j communicate on RBs r_i and r_j at the same time. In Equation (52), if reusing the RB leads to a decrease in the data rate below $\phi_{\min}$ for either p_i or p_j, the coalition is not created, so $f_{i,j}$ is set to -1. Otherwise, a rate gain $\phi_{i,j}^{\mathsf{gain}}$ introduced by the new coalition of both D2D pairs is calculated by

$$\phi_{i,j}^{\mathsf{gain}} = (\phi_{i,i} + \phi_{i,j} + \phi_{j,i} + \phi_{j,j}) - (\phi_{i,i}^{\mathsf{sole}} + \phi_{j,j}^{\mathsf{sole}}), \tag{53}$$

where $\phi_{i,i}^{\mathsf{sole}}$ and $\phi_{j,j}^{\mathsf{sole}}$ indicate the data rates of p_i or p_j without RB sharing, respectively. The utility $f_{i,j}$ is obtained for all possible coalitions created by any two pairs $p_i, p_j \in \hat{\mathcal{P}}$, which are inserted into a bilateral utility matrix:

$$\mathbf{F} = \begin{bmatrix} 0 & \cdots & f_{1,|\hat{\mathcal{P}}|} \\ \vdots & \ddots & \vdots \\ f_{|\hat{\mathcal{P}}|,1} & \cdots & 0 \end{bmatrix} \tag{54}$$

The bilateral utility matrix is symmetric (that is, $f_{i,j} = f_{j,i}$), and the diagonal values in $\mathbf{F}$ are zeros (since D2D pairs cannot create a coalition with themselves). Then, the positive elements in $\mathbf{F}$ are sorted decreasingly, where every couple of symmetric positive elements is treated as one element ($f_{i,j} = f_{j,i}$). The sorted positive elements $f_{i,j}$ stand for a vector of sub-games played sequentially over time in a way that one sub-game is played in every step. Initially, the sub-game is played between two D2D pairs p_i and p_j on their dedicated RBs r_i and r_j. The coalition is created if p_i and p_j both agree to reuse their RBs with each other. After that, when a D2D pair p_i wants to join a coalition Θ_m, the sub-game is played between p_i and all D2D pairs in Θ_m. In this case, p_i is allowed to joint Θ_m if all D2D pairs in Θ_m agree (that is, $f_{i,j} > 0, \forall p_j \in \Theta_m$).

4.3 Coloring-based Management Schemes

In the coloring-based management schemes, a graph is constructed to show the interference relationship between UEs, where the vertex set contains the involved UEs (i.e., CUEs and D2D pairs). When two vertices are connected by an edge, it means that the corresponding UEs will impose significant interference on each other. In this case, they cannot share the same RB. This is similar to the *vertex coloring problem* [36], where two adjacent vertices cannot be painted with the same color. In other words, if a group of vertices can be painted with the same color, their UEs are viewed as interference-free. In this case, these UEs are able to use the same RB.

Cai et al. [37] build a graph to help a set $\hat{\mathcal{P}}$ of D2D pairs reuse the RBs allocated to a set $\hat{\mathcal{U}}_{\mathsf{DL}}$ of downlink CUEs, where each vertex in the graph corresponds to one D2D pair in $\hat{\mathcal{P}}$. When the distance between the sender of a D2D pair and the receiver of another D2D pair is shorter than a threshold, the sender will interfere with that receiver. In this case, the two vertices corresponding to these two D2D pairs will be linked by an edge. On the other hand, each CUE $u_i \in \hat{\mathcal{U}}_{\mathsf{DL}}$ is treated as one color $\tilde{c}_i$. Once a D2D sender is close to CUE u_i, the sender also imposes non-neglected interference on u_i. Because of this, a *SINR limited area (SLA)* for CUE u_i is used to identify a set of D2D pairs that cannot reuse u_i's RB. More concretely, u_i's SLA is a circular area centered at u_i, whose radius is defined by

$$\sqrt[\varepsilon]{\frac{\tilde{\mathbf{t}}(p_j^{\mathsf{S}}) \times \beta \times \lambda_i^{\min}}{\tilde{\mathbf{t}}(\tau[i]) \times 10^{-L(\tau, u_i)/10}}}, \tag{55}$$

where a D2D pair $p_j \in \hat{\mathcal{P}}$ wants to reuse u_i's RB. In Equation (55), ε is the exponent for path loss, β is a normalization factor, $\lambda_i^{\min}$ is the minimum required SINR of u_i, $\tilde{\mathbf{t}}(\tau[i])$ is the BS's transmitted power to send data to u_i, and $L(\tau, u_i)$ is the distance from the BS to u_i. In particular, if the distance between CUE u_i and D2D sender p_j^{S} is no larger than the radius, D2D pair p_j is located in u_i's SLA and it cannot reuse u_i's RB. In other words, vertex v_j cannot be painted with color $\tilde{c}_i$.

For each vertex v_j, if color $\tilde{c}_i$ is available, the correlation degree of vertex v_j for color $\tilde{c}_i$ (denoted by $\rho_{i,j}$) is defined by the number of v_j's neighboring vertices whose candidate color sets also contain $\tilde{c}_i$. However, if color $\tilde{c}_i$ is not available for vertex v_j, $\rho_{i,j}$ is set to $-\infty$. Then, the *label* of vertex v_j for color c_i is defined by

$$\frac{\log_2(1+\lambda_i)+\log_2(1+\lambda_j)}{\rho_{i,j}+1}. \tag{56}$$

To find the D2D pairs from $\hat{\mathcal{P}}$ to share the RBs of the CUEs in $\hat{\mathcal{U}}_{\mathsf{DL}}$, we iteratively select the vertex with the largest label and dye it with a color $\tilde{c}_i$. Then, $\tilde{c}_i$ is removed from the candidate color set of the selected vertex and each of its neighbors. The above procedure is repeated until the candidate color sets of all vertices become empty.

Yang et al. [12] consider a full-duplex cellular network that contains uplink CUEs (i.e., $\hat{\mathcal{U}}_{\mathsf{UL}}$), downlink CUEs (i.e., $\hat{\mathcal{U}}_{\mathsf{DL}}$), and D2D pairs (i.e., $\hat{\mathcal{P}}$). An interference graph is drawn for RB allocation, where each vertex $v_i \in \hat{\mathcal{V}}$ denotes a communication link (i.e., an uplink in $\hat{\mathcal{U}}_{\mathsf{UL}}$, a downlink in $\hat{\mathcal{U}}_{\mathsf{DL}}$, or a D2D link in $\hat{\mathcal{P}}$) and $\hat{\mathcal{V}}$ is the vertex set. Each edge (v_i, v_j) expresses the mutual interference between two vertices v_i and v_j, whose weight is defined by

$$w(v_i, v_j) = I_{v_i,v_j} + I_{v_j,v_i}, \tag{57}$$

where I_{v_i,v_j} denotes the interference from v_i to v_j, which is calculated as follows:

$$I_{v_i,v_j} = \begin{cases} 0, & \text{if } v_i = v_j \\ \bar{g}_\tau \times \tilde{\mathbf{t}}(\tau[i]), & \text{if } v_i \in \hat{\mathcal{U}}_{\mathsf{DL}} \text{ and } v_j \in \hat{\mathcal{U}}_{\mathsf{UL}} \\ \infty, & \text{if } v_i, v_j \in \hat{\mathcal{U}}_{\mathsf{UL}} \text{ or } v_i, v_j \in \hat{\mathcal{U}}_{\mathsf{DL}} \\ \tilde{\mathbf{g}}(v_i, v_j) \times \tilde{\mathbf{t}}(v_i), & \text{otherwise} \end{cases} \tag{58}$$

In Equation (58), case 1 means that a communication link will not interfere with itself. Case 2 is that a link couple of uplink CUE and downlink CUE share the same RB. As discussed in Section 3.2, the self-interference will occur at the BS, which is evaluated by Equation (4). Case 3 means that two uplink CUEs or two downlink CUEs cannot share the same RB. In case 4, $\tilde{\mathbf{g}}(v_i, v_j)$ is the channel gain from v_i's sender (i.e., the uplink CUE, the BS, and the D2D sender if v_i belongs to $\hat{\mathcal{U}}_{\mathsf{UL}}$, $\hat{\mathcal{U}}_{\mathsf{DL}}$, and $\hat{\mathcal{P}}$, respectively) to v_j's receiver (i.e., the BS, the downlink CUE, and the D2D receiver if v_j belongs to $\hat{\mathcal{U}}_{\mathsf{UL}}$, $\hat{\mathcal{U}}_{\mathsf{DL}}$, and $\hat{\mathcal{P}}$, respectively), and $\tilde{\mathbf{t}}(v_i)$ is the transmitted power of v_i's sender. By considering each RB in $\hat{\mathcal{R}}$ as one color, the resource allocation problem can be translated into the vertex coloring problem. Let $\hat{\mathcal{V}}_k \subseteq \hat{\mathcal{V}}$ be the set of vertices painted with color $r_k \in \hat{\mathcal{R}}$. In other words, all communication links in $\hat{\mathcal{V}}_k$ can share RB r_k. Moreover, three terms are defined for $\hat{\mathcal{V}}_k$:

- The *complementary set* $\hat{\mathcal{V}}_k^{\mathsf{C}}$ contains all vertices not in $\hat{\mathcal{V}}_k$ (i.e., $\hat{\mathcal{V}}_k^{\mathsf{C}} = \hat{\mathcal{V}} - \hat{\mathcal{V}}_k$).
- The *throughput value* $\xi_T(\hat{\mathcal{V}}_k)$ is the sum of the data rate of each communication link in $\hat{\mathcal{V}}_k$, taking account of the mutual interference, which can be expressed by

$$\xi_T(\hat{\mathcal{V}}_k) = \sum\nolimits_{v_i \in \hat{\mathcal{V}}_k} \frac{B}{|\hat{\mathcal{R}}|} \log_2(1 + \lambda_{v_i}^k), \tag{59}$$

  where B is the channel bandwidth and $\lambda_{v_i}^k$ is the SINR of the communication link v_i on RB r_k.
- The *interference value* $\xi_I(\hat{\mathcal{V}}_k)$ is the sum of the mutual interference value between every two communication links in $\hat{\mathcal{V}}_k$, which is calculated by

$$\xi_I(\hat{\mathcal{V}}_k) = \sum\nolimits_{v_i, v_j \in \hat{\mathcal{V}}_k} w(v_i, v_j). \tag{60}$$

For each $r_k \in \hat{\mathcal{R}}$, $\hat{\mathcal{V}}_k$ is initially set to $\emptyset$ (so $\xi_T(\hat{\mathcal{V}}_k) = \xi_I(\hat{\mathcal{V}}_k) = 0$). Afterward, we select a vertex $v_i \in \hat{\mathcal{V}}_k^{\mathsf{C}}$ to dye with a color and update $\xi_T(\hat{\mathcal{V}}_k)$. If $v_i \in \hat{\mathcal{U}}_{\mathsf{UL}} \cup \hat{\mathcal{U}}_{\mathsf{DL}}$, another vertex v_j is chosen to make them form a vertex pair (that is, v_i and v_j would become a link couple). After all possible coloring choices have been tried, we update the throughput value with the largest $\xi_T(\hat{\mathcal{V}}_k)$, and dye the corresponding vertex pair or D2D vertex (i.e., $v_i \in \hat{\mathcal{P}}$). Whenever a vertex pair or D2D vertex is dyed, the information of all vertices (e.g., $\xi_T(\hat{\mathcal{V}}_k)$ and $\xi_I(\hat{\mathcal{V}}_k)$) should be updated. The above resource allocation procedure is repeated until coloring a new vertex pair or a D2D vertex cannot improve the throughput value $\xi_T(\hat{\mathcal{V}}_k)$.

After all $|\hat{\mathcal{R}}|$ colors have been used to dye vertices, we can decide the transmitted power of each sender based on the interference value. More concretely, a power allocation factor for RB r_k is defined by

$$\delta_k = \frac{1/\xi_I(\hat{\mathcal{V}}_k)}{\sum_{r_a \in \hat{\mathcal{R}}} 1/\xi_I(\hat{\mathcal{V}}_a)}. \tag{61}$$

For the sender of the communication link in vertex $v_i \in \hat{\mathcal{V}}_k$, its transmitted power is calculated by

$$\tilde{\mathbf{t}}(v_i) = \begin{cases} \delta_k \times t_{\max}^{\mathsf{CUE}}, & \text{if } v_i \in \hat{\mathcal{U}}_{\mathsf{UL}} \\ \delta_k \times t_{\max}^{\mathsf{BS}}, & \text{if } v_i \in \hat{\mathcal{U}}_{\mathsf{DL}} \\ \delta_k \times t_{\max}^{\mathsf{D2D}}, & \text{if } v_i \in \hat{\mathcal{P}} \end{cases} \tag{62}$$

where $t_{\max}^{\mathsf{CUE}}$, $t_{\max}^{\mathsf{BS}}$, and $t_{\max}^{\mathsf{D2D}}$ represent the maximum transmitted power of CUEs, the BS, and D2D senders, respectively. After performing the power allocation procedure, the updated transmitted power for each communication link is used as the input to the resource allocation procedure. In [12], the resource and power allocation procedures will be performed iteratively until either of the two conditions holds: (1) The improvement of network throughput is below ς, where ς is a sufficiently small threshold (in other words, the improvement of network throughput is insignificant). (2) The number of iterations reaches a predefined bound α_3. Therefore, the overall time complexity is $O(\alpha_3(N_{\mathsf{RB}} \times N_{\mathsf{DP}}^2))$, where $N_{\mathsf{RB}} = |\hat{\mathcal{R}}|$ and $N_{\mathsf{DP}} = |\hat{\mathcal{P}}|$.

Zhao et al. [38] allocate a set $\hat{\mathcal{R}}$ of RBs to a set $\hat{\mathcal{U}}_{\mathsf{UL}}$ of uplink CUEs, where $|\hat{\mathcal{U}}_{\mathsf{UL}}| = |\hat{\mathcal{R}}|$ (in other words, each CUE will be given one RB). They want to make a set $\hat{\mathcal{P}}$ of D2D pairs reuse these RBs in $\hat{\mathcal{R}}$, such that the amount of suffered interference of UEs can be minimized. To do so, a bidirected interference graph is adopted to delineate the interference between pairs of communication links when these links share the same RB. In the bidirected graph, each vertex v_i stands for a communication link, where $v_i \in \hat{\mathcal{U}}_{\mathsf{UL}}$ indicates the cellular link between an uplink CUE and the BS, and $v_i \in \hat{\mathcal{P}}$ represents the D2D link. Each edge (v_i, v_j) depicts the interference relationship between two vertices v_i and v_j, whose weight, as denoted by $w(v_i, v_j)$, gives the amount of interference that v_i suffers from v_j when they share the same RB:

$$w(v_i, v_j) = \begin{cases} \infty, & v_i \in \hat{\mathcal{U}}_{\mathsf{UL}}, v_j \in \hat{\mathcal{U}}_{\mathsf{UL}}, v_i \neq v_j \\ \infty, & v_i = v_j \\ \tilde{\mathbf{g}}(p_j^{\mathsf{S}}, \tau) \times \tilde{\mathbf{t}}(p_j^{\mathsf{S}}), & v_i \in \hat{\mathcal{U}}_{\mathsf{UL}}, v_j \in \hat{\mathcal{P}} \\ \tilde{\mathbf{g}}(u_j, p_i^{\mathsf{R}}) \times \tilde{\mathbf{t}}(u_j), & v_i \in \hat{\mathcal{P}}, v_j \in \hat{\mathcal{U}}_{\mathsf{UL}} \\ \tilde{\mathbf{g}}(p_j^{\mathsf{S}}, p_i^{\mathsf{R}}) \times \tilde{\mathbf{t}}(u_j), & v_i \in \hat{\mathcal{P}}, v_j \in \hat{\mathcal{P}}, v_i \neq v_j \end{cases} \tag{63}$$

Since two CUEs cannot co-use the same RB and a communication link will not interfere with itself, the weight is set to infinity in the first two cases. The other three cases in Equation (63) describe in order the D2D-to-CUE, CUE-to-D2D, and D2D-to-D2D interference. Then, the *sum of suffered interference* for a D2D pair $v_i \in \hat{\mathcal{P}}$ is calculated by

$$S_i = \sum\nolimits_{v_j \in \hat{\mathcal{U}}_{\mathsf{UL}} \cup \hat{\mathcal{P}}, v_j \neq v_i} w(v_i, v_j) + w(v_j, v_i). \quad (64)$$

Each RB in $\hat{\mathcal{R}}$ is viewed as one color used to dye vertices. Because $|\hat{\mathcal{U}}_{\mathsf{UL}}| = |\hat{\mathcal{R}}|$, for each vertex in $\hat{\mathcal{U}}_{\mathsf{UL}}$, it is painted with a different color. After that, a greedy approach is adopted to color the vertices in $\hat{\mathcal{P}}$, which sorts them decreasingly according to their S_i values. In other words, the D2D pair with the strongest interference will be handled first. The above iteration is repeated until all vertices in $\hat{\mathcal{P}}$ have been painted or there is no available color. The time complexity of the management scheme in [38] is $O(N_{\mathsf{DP}} \times (N_{\mathsf{UL}} + N_{\mathsf{DP}})^2)$, where N_{DP} and N_{UL} are the numbers of D2D pairs and uplink CUEs, respectively.

Lai et al. [39] allot a set $\hat{\mathcal{R}}$ of RBs to downlink CUEs (i.e., $\hat{\mathcal{U}}_{\mathsf{DL}}$) and D2D pairs (i.e., $\hat{\mathcal{P}}$), where they use a set $\hat{\mathcal{U}}$ to indicate the involved receivers. In other words, $\hat{\mathcal{U}}$ contains all CUEs in $\hat{\mathcal{U}}_{\mathsf{DL}}$ and the receivers of all D2D pairs in $\hat{\mathcal{P}}$. Each UE $u_i \in \hat{\mathcal{U}}$ has a minimum required SINR (as denoted by $\lambda_i^{\min}$), and an RB $r_k \in \hat{\mathcal{R}}$ can be allocated to u_i only if u_i's SINR on r_k is no smaller than $\lambda_i^{\min}$. The objective is to minimize the *outage ratio*, which is the ratio of the number of UEs not assigned with any RB (due to the violation of the $\lambda_i^{\min}$ requirement) to the total number of UEs in $\hat{\mathcal{U}}$. To do so, a graph is built to reveal the interference relationship among UEs, where the vertex set includes each UE in $\hat{\mathcal{U}}$. For any two UEs u_i and u_j, if the signal strength $\tilde{\mathbf{s}}(\xi(u_i), u_j)$ of u_i's sender, as denoted by $\xi(u_i)$, gotten by u_j exceeds a threshold, there will be an edge to link u_i and u_j in the graph, which means that $\xi(u_i)$ imposes significant interference on u_j. In this case, u_i and u_j are the *neighbors* of each other. Let $\hat{\mathcal{N}}_i$ denote the set of neighbors of u_i. All UEs in $\hat{\mathcal{U}}$ are sorted by their number of neighbors (i.e., $|\hat{\mathcal{N}}_i|$) decreasingly, whose result is stored in $\hat{\mathcal{C}}$. Then, for each UE $u_i \in \hat{\mathcal{C}}$, an RB $r_k \in \hat{\mathcal{R}}$ can be assigned to it if (1) $\hat{\mathcal{G}}_k \cap \hat{\mathcal{N}}_i = \emptyset$ and (2) u_i is not a CUE or $\hat{\mathcal{G}}_k$ contains no CUEs, where $\hat{\mathcal{G}}_k$ is the group of UEs sharing r_k. Here, the first condition means that u_i will not share r_k with any neighbor (due to interference) and the second condition indicates that each RB can be allocated to at most one CUE. Afterward, u_i is removed from $\hat{\mathcal{C}}$, and the transmitted power of $\xi(u_i)$ is set to

$$\tilde{\mathbf{t}}(\xi(u_i)) = \lambda_i^{\min} \times \sigma / \tilde{\mathbf{g}}(\xi(u_i), u_i), \quad (65)$$

where $\tilde{\mathbf{g}}(\xi(u_i), u_i)$ is the channel gain between $\xi(u_i)$ and u_i, so as to meet the $\lambda_i^{\min}$ requirement while mitigating the interference in $\hat{\mathcal{G}}_k$. The above procedure is repeated until every UE in $\hat{\mathcal{C}}$ has been checked.

However, when $\hat{\mathcal{C}}$ is not empty (that is, some UEs are still not given RBs), the *branch-and-bound (BnB)* method [40] is applied to find new members from $\hat{\mathcal{C}}$ for each group $\hat{\mathcal{G}}_k$. More concretely, BnB builds a binary tree to decide whether to add each UE in $\hat{\mathcal{C}}$ to $\hat{\mathcal{G}}_k$. The root (at level 0) is a starting node. At level i ($i > 0$), the left and right children mean to and not to add u_i, respectively. After that, BnB checks each tree node by the bread-first search. Since the tree size may be large, a bound function is employed to reduce the computational cost. Here, the bound function checks whether adding u_i to $\hat{\mathcal{G}}_k$ can enlarge $|\hat{\mathcal{G}}_k|$ (i.e., more UEs can share RB r_k) or the interference in $\hat{\mathcal{G}}_k$ can be decreased. Once a tree node fails to pass the bound function, including that node will make the

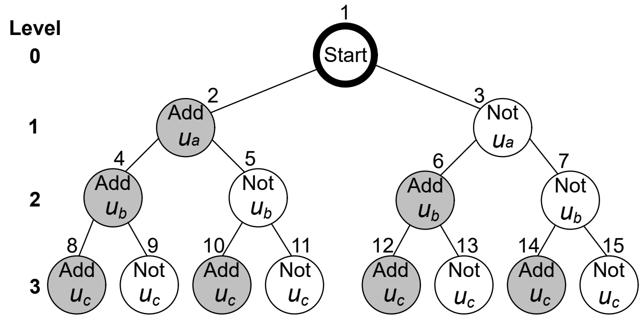

Fig. 4: An example of the binary tree built by the BnB method in the work [39].

solution worse, so its subtree is pruned accordingly. Figure 4 shows an example, where $\hat{\mathcal{C}} = \{u_a, u_b, u_c\}$. Supposing that node 6 cannot pass the bound function, nodes 12 and 13 need not be checked, because they will not be a part of the optimal solution. When a branch "node 1 $\rightarrow$ node 3 $\rightarrow$ node 7 $\rightarrow$ node 14" is found by BnB, the best solution is to add u_c to $\hat{\mathcal{G}}_k$. After adding new members to a group $\hat{\mathcal{G}}_k$ by the BnB method, the transmitted power of the senders of some UEs in $\hat{\mathcal{G}}_k$ is increased to improve their throughput. Given N_{RB} RBs in $\hat{\mathcal{R}}$, N_{DL} downlink CUEs in $\hat{\mathcal{U}}_{\mathsf{DL}}$, and N_{DP} D2D pairs in $\hat{\mathcal{P}}$, the time complexity of the management scheme proposed in [39] is $O(N_{\mathsf{RB}} \times (N_{\mathsf{DL}} + N_{\mathsf{DP}}) \times (N_{\mathsf{DL}} + N_{\mathsf{DP}} - N_{\mathsf{RB}})^3)$.

4.4 Other Management Schemes

Except for the aforementioned matching-based, game-based, and coloring-based management schemes, there have been various management schemes proposed to handle resource allocation and power control for in-band D2D communications.

Duong et al. [41] assume that the location of each UE can be known through the global positioning system or some positioning technologies [42]. Given a set $\hat{\mathcal{U}}_{\mathsf{UL}}$ of uplink CUEs and a set $\hat{\mathcal{P}}$ of D2D pairs, they want to select a CUE u_i from $\hat{\mathcal{U}}_{\mathsf{UL}}$ for each D2D pair p_j in $\hat{\mathcal{P}}$ to reuse its RB, such that p_j's *outage probability* can be minimized. Here, the outage means that the SINR of p_j cannot meet its SINR demand. More concretely, let λ_j and $\lambda_j^{\min}$ be the current SINR and the target SINR of D2D pair p_j, respectively. The outage probability of p_j conditioned on a selected CUE u_i is calculated as follows:

$$\mathbf{Pr}\left[\lambda_j < \lambda_j^{\min} \mid u_i\right] = 1 - \frac{\tilde{\mathbf{s}}(p_j^{\mathsf{S}}, p_j^{\mathsf{R}}) - \sigma \times \lambda_j^{\min}}{\tilde{\mathbf{s}}(p_j^{\mathsf{S}}, p_j^{\mathsf{R}}) + \chi}, \quad (66)$$
$$\chi = \sigma \times \lambda_j^{\min} \times \lambda_i^{\min} \times L(u_i, \tau)^{-\varepsilon} \times L(u_i, p_j^{\mathsf{R}})^{-\varepsilon},$$

where $\tilde{\mathbf{s}}(p_j^{\mathsf{S}}, p_j^{\mathsf{R}})$ denotes the received signal power at D2D receiver p_j^{R}, σ is the power of the thermal noise, $\lambda_i^{\min}$ is the minimum required SINR of u_i, and ε is the path-loss exponent. From Equation (66), it is apparent that the outage probability highly depends on the distance between u_i and the BS (i.e., $L(u_i, \tau)$) and the distance from u_i to p_j^{R} (i.e., $L(u_i, p_j^{\mathsf{R}})$). Then, three options are proposed to select CUEs for D2D pairs to share their RBs as follows:

[Option 1] Choose a CUE u_{i^*} that minimizes the outage probability of a specific D2D pair p_j, which is expressed by

$$u_{i^*} = \arg \min_{u_i \in \hat{\mathcal{U}}_{\mathsf{UL}}} \mathbf{Pr}\left[\lambda_j < \lambda_j^{\min} \mid u_i\right]. \quad (67)$$

[Option 2] Choose a CUE u_i that minimizes the sum of outage probabilities of all D2D pairs in $\hat{\mathcal{P}}$, which is expressed by

$$u_{i^*} = \arg\min_{u_i \in \hat{\mathcal{U}}_{\mathsf{UL}}} \sum_{p_j \in \hat{\mathcal{P}}} \mathbf{Pr}\left[\lambda_j < \lambda_j^{\min} \mid u_i\right]. \quad (68)$$

[Option 3] Choose a CUE u_i that minimizes the maximum of outage probabilities of all D2D pairs in $\hat{\mathcal{P}}$, which is expressed by

$$u_{i^*} = \arg\min_{u_i \in \hat{\mathcal{U}}_{\mathsf{UL}}} \left(\max_{p_j \in \hat{\mathcal{P}}} \mathbf{Pr}\left[\lambda_j < \lambda_j^{\min} \mid u_i\right]\right). \quad (69)$$

Note that options 2 and 3 are applicable to a small set $\hat{\mathcal{P}}$ of D2D pairs.

Given $\hat{\mathcal{U}}_{\mathsf{UL}}$ and $\hat{\mathcal{P}}$, Xu et al. [43] formulate an MINP problem to allocate a set $\hat{\mathcal{R}}$ of RBs to the uplink CUEs in $\hat{\mathcal{U}}_{\mathsf{UL}}$ and the D2D pairs in $\hat{\mathcal{P}}$ and also decide their transmitted power, so as to maximize the energy efficiency of D2D pairs while ensuring the minimum (guaranteed) throughput for CUEs. More concretely, this problem is expressed mathematically as follows:

$$\max_{\mathbf{Z}_{\mathsf{UL}}, \mathbf{T}_{\mathsf{UL}}, \mathbf{T}_{\mathsf{DP}}} \frac{\mathbb{S}_{\hat{\mathcal{P}}}}{\mathbb{T}_{\hat{\mathcal{P}}}} = \frac{\sum_{p_j \in \hat{\mathcal{P}}} \sum_{r_k \in \hat{\mathcal{R}}} \log_2(1+\lambda_j^k)}{\frac{1}{\eta}\sum_{p_j \in \hat{\mathcal{P}}} \sum_{r_k \in \hat{\mathcal{R}}} \tilde{\mathbf{t}}(p_j^{\mathsf{S}}, r_k) + 2N_{\mathsf{DP}} \times e_{\mathsf{cir}}}, \quad (70)$$

subject to

$$\sum_{r_k \in \hat{\mathcal{R}}} \log_2\left(1+\lambda_i^k\right) \geq \phi_i^{\min}, \quad \forall u_i \in \hat{\mathcal{U}}_{\mathsf{UL}}, \quad (71)$$

$$0 \leq \tilde{\mathbf{t}}(u_i, r_k) \leq z_i^k \times t_i^{\max}, \quad \forall u_i \in \hat{\mathcal{U}}_{\mathsf{UL}}, \quad (72)$$

$$\sum_{r_k \in \hat{\mathcal{R}}} \tilde{\mathbf{t}}(p_j^{\mathsf{S}}, r_k) \leq t_j^{\max}, \quad \forall p_j \in \hat{\mathcal{P}}, \quad (73)$$

$$\tilde{\mathbf{t}}(p_j^{\mathsf{S}}, r_k) \geq 0, \quad \forall p_j \in \hat{\mathcal{P}}, \forall r_k \in \hat{\mathcal{R}}, \quad (74)$$

$$z_i^k \in \{0,1\} \quad \forall u_i \in \hat{\mathcal{U}}_{\mathsf{UL}}, \forall r_k \in \hat{\mathcal{R}}, \quad (75)$$

$$\sum_{r_k \in \hat{\mathcal{R}}} z_i^k = 1, \quad \forall u_i \in \hat{\mathcal{U}}_{\mathsf{UL}}, \quad (76)$$

$$\sum_{u_i \in \hat{\mathcal{U}}_{\mathsf{UL}}} z_i^k = 1, \quad \forall r_k \in \hat{\mathcal{R}}. \quad (77)$$

In Equation (70) (i.e., the objective function), $\mathbf{Z}_{\mathsf{UL}} = \left[z_i^k\right]_{N_{\mathsf{UL}} \times N_{\mathsf{RB}}}$ is the matrix of RB allocation for uplink CUEs, where z_i^k is an indicator to reveal whether CUE u_i uses RB r_k, $\mathbf{T}_{\mathsf{UL}} = \left[\tilde{\mathbf{t}}(u_i, r_k)\right]_{N_{\mathsf{UL}} \times N_{\mathsf{RB}}}$ is the matrix of power allocation for uplink CUEs, where $\tilde{\mathbf{t}}(u_i, r_k)$ is u_i's transmitted power on RB r_k, and $\mathbf{T}_{\mathsf{DP}} = \left[\tilde{\mathbf{t}}(p_j^{\mathsf{S}}, r_k)\right]_{N_{\mathsf{DP}} \times N_{\mathsf{RB}}}$ is the power allocation for D2D pairs, where $\tilde{\mathbf{t}}(p_j^{\mathsf{S}}, r_k)$ is the transmitted power of the sender in D2D pair p_j on RB r_k. Moreover, η denotes the power amplifier efficiency ($0 < \eta < 1$) and e_{cir} signifies the circuit power. Here, the numerator in Equation (70) is the overall spectral efficiency of the D2D pairs in $\hat{\mathcal{P}}$ and the denominator gives their total power consumption. As to constraints, Equation (71) means that the minimum rate requirement of each CUE (denoted by $\phi_i^{\min}$) should be granted. Equation (72) limits the transmitted power of CUEs. On the other hand, both Equations (73) and (74) limit the transmitted power of D2D senders. Equation (75) points out that z_i^k is an indicator whose value is either 0 or 1. Equations (76) and (77) indicate that a CUE should be allocated with an RB and an RB can be used by only one CUE, respectively.

However, since the MINP problem is intractable, it is divided into two subproblems:

[Subproblem 1] *RB allocation and power control for CUEs.* For a fixed $\mathbf{T}_{\mathsf{DP}}$ matrix (that is, the power allocation of D2D senders is given), the MINP problem can be rewritten by

$$\max_{\mathbf{Z}_{\mathsf{UL}}, \mathbf{T}_{\mathsf{UL}}} \frac{\mathbb{S}_{\hat{\mathcal{P}}}(\mathbf{Z}_{\mathsf{UL}}, \mathbf{T}_{\mathsf{UL}})}{\mathbb{T}_{\hat{\mathcal{P}}}}, \quad (78)$$

subject to Equations (71), (72), (75), (76), and (77). Subproblem 1 can be translated into an assignment problem and solved by the Kuhn-Munkres algorithm.

[Subproblem 2] *Power control for D2D pairs.* For fixed $\mathbf{Z}_{\mathsf{UL}}$ and $\mathbf{T}_{\mathsf{UL}}$ matrices (that is, the RB and power allocation of CUEs is given), the MINP problem can be rewritten as follows:

$$\max_{\mathbf{T}_{\mathsf{DP}}} \frac{\mathbb{S}_{\hat{\mathcal{P}}}(\mathbf{T}_{\mathsf{DP}})}{\mathbb{T}_{\hat{\mathcal{P}}}(\mathbf{T}_{\mathsf{DP}})}, \quad (79)$$

subject to Equations (71), (73), and (74). Subproblem 2 is in the form of fractional programming, which can be solved by the parametric algorithm proposed in [44].

Kose et al. [45] assign each RB in $\hat{\mathcal{R}}$ to an uplink CUE $u_i \in \hat{\mathcal{U}}_{\mathsf{UL}}$ with the best channel gain and calculate its transmitted power by

$$\tilde{\mathbf{t}}(u_i) = \frac{\lambda_i^{\min} \times (\sigma + \mathbf{I}_{\mathsf{BS}})}{\tilde{\mathbf{g}}(u_i, \tau)}, \quad (80)$$

where $\lambda_i^{\min}$ is the target SINR of u_i and $\mathbf{I}_{\mathsf{BS}}$ is the maximum allowed interference at the BS. Then, they choose D2D pairs from $\hat{\mathcal{P}}$ to share the RBs allocated to the uplink CUEs. Like the work [26], a conflict graph is constructed for $\hat{\mathcal{P}}$ to find an MIS $\hat{\mathcal{P}}_{\mathsf{MIS}}$ of D2D pairs, where these D2D pairs will not impose significant interference on each other (the detail has be discussed in Section 4.2). After that, a knapsack problem is considered to choose D2D pairs from $\hat{\mathcal{P}}_{\mathsf{MIS}}$ to share an RB $r_k \in \hat{\mathcal{R}}$, which can be expressed as follows:

$$\text{Maximize: } \sum_{p_j \in \hat{\mathcal{P}}_{\mathsf{MIS}}} \varphi_j \times z_j^k, \quad (81)$$

subject to

$$\sum_{p_j \in \hat{\mathcal{P}}_{\mathsf{MIS}}} z_j^k \times \left(\tilde{\mathbf{g}}(p_j^{\mathsf{S}}, \tau) \times \tilde{\mathbf{t}}(p_j^{\mathsf{S}})\right) \leq \mathbf{I}_{\mathsf{BS}}, \quad (82)$$

$$z_j^k \in \{0,1\}, \ \forall p_j \in \hat{\mathcal{P}}_{\mathsf{MIS}}. \quad (83)$$

Equation (81) gives the objective function, where φ_j is the value of D2D pair p_j (which is set to 1, making all D2D pairs equal in significance) and z_j^k is an indicator to reveal whether p_j shares RB r_k (as shown in Equation (83), where $z_j^k = 1$ if so, or $z_j^k = 0$ otherwise). On the other hand, the constraint in Equation (82) means that the aggregate interference caused by the sender p_j^{S} of each selected D2D pair from $\hat{\mathcal{P}}_{\mathsf{MIS}}$ on the BS (i.e., τ) cannot exceed a specific level $\mathbf{I}_{\mathsf{BS}}$. The above procedure of MIS and knapsack is repeated until the conflict graph becomes empty.

Hong et al. [46] deal with both resource and power allocation for D2D communications in *millimeter wave (mmWave)* cellular networks. They assume that each uplink CUE $u_i \in \hat{\mathcal{U}}_{\mathsf{UL}}$ is allocated with an RB $r_k \in \hat{\mathcal{R}}$ and let a set $\hat{\mathcal{P}}$ of D2D pairs reuse their RBs. To do so, a greedy algorithm is proposed, which sets the provisional transmitted power of the sender in a D2D pair $p_j \in \hat{\mathcal{P}}$ as follows:

$$\tilde{\mathbf{t}}(p_j^{\mathsf{S}})^* = \min\left\{t_j^{\max}, \mathbf{I}_{\mathsf{BS}}/|h(p_j^{\mathsf{S}}, \tau, k)|^2\right\}, \quad (84)$$

where $t_j^{\max}$ is the maximum transmitted power of p_j^{S}, $\mathbf{I}_{\mathsf{BS}}$ denotes the interference constraint at the BS, and $h(p_j^{\mathsf{S}}, \tau, k)$

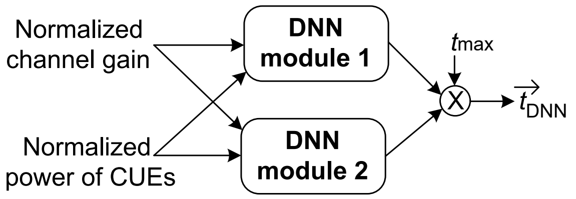

Fig. 5: The DNN structure used in [48] to find the power vector $\vec{t}_{\mathsf{DNN}}$ for D2D pairs.

is the small-scale fading coefficient from D2D sender p_j^{S} to the BS τ on RB r_k. In this way, the SINR for D2D pair p_j on RB r_k can be estimated by

$$\lambda_j^k = \frac{|h(p_j^{\mathsf{S}}, p_j^{\mathsf{R}}, k)|^2 \times \tilde{\mathbf{t}}(p_j^{\mathsf{S}})^*}{|h(u_i, p_j^{\mathsf{R}}, k)|^2 \times \tilde{\mathbf{t}}(u_i) + \sigma}, \tag{85}$$

where $\tilde{\mathbf{t}}(u_i)$ is the transmitted power of CUE u_i. Then, for each CUE in $\hat{\mathcal{U}}_{\mathsf{UL}}$, the greedy algorithm picks the D2D pair with the maximum SINR λ_j^k to share its RB. The time complexity of this algorithm is $O(N_{\mathsf{DP}}^2)$, where N_{DP} is the number of D2D pairs in $\hat{\mathcal{P}}$.

After RB allocation, the optimal transmitted power of each D2D sender is found by the *difference of convex (DC)* programming. Let $\hat{\mathcal{P}}_k$ be the set of D2D pairs using RB r_k. The power allocation problem on r_k is formulated as follows:

$$\max_{\mathbf{T}_k} \sum\nolimits_{p_j \in \hat{\mathcal{P}}_k} \phi_j^k, \tag{86}$$

subject to

$$0 \leq \tilde{\mathbf{t}}(p_j^{\mathsf{S}}) \leq t_j^{\max}, \forall p_j \in \hat{\mathcal{P}}_k, \tag{87}$$

$$\sum\nolimits_{p_j \in \hat{\mathcal{P}}_k} |h(p_j^{\mathsf{S}}, \tau, k)|^2 \times \tilde{\mathbf{t}}(p_j^{\mathsf{S}}) \leq \mathbf{I}_{\mathsf{BS}}, \tag{88}$$

where $\mathbf{T}_k$ denotes the vector of transmitted power for the D2D pairs in $\hat{\mathcal{P}}_k$. More specifically, the objective function in Equation (86) is to maximize the sum rate of D2D pairs in $\hat{\mathcal{P}}_k$, where ϕ_j^k is the data rate of D2D pair p_j on RB r_k. The constraint in Equation (87) puts the lower and upper bounds on the transmitted power, while the constraint in Equation (88) is to limit the interference at the BS below threshold $\mathbf{I}_{\mathsf{BS}}$. To let the objective function be convex, ϕ_j^k is formulated as follows:

$$\phi_j^k = f_1(\mathbf{T}_k) - f_2(\mathbf{T}_k), \tag{89}$$

where

$$f_1(\mathbf{T}_k) = \log_2(\chi_1 + \chi_2 + \sigma), \tag{90}$$
$$\chi_1 = |h(u_i, p_j^{\mathsf{R}}, k)|^2 \times \tilde{\mathbf{t}}(u_i),$$
$$\chi_2 = \sum\nolimits_{p_l \in \hat{\mathcal{P}}_k} |h(p_l^{\mathsf{S}}, p_j^{\mathsf{R}}, k)|^2 \times \tilde{\mathbf{t}}(p_l^{\mathsf{S}}),$$

and

$$f_2(\mathbf{T}_k) = \log_2(\chi_3 + \chi_4 + \sigma). \tag{91}$$
$$\chi_3 = |h(u_i, p_j^{\mathsf{R}}, k)|^2 \times \tilde{\mathbf{t}}(u_i),$$
$$\chi_4 = \sum\nolimits_{p_l \in \hat{\mathcal{P}}_k \setminus \{p_j\}} |h(p_l^{\mathsf{S}}, p_j^{\mathsf{R}}, k)|^2 \times \tilde{\mathbf{t}}(p_l^{\mathsf{S}}),$$

Here, both $f_1(\mathbf{T}_k)$ and $f_2(\mathbf{T}_k)$ are concave functions, as they are the logarithmic functions of affine functions. After that, the above DC problem can be solved by using the first order Taylor series approximation with an iterative method proposed in [47].

Lee et al. [48] apply the *deep neural network (DNN)* technique and a heuristic *equally reduced power (ERP)* scheme (proposed in [49]) to handle resource and power management for in-band D2D communications. They consider that a set $\hat{\mathcal{R}}$ of RBs have been allocated to a set $\hat{\mathcal{U}}_{\mathsf{UL}}$ of uplink CUEs, where each CUE $u_i \in \hat{\mathcal{U}}_{\mathsf{UL}}$ is given one RB $r_k \in \hat{\mathcal{R}}$, whose transmitted power on r_k is $\bar{t}_i^k$. There is also a set $\hat{\mathcal{P}}$ of D2D pairs that want to share the RBs in $\hat{\mathcal{R}}$. Let t_j^k denote the transmitted power of the sender in a D2D pair p_j on an RB r_k and $\vec{t} = \left\{t_j^k \,|\, \forall p_j \in \hat{\mathcal{P}}, \forall r_k \in \hat{\mathcal{R}}\right\}$ be the power vector of all D2D pairs on each RB. Then, the achievable rate of D2D pair p_j can be calculate by

$$\mathrm{DR}_j(\vec{t}) = \sum_{r_k \in \hat{\mathcal{R}}} \frac{B}{|\hat{\mathcal{R}}|} \log_2\left(1 + \frac{\tilde{\mathbf{g}}(p_j^{\mathsf{S}}, p_j^{\mathsf{R}}) \times t_j^k}{\sigma + \chi_1 + \chi_2}\right), \tag{92}$$
$$\chi_1 = \sum\nolimits_{p_l \in \hat{\mathcal{P}} \setminus \{p_j\}} \tilde{\mathbf{g}}(p_l^{\mathsf{S}}, p_j^{\mathsf{R}}) \times t_l^k,$$
$$\chi_2 = \tilde{\mathbf{g}}(u_i, p_j^{\mathsf{R}}) \times \bar{t}_i^k,$$

where B is the channel bandwidth. Then, Figure 5 presents the DNN structure to find the power vector, whose result is denoted by $\vec{t}_{\mathsf{DNN}}$. Both DNN modules 1 and 2 are based on a feed-forward neural network, whose inputs contain the normalized channel gain between two nodes x and y on a dB scale:

$$\frac{\log_{10}(\tilde{\mathbf{g}}(x, y)) - \mu_{\hat{g}}}{\sqrt{\mathbb{E}[(\log_{10}(\tilde{\mathbf{g}}(x, y)) - \mu_{\hat{g}})^2]}}, \tag{93}$$

where $\mu_{\hat{g}} = \mathbb{E}[\log_{10}(\tilde{\mathbf{g}}(x, y))]$ and $\mathbb{E}[\cdot]$ is the expectation operation with respect to $\tilde{\mathbf{g}}(x, y)$, and also the normalized transmitted power of each CUE $u_i \in \hat{\mathcal{U}}_{\mathsf{UL}}$:

$$\frac{\bar{t}_i^k}{t_{\max}}, \tag{94}$$

where $t_{\max}$ is the maximum transmitted power of any UE. In Figure 5, DNN module 1 decides the normalized total transmitted power of each D2D pair $p_j \in \hat{\mathcal{P}}$:

$$\frac{\sum_{r_k \in \hat{\mathcal{R}}} t_j^k}{t_{\max}}. \tag{95}$$

DNN module 2 finds the proportion of transmitted power assigned to each RB $r_k \in \hat{\mathcal{R}}$:

$$\frac{t_j^k}{\sum_{r_k \in \hat{\mathcal{R}}} t_j^k}. \tag{96}$$

After that, $\vec{t}_{\mathsf{DNN}}$ can be derived by multiplying the outputs of both DNN modules by $t_{\max}$, as shown in Figure 5.

On the other hand, the ERP scheme assumes that each D2D sender has the same transmitted power on each RB, as denoted by t_{erp}, whose optimal value can be found through the following optimization problem:

$$\text{Maximize: } \sum\nolimits_{p_j \in \hat{\mathcal{P}}} \mathrm{DR}_j(\vec{t}_{\mathsf{ERP}}), \tag{97}$$

subject to

$$\sum\nolimits_{p_j \in \hat{\mathcal{P}}} \tilde{\mathbf{g}}(p_j^{\mathsf{S}}, \tau) \times t_{\mathsf{erp}} \leq \mathbf{I}_{\mathsf{BS}}, \quad \forall r_k \in \hat{\mathcal{R}} \tag{98}$$
$$\mathrm{DR}_j(\vec{t}_{\mathsf{ERP}}) \geq \mathrm{DR}_{\mathrm{th}}, \quad \forall p_j \in \hat{\mathcal{P}}. \tag{99}$$

In Equation (97), $\vec{t}_{\mathsf{ERP}} = t_{\mathsf{erp}} \times \mathbf{1}_{|\hat{\mathcal{P}}| \times |\hat{\mathcal{R}}|}$ is the power vector calculated by ERP, where $\mathbf{1}_{|\hat{\mathcal{P}}| \times |\hat{\mathcal{R}}|}$ is the vector of all 1's with size of $|\hat{\mathcal{P}}| \times |\hat{\mathcal{R}}|$. The constraint in Equation (98) indicates that the interference caused by all D2D pairs on the BS cannot exceed threshold $\mathbf{I}_{\mathsf{BS}}$. In addition, the constraint in Equation (99)

TABLE 3: Comparison of the resource and power management schemes for in-band D2D communications discussed in Section 4.

work	category	partner CUEs	power control	multi-pairs	key techniques	time complexity
[16]	matching	uplink			Kuhn-Munkres algorithm	$O(N_{\mathsf{UL}}^3)$
[18]	matching	uplink	✓		Kuhn-Munkres algorithm	$O(N_{\mathsf{UL}}^3)$
[19]	matching	downlink			Gale-Shapley algorithm	$O(N_{\mathsf{DL}} \times N_{\mathsf{DP}})$
[21]	matching	uplink	✓		Gale-Shapley algorithm	$O(\alpha_1 N_{\mathsf{DL}} \times N_{\mathsf{DP}})$
[23]	matching	uplink	✓		Blossom algorithm	$O((\alpha_2 N_{\mathsf{DP}})^3)$
[26]	game	uplink	✓	✓	Stackelberg game + MIS	$O(N_{\mathsf{DP}}^3)$
[29]	game	uplink	✓	✓	matching and Stackelberg games	not mentioned
[32]	game	uplink	✓		coalition formation game + WOA	not mentioned
[34]	game	none		✓	sequential bargaining game	not mentioned
[37]	coloring	downlink		✓	SLA + labeling	not mentioned
[12]	coloring	both	✓	✓	iterative	$O(\alpha_3(N_{\mathsf{RB}} \times N_{\mathsf{DP}}^2))$
[38]	coloring	uplink		✓	bidirected interference graph	$O(N_{\mathsf{DP}} \times (N_{\mathsf{UL}} + N_{\mathsf{DP}})^2)$
[39]	coloring	downlink	✓	✓	BnB method	$O(N_{\mathsf{RB}} \times (N_{\mathsf{DL}} + N_{\mathsf{DP}}) \times (N_{\mathsf{DL}} + N_{\mathsf{DP}} - N_{\mathsf{RB}})^3)$
[41]	other	uplink		✓	outage probability	not mentioned
[43]	other	uplink	✓	✓	assignment + fractional programming	not mentioned
[45]	other	uplink	✓	✓	MIS + knapsack solution	not mentioned
[46]	other	uplink	✓	✓	greedy algorithm + DC programming	$O(N_{\mathsf{DP}}^2)$
[48]	other	uplink	✓	✓	DNN + ERP	not mentioned

means that the data rate of each D2D pair should be at least $\mathrm{DR}_{\mathrm{th}}$. After obtaining both $\vec{t}_{\mathsf{DNN}}$ and $\vec{t}_{\mathsf{ERP}}$, the final power vector $\vec{t}$ will be the one of $\vec{t}_{\mathsf{DNN}}$ and $\vec{t}_{\mathsf{ERP}}$ that can maximize the sum rate of all D2D pairs in $\hat{\mathcal{P}}$.

4.5 Discussion

Table 3 presents a comparison between the resource and power management schemes for in-band D2D communications discussed in Section 4. Except for the "category" field, the meanings of other fields are detailed as follows:

- *Partner CUEs:* This field indicates whether a management scheme makes D2D pairs share the RBs allocated to "uplink" CUEs (i.e., $\hat{\mathcal{U}}_{\mathsf{UL}}$) or "downlink" CUEs (i.e., $\hat{\mathcal{U}}_{\mathsf{DL}}$). If this field is marked as "both", it means that the management scheme allows D2D pairs to share the RBs of the CUEs in both $\hat{\mathcal{U}}_{\mathsf{UL}}$ and $\hat{\mathcal{U}}_{\mathsf{DL}}$. On the other hand, if the field is marked as "none", the management scheme considers using the overlay mode, where D2D pairs have their dedicated RBs.
- *Power control:* A check mark (i.e., "✓") indicates that the management scheme can find the adequate transmitted power of each sender (including the BS, uplink CUEs, and D2D senders) to mitigate its interference or increase the throughput. Otherwise, the transmitted power of all senders is considered as predefined and will not change.
- *Multi-pairs:* A check mark indicates that the management scheme permits multiple D2D pairs to share the same RB. Otherwise, each RB can be co-used by at most one CUE and one D2D pair.
- *Key techniques:* This field presents the techniques adopted by a management scheme to solve the resource and power management problem.
- *Time complexity:* The notations N_{UL}, N_{DL}, N_{DP}, N_{RB} indicate the numbers of uplink CUEs, downlink CUEs, D2D pairs, and RBs, respectively.

In the matching-based category, most management schemes (except that in [19]) make D2D pairs reuse the RBs allotted to uplink CUEs. The schemes in [18], [21], and [23] adjust the transmitted power of D2D senders to maximize their throughput, under the premise that they will not cause non-neglected interference on the CUEs that use the same RBs. Since the matching-based management schemes construct a weighted bipartite graph and then find one-to-one assignments between CUEs and D2D pairs to share RBs, each RB can be reused by at most one D2D pair. Thus, the spectral efficiency of the matching-based management schemes would be lower than those management schemes that allow multiple D2D pairs to share the same RB. To find a maximum-weight matching from the bipartite graph, the studies [16] and [18] adopt the Kuhn-Munkres algorithm, the studies [19] and [21] employ the Gale-Shapley algorithm, and the work [23] uses the Blossom algorithm. As to the time complexity, α_1 is the number of iterations taken by [21] to calculate the transmitted power for all senders and construct the partner selection matrices. Moreover, α_2 is the maximum number of RBs allocated to each D2D pair in [23]. Note that in the work [18], we only list the time complexity of its resource allocation method.

In the game-based category, the studies [26], [29], [32] consider the scenario of sharing RBs with uplink CUEs and find suitable transmitted power for D2D senders. Both [26] and [29] allow multiple D2D pairs to share the same RB, but the work [32] restricts each CUE to share its RB with only one D2D pair. On the other hand, the work [34] adopts the overlay mode, so D2D pairs have their dedicated RBs. Multiple D2D pairs can co-use the same RB, but their transmitted power is fixed. Speaking of the methodology, Chen et al. [26] use the Stackelberg game to find transmitted power for D2D senders and deal with RB allocation by MIS. Yuan et al. [29] apply both matching and Stackelberg games to handle resource and power allocation. Sun et al. [32] first formulate the resource allocation problem by the coalition formation game, and then solve the power control problem by WOA. Najla et al. [34] propose a sequential bargaining game to find a group of D2D pairs to share each RB. As to the time complexity, the Stackelberg game along with the MIS solution in [26] take $O(N_{\mathsf{DP}}^3)$ time. Other studies [29], [32], [34] do not analyze the time complexity.

In the coloring-based category, both studies [37], [39] consider the downlink case, while the study [38] aims at the uplink case. The work [12] assumes a full-duplex cellular network, where D2D pairs can share the RBs of both uplink and downlink CUEs. All of them allow multiple D2D pairs to share the same RB, but only [12] and [39] take the power control issue into account. Speaking of the key techniques, Cai et al. [37] combine both SLA and labeling to deal with RB allocation. Yang et al. [12] iteratively carry out the resource and power allocation procedures to improve network throughput. Zhao et al. [38] construct a bidirected interference graph to allocate RBs to uplink CUEs and D2D pairs. Lai et al. [39] employ the BnB method to find more D2D pairs to share the RBs given to downlink CUEs. As to the time complexity, α_3 is the maximum number of iterations to perform the resource and power allocation procedures in [12].

Except for the matching-based, game-based, and coloring-based management schemes, there have been various management schemes developed. In particular, Duong et al. [41] discuss how to minimize the outage probability of D2D pairs. Xu et al. [43] cope with both RB allocation and power control for uplink CUEs by an assignment solution, and handle power control for D2D pairs by the fractional programming. Kose et al. [45] combine both MIS and a knapsack solution to allocate RBs to D2D pairs. Hong et al. [46] propose one greedy algorithm to find D2D pairs to share the RBs of uplink CUEs, and then use the DC programming to decide their transmitted power. Lee et al. [48] find two power vectors for D2D pairs on each RB by DNN and ERP, and choose the power vector that can maximize the sum rate of all D2D pairs. These management schemes consider the scenario of sharing RBs with uplink CUEs, and allow multiple D2D pairs to co-use the same RB. To do so, they compute the transmitted power of UEs (except [41]) according to the result of RB allocation to mitigate interference. As to the time complexity, the greedy algorithm in [46] requires $O(N_{\mathsf{DP}}^2)$ time. Other studies [41], [43], [45], [48] do not mention the time complexity of their proposed schemes.

5 Research Directions and Challenges

In this section, we discuss some research directions and challenges of resource and power management for in-band D2D communications.

First of all, many resource and power management schemes aim to maximize network throughput, as referred to the objective function in Equation (11). Nevertheless, some CUEs or D2D pairs may encounter bad channel quality for a pretty long time. For example, they are located near the cell's boundary or interfered by some long-lasting noises. In this case, these UEs may be allocated with very few RBs or even no RBs, which causes *starvation*. There have been a number of RB allocation strategies proposed to support fair transmissions among UEs, but blindly ensuring fair transmissions could substantially reduce the overall network throughput [50]. Consequently, how to strike a good balance between the fairness and the throughput will be a big challenge in resource and power management for in-band D2D communications.

Second, most resource and power management schemes assume a simple network environment with just macro-cells. Except for the thermal noise σ, each CUE and D2D pair will be only interfered by other transmitters (i.e., the macro-cell BS, uplink CUEs, or D2D senders) that share the same RBs in a macro-cell. In practice, a cellular network may comprise *heterogeneous cells* [51]. More concretely, macro-cells act as the network backbone to provide signal coverage in large geographic regions. On the other hand, small cells such as pico-cells or femto-cells are deployed inside some macro-cells to enhance the signal quality. In order to increase the spectrum usage, these small cells usually operate in similar subchannels with the macro-cell in which they reside. Unavoidably, the transmitters located in the small cells (including their BSs) will impose significant interference on the receivers in the macro-cell, and vice versa. To mitigate such interference, we need to manage spectrum resources and transmitted power for the UEs in these cells at the same time.

Third, IoT devices have increased substantially in number year by year [1]. Therefore, it can be expected that there will be more and more D2D communications originated from IoT devices. Unlike those D2D communications originated from user devices (e.g., mobile phones and tablets) which could not be predictable, IoT devices usually report their sensing data in a regular manner. Furthermore, some popular communication protocols developed for IoT applications such as the *constrained application protocol (CoAP)* can allow users to specify the time interval for each individual IoT device to report its data [52]. In view of this, it is an interesting issue to take into account the reporting intervals of IoT devices when allocating resources and transmitted power to their D2D communications. For example, we can prioritize each D2D pair on reusing the RBs of a CUE according to the reporting interval and the type of sensing data of the D2D sender in the pair.

Fourth, 3GPP has recently proposed the *radio access network (RAN) sharing* scenario [53], which allows multiple service providers to jointly use a BS (connecting to their EPCs through S1 interfaces) and share the BS's spectrum resources. The RAN sharing scenario has a great impact on the existing resource and power management schemes, because they assume that all the BS's RBs are dedicated to a single service provider. In the RAN sharing scenario, each service provider owns merely a part of the BS's RBs [54]. Since the number of subscribed UEs of each service provider in the cell may not necessarily be similar, some service providers could have not enough RBs to serve their UEs, whereas some other service providers need to serve just a few UEs and thereby have unused RBs (which are evidently wasted). In this case, it deserves further investigation on how to let service providers borrow RBs from each other, such that the traffic demands of more UEs can be satisfied.

Finally, the discussion in Section 4 targets at the management of RBs and transmitted power for the UEs located in the same cell. Sometimes, the sender and the receiver of a D2D pair may reside in different cells. Since RBs could be reused across the two cells, some UEs in the overlap of both cells may be allocated with the same RBs, thereby causing inter-cell interference [55]. In this case, the management of *inter-cell D2D links* should involve the collaboration of neighboring BSs, whose objective is to mitigate the overall interference. A few studies [56], [57] adopt the game theory, where each inter-cell D2D pair plays a repeated game with the nearby BSs in such a way that these players share a subset of their initially allocated RBs in order to maximize the utility. Inter-cell D2D communications result in a more complex situation, which is worthy of more in-depth study.

6 Conclusion

In-band D2D communications not only alleviate the dilemma of insufficient spectrum resources, but also increase the overall throughput of a cellular network. Through the careful selection of D2D pairs to share the RBs allocated to uplink or downlink CUEs and also adjusting their transmitted power, the spectral efficiency can be significantly improved. This chapter introduces the system architecture, control policy, and communication mode for in-band D2D communications, and formulates the resource and power management problem. After that, we discuss and compare a variety of management schemes, including matching-based, game-based, coloring-based, and other schemes. Moreover, some research directions and challenges such as fair transmissions, heterogeneous cells, regular reporting intervals, RAN sharing, and inter-cell D2D links are also addressed in the chapter.

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