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RESEARCH ARTICLE

Trade-Off Analysis of NOMA-D2D and OFDMA-D2D Systems: Resource Allocation Perspective

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ABSTRACT Mutual interference between NOMA cellular users (CUs) and D2D links poses a challenge in extending NOMA's resource allocation schemes to NOMA-D2D models. In this paper, we develop a novel resource allocation algorithm for NOMA-D2D systems and utilize it for comparing NOMA-D2D and OFDMA-D2D models. The proposed scheme aims to optimize the system sum rate and ensure a minimal rate for CUs. We formulate this as a mixed integer non-linear programming (MINLP) problem encompassing resource block (RB) allocation and power control. We propose a heuristic sub-optimal solution to lower the computational complexity. Our solution has two stages. In the first stage, D2D pairs and half of the CUs are admitted to the system to maximize the system sum rate. The rest of the CUs join the system in the next stage, while the upper bound for their achievable signal-to-interference-plus-noise-ratio (SINR) is maximized. Our first stage involves resource allocation for an OFDMA-D2D system. Employing an equal power allocation policy, we decompose the resource allocation problem for D2D pairs and CUs into two assignment problems. In the next step, the RB allocation scheme for CUs, which complies with the NOMA principle, is formulated as another assignment problem, and the power control strategy is updated. This two-stage heuristic solution allows a comparison of NOMA-D2D and OFDMA-D2D performances with identical power budgets, while the number of cellular connections in the NOMA-D2D system is twice that of the OFDMA-D2D system. Our results indicate that OFDMA-D2D achieves a higher sum rate and individual rates over NOMA-D2D.

INDEX TERMS Device-to-device communications, interference management, non-orthogonal multiple access, power control, resource allocation.

I. INTRODUCTION

A. RELATED WORKS

Non-orthogonal multiple access (NOMA) is a novel radio access technology, which has been proposed in response to the demand for improved spectral efficiency and massive connectivity in cellular networks. NOMA allows the messages of multiple cellular users (CU) to be multiplexed on the same resource block (RB). Successive interference cancellation (SIC) is employed at the receiver side for detecting the messages of users. This is in contrast to orthogonal frequency division multiple access (OFDMA) in which a RB is exclusively assigned to a CU.

Many research papers have studied the NOMA technology and have reported its superior performance over orthogonal multiple access (OMA) technologies under proper settings. The authors in [1], [2], [3], and [4] have concentrated on the performance of NOMA in terms of outage probability, system sum rate, and users' individual rates. Vaezi et al. [5] have investigated some misbeliefs about NOMA. For instance, it has been clarified that NOMA does not necessarily improve spectral efficiency. Kotaba et al. [6] have proposed an efficient re-transmission strategy based on NOMA for ultra-reliable and low-latency communications (URLLC). Popovski et al. [7] have investigated the implementation

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TABLE 1. Summary of background work.

System Description	Up/Downlink Cellular System	Up/Downlink D2D group	Power Control	Resource Allocation	Results
NOMA-based D2D group, OFDMA-based cellular system: [8], [9] , [10], [11].	Uplink	Downlink	D2Ds: [8], [9], [10], [11]. CUs: [9], [10].	D2Ds: [8], [9], [10], [11]. CUs: [9], [10].	Improved network sum rate [8], Improved network power consumption [9], Improved D2D sum rate [10], Improved network sum rate and secrecy capacity [11].
NOMA-based D2D group, NOMA-based cellular system, WiFi System [12]	Uplink	Downlink	D2Ds	D2Ds	Improved D2D sum rate.
NOMA-based D2D group [13], OFDMA-based cellular system	Uplink	Uplink	D2Ds, CUs	D2Ds	Improved energy efficiency.
D2D transmission, NOMA-based cellular system [14], [15].	Downlink	—	D2Ds: [15]. CUs: [14], [15].	D2Ds: [15]	Improved performance over TDMA+D2D [14], Improved performance over FDMA+D2D [15].

of network slicing based on NOMA to address resource requirements of heterogeneous 5G services.

One of the challenges that should be tackled in adopting NOMA as a future radio access technology is its coexistence with other 5G technologies, e.g., device-to-device (D2D) communications. D2D communication allows proximate cellular users to communicate with each other directly without sending their messages to the base station (BS). The control channel between CUs and the BS might be held for handling D2D connections [16]. Some papers have considered mixed scenarios including, D2D and NOMA communications.

Zhang et al. [17] have studied a cooperative scenario in which the NOMA user with strong channel conditions employs a full-duplex device-to-device communication scheme to improve the outage performance of the NOMA user with poor channel conditions. Xu et al. [18] and Kader et al. [19] have also considered cooperative D2D-assisted scenarios based on the NOMA protocol. A joint user pairing, mode selection, and power control scheme has been devised in [20] to achieve maximum connectivity while minimizing power consumption. A cooperative device-to-multi-device system with a two-phase transmission based on NOMA has been presented in [21]. The authors of [22] have investigated energy harvesting in a NOMA cellular system including a D2D pair. Shen et al. [23] have proposed a scenario in which D2D communication between a pair of NOMA users is utilized in file downloading.

In the aforementioned works, the D2D-NOMA scenarios are not affected by the mutual interference between NOMA and D2D links. The D2D connections cause interference at cellular NOMA receivers when they reuse cellular RBs. Meanwhile, NOMA can be employed as a multiple access technique in D2D multi-casting scenarios, where a D2D transmitter communicates with a group of D2D receivers [8]. D2D NOMA receivers are susceptible to mutual interference if they use the spectrum of cellular systems. In the described scenarios, where there is an external source of interference along with co-channel NOMA interference, channel order does not determine the interference cancellation policy as it does in pure NOMA [2], [4]. Hence, the developed resource allocation schemes for NOMA models cannot be easily extended to NOMA-D2D models.

The authors in [8], [9], and [10] have developed resource allocation schemes for groups of D2D users with NOMA-based transmission, where each D2D group reuses the frequency band of a CU in an uplink OFDMA cellular system. Sun et al. [12] have enhanced the NOMA-based D2D group communications performance by reusing licensed resources of a NOMA cellular system in uplink and unlicensed resources of a WiFi system. Gupta et al. [11] have also proposed a zero-sum game-based scenario for D2D communications with NOMA protocol, which reuses uplink resources of an OFDMA cellular system and reported enhanced network sum rate and secrecy capacity. Different from the mentioned works, which have considered downlink

NOMA-based D2D communications, Li et al. [13] have studied NOMA-based communications for a group of D2D users in an uplink scenario. Moreover, each D2D group reuses an uplink resource of an OFDMA cellular system. The target is to maximize energy efficiency for cellular and D2D users.

The authors in [14] and [15] have studied the performance of downlink NOMA cellular systems considering the interference between D2D pairs and NOMA CUs. A scenario consisting of a D2D pair and two CUs has been investigated in [14]. The results show that NOMA-D2D outperforms TDMA-D2D under a proper power allocation policy at the BS. Moreover, the integration of D2D communication into a NOMA-based cellular system consisting of multiple CUs and D2D pairs has been studied in [15]. This work has maximized the D2D sum rate while considering a minimum rate requirement for CUs through channel allocation for D2D pairs and power control for all users. Their results indicate that D2D pairs can achieve a higher sum rate in the NOMA-D2D model compared to the FDMA-D2D model. The summary of related works on resource management and power control in D2D-NOMA models is shown in Table 1. As indicated, there is a lack of work on scenarios considering D2D transmission underlaying NOMA-based cellular systems. Meanwhile, RB allocation for all users, i.e. CUs and D2Ds, has only been considered in [9] and [10]. These references have studied NOMA-based D2D group.

B. OUR CONTRIBUTION

To extend the results presented in the previous works, we consider developing a resource allocation scheme for a NOMA-D2D model, where there is mutual interference between NOMA CUs and D2D pairs. We focus on the downlink phase. The interference problem is more critical in this phase as CUs collect a high interference level from nearby D2D transmitters.

We aim to maximize the system sum rate while maintaining a minimum rate requirement for CUs. We formulate this as a mixed integer non-linear programming (MINLP) comprising RB allocation for CUs and D2D pairs as well as power control at the BS. To reduce the complexity of the problem, we consider a heuristic sub-optimal solution with two stages. In the first stage, half of the CUs, called primary CUs, and D2D pairs are admitted to the system while the system sum rate is optimized. In the next stage, the rest of CUs, called secondary CUs, are admitted to the system in a way that an upper bound for their signal-to-interference-plus-noise-ratio (SINR) is achieved. The first stage leads to a resource allocation algorithm for an OFDMA-D2D model. The scheme is upgraded and applicable to the NOMA-D2D model in the second stage.

Another goal of this paper is to reconsider comparing NOMA-D2D and OFDMA-D2D models with a new perspective. We employ the proposed resource allocation scheme to study how NOMA's capability to serve more CUs influences its performance. In the case of power budget constraint at the BS, we show that the OFDMA-D2D model can achieve better performance. Our contribution in this paper can be summarized as follows:

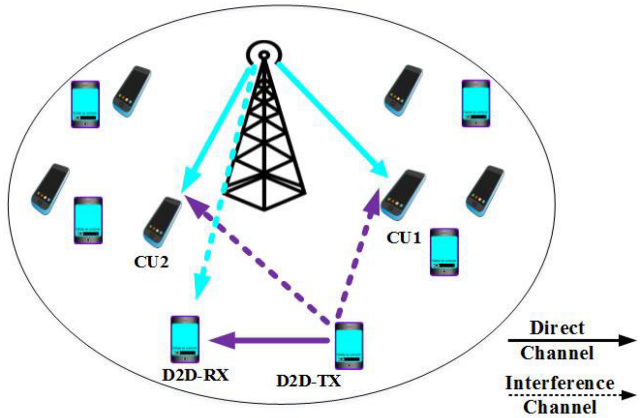

FIGURE 1. System model comprising multiple cellular users and multiple D2D pairs. D2D-TX denotes D2D transmitter and D2D-RX denotes D2D receiver.

- A novel resource management scheme for a NOMA-D2D model is proposed considering RB allocation for CUs and D2D pairs. Existing works on downlink NOMA cellular systems underlaid with D2D communication, i.e. [14] and [15], have considered resource allocation only for D2D pairs.
- The SINR condition of CUs in the OFDMA-D2D model is used for determining the order of SIC in NOMA-D2D model.
- An upper bound is derived for the achievable SINR of secondary CUs in the NOMA-D2D model.
- The performance of OFDMA-D2D and NOMA-D2D models are compared with equal BS power budgets for both models, while the latter serves twice the connections of the former. Our results indicate that the OFDMA-D2D model achieves a higher cellular sum-rate and individual rates compared to the NOMA-D2D model, whereas both models can gain the same D2D sum rate.

C. ORGANIZATION

This paper is organized as follows: Section II presents the system model. The resource management for the OFDMA-D2D model is described in section III. Section IV is devoted to the resource management of the NOMA-D2D model. Simulation results are presented in section V and finally section VI concludes our work.

II. SYSTEM MODEL AND PROBLEM FORMULATION

We focus on the downlink phase of a single-cell scenario, as shown in Fig. 1. A base station, $2N$ CUs, and N D2D pairs are the entities within the cell. There are N RBs, denoted by $\mathcal{S} = \{1, \ldots, N\}$, available in the cell for serving users. The sets of CUs and D2D pairs are denoted by $\mathcal{C} = \{1, \ldots, 2N\}$, and $\mathcal{D} = \{1, \ldots, N\}$, respectively. OFDMA allows only one CU to occupy each RB, while NOMA permits the multiplexing of two CU messages within a single RB. Each D2D pair is permitted to reuse a RB.

Each CU is equipped with the capability to detect and cancel the signal intended for its paired CU (in the NOMA scheme). However, the signal from the co-channel D2D transmitters is treated as noise. Similarly, D2D receivers regard interference from the BS as noise. Such an approach is driven by the aim to cut down signaling overhead, minimize power consumption, and reduce hardware complexity [14]. Moreover, we consider equal noise power at all receivers, and we normalize all channel gains with noise power. All D2D transmitters transmit with the same power level.

Some assumptions about our model are based on practical considerations. As the number of co-channel CUs increases in NOMA, interference cancellation incurs higher complexity in software and hardware and causes more delay. Therefore, we have assumed that two CUs are multiplexed in each RB. We do not consider power control for D2D transmitters to reduce the complexity. Our system settings can support heterogeneous services with different quality of service (QoS) requirements. The NOMA system can serve IoT devices with low data rate transmissions besides conventional CUs. D2D links can also be employed for offloading cellular traffic data.

Without loss of generality, we assume that data streams intended for CU i and CU j are multiplexed on the n-th RB in the NOMA scheme and the m-th D2D pair reuses the same RB for communication. Besides its own message, CU i receives the message of CU j and that of the D2D transmitter m. Therefore, the SINR of CU i when detecting its message is:

$$\gamma_{ii}^{n} = \frac{p_{c_i}^{n} h_{c_i}^{n}}{1 + p_{c_j}^{n} h_{c_i}^{n} + p_d h_{c_i d_m}^{n}}, \tag{1}$$

where $h_{c_i}^{n}$ is the channel gain between the BS and CU i and $h_{c_i d_m}^{n}$ is the channel gain between D2D transmitter m and CU i. Moreover, $p_{c_i}^{n}$ and $p_{c_j}^{n}$ are, respectively, the assigned power levels to CU i and CU j in RB n at the BS. p_d indicates the transmit power level of D2D pairs.

CU i can also detect the message of CU j. The SINR of CU i when it aims at detecting the message of CU j is as follows:

$$\gamma_{ij}^{n} = \frac{p_{c_j}^{n} h_{c_i}^{n}}{1 + p_{c_i}^{n} h_{c_i}^{n} + p_d h_{c_i d_m}^{n}} \tag{2}$$

The SINR of CU j when detecting its own message is denoted by γ_{jj}^{n} and is obtained similar to γ_{ii}:

$$\gamma_{jj}^{n} = \frac{p_{c_j}^{n} h_{c_j}^{n}}{1 + p_{c_i}^{n} h_{c_j}^{n} + p_d h_{c_j d_m}^{n}}. \tag{3}$$

We assume that CU j can detect its own messages with a desired small probability of error. CU i can also successfully detect the message of CU j, provided that $\gamma_{ij}^{n} > \gamma_{jj}^{n}$ [8], [14], [24]. This condition can be expressed in terms of SINRs of CU i and CU j when they operate in OFDMA mode. Let $\gamma_{c_i^n} = \frac{h_{c_i}^{n}}{1+p_d h_{c_i d_m}^{n}}$ indicate the SINR [1] of CU i when RB n is jointly used by CU i and D2D pair m and the BS transmits at unit power in this RB. This is the SINR of CU i in OFDMA mode. Similarly, $\gamma_{c_j^n} = \frac{h_{c_j}^{n}}{1+p_d h_{c_j d_m}^{n}}$ indicates the SINR of CU j in RB n in OFDMA mode. Now, we can re-express (2) and (3) as follows:

$$\gamma_{ij}^{n} = \frac{p_{c_j}^{n} \gamma_{c_i}^{n}}{1 + p_{c_i}^{n} \gamma_{c_i}^{n}} \tag{4}$$

$$\gamma_{jj}^{n} = \frac{p_{c_j}^{n} \gamma_{c_j}^{n}}{1 + p_{c_i}^{n} \gamma_{c_j}^{n}}. \tag{5}$$

Based on (4) and (5), it can be verified that the condition $\gamma_{ij}^{n} > \gamma_{jj}^{n}$ is equal to $\gamma_{c_i}^{n} > \gamma_{c_j}^{n}$. This means CU i can successfully detect the message of CU j and can subtract it from its received signal as far as it has a better SINR condition in the OFDMA-D2D scheme. Consequently, CU i can achieve the Shannon rate of

$$\begin{aligned} R_{c_i}^{n} &= \log\left(1 + \frac{p_{c_i}^{n} h_{c_i}^{n}}{1 + p_d h_{c_i d_m}^{n}}\right), \\ &= \log(1 + p_{c_i}^{n} \gamma_{c_i}^{n}). \end{aligned} \tag{6}$$

Meanwhile, CU j treats the received signal of CU i and that of the D2D transmitter m as noise and achieves the rate of

$$\begin{aligned} R_{c_j}^{n} &= \log\left(1 + \frac{p_{c_j}^{n} h_{c_j}^{n}}{1 + p_{c_i}^{n} h_{c_j}^{n} + p_d h_{c_j d_m}^{n}}\right), \\ &= \log(1 + \frac{p_{c_j}^{n} \gamma_{c_j}^{n}}{1 + p_{c_i}^{n} \gamma_{c_j}^{n}}). \end{aligned} \tag{7}$$

We call CUs capable of interference cancellation and CUs treating interference as noise primary CUs and secondary CUs, respectively. We will later show that this definition is equal to what we introduced as primary and secondary CUs in Sec. I.

It is straightforward to check that the D2D pair m achieves the same rate in both NOMA-D2D and OFDMA-D2D schemes as follows:

$$R_{d_m}^{n} = \log\left(1 + \frac{p_d h_{dd_m}^{n}}{1 + p_c^{n} h_{d_m}^{n}}\right), \tag{8}$$

where $h_{dd_m}^{n}$ is the channel gain between the transmitter and the receiver of m-th D2D pair in RB n. Also, $h_{d_m}^{n}$ indicates the channel gain between the BS and the D2D receiver m in RB n. The transmit power level of the BS in RB n is denoted by $p_c^{n} = p_{c_i}^{n} + p_{c_j}^{n}$.

With this introduction, we can reach an early conclusion that an OFDMA-D2D model has superior cellular sum rate over the NOMA-D2D model as far as the power budget is equal in both models. In what follows, we present a

[1]Hereinafter, by the SINR of CUs in OFDMA-D2D mode we mean the SINR normalized by transmit power level.

mathematical proof to verify this:

$$
\begin{aligned}
R_c^n &= \log\left(1 + p_c^n \gamma_{c_i}^n\right) &\text{(9a)}\\
&= \log\left(1 + \left(p_{c_i}^n + p_{c_j}^n\right)\gamma_{c_i}^n\right) &\text{(9b)}\\
&> \log\left(1 + p_{c_i}^n \gamma_{c_i}^n + p_{c_j}^n \gamma_{c_j}^n\right) &\text{(9c)}\\
&= \log\left(\left(1 + p_{c_i}^n \gamma_{c_j}^n\right)\left(1 + \frac{p_{c_j}^n \gamma_{c_j}^n}{1 + p_{c_i}^n \gamma_{c_i}}\right)\right) &\text{(9d)}\\
&= \log\left(1 + p_{c_i}^n \gamma_{c_j}^n\right) + \log\left(1 + \frac{p_{c_j}^n \gamma_{c_j}^n}{1 + p_{c_i}^n \gamma_{c_i}^n}\right) &\text{(9e)}\\
&= R_{c_i}^n + R_{c_j}^n &\text{(9f)}
\end{aligned}
$$

(9a) defines the rate of CU i on RB n in OFDMA-D2D model. (9c) is derived base on the assumption that $\gamma_{c_i} > \gamma_{c_j}$. (9f) indicates the sum rate of CU i and CU j in the NOMA-D2D model and is inferred based on (7) and (6). As above relations demonstrate when two CUs are paired on the same RB based on NOMA, their sum rate is not higher than the achievable rate of the user with better SINR in OFDMA-D2D model. The result is valid as long as both models have the same power budgets. This conclusion can be applied to each RB. Therefore, the sum rate of OFDMA-D2D model can be considered as an upper bound for sum rate of NOMA-D2D model in our scenario.

To study the performance of the NOMA-D2D model, we formulate a resource management problem with the aim of maximizing system sum rate by allocating power to CUs and RBs to both CUs and D2D pairs. We also consider a minimum rate requirement for the secondary CUs, which cannot cancel the interference of their co-channel primary CU, and exclude their rates from the system sum rate. The problem is stated in (10), as shown at the bottom of the next page.

In this equation P_B, denotes the power budget of the BS. ρ_m^n is a binary variable that indicates if RB n is assigned to the D2D pair m. Similarly, the binary variable β_i^n denotes if the RB n is allocated to CU i. Additionally, $\mathcal{C}_1$ indicates that each D2D pair uses only one RB and each RB hosts only one D2D pair. $\mathcal{C}_2$ implies that each RB is allocated to two CUs and each CU can transmit only in one RB. $\mathcal{C}_3$ denotes that each secondary CU must achieve a target rate R_{th}.

The aforementioned problem is a MINLP [25]. Finding the optimal solution requires an exhaustive search over $(C_N^{2N})! \times N!$ allocation strategies. The power control should then be solved for each allocation. The problem becomes intractable as N increases. To reduce the complexity of the problem, we propose a sub-optimal heuristic approach realized in two stages. In the first stage, we relax the rate constraint in $\mathcal{C}_3$ and consider maximizing the objective. This stage includes power control at the BS, RB allocation for D2D pairs, admitting N CUs and assigning their corresponding RBs. In the next stage, we devise the RB allocation policy for the rest of CUs. We first derive an upper bound for their achievable SINR and assign the RBs to them to maximize this upper bound. Finally, we update the power allocation at the BS to serve all CUs. This approach is not optimal, but has low-complexity and the result can be considered as a lower bound for the optimal solution of (10). Furthermore, it provides insights about OFDMA-D2D and NOMA-D2D model performance. Our proposed scheme in the first step resembles devising a resource allocation algorithm for an OFDMA-D2D model. This algorithm is extended for the NOMA-D2D model in the next stage.

III. RESOURCE MANAGEMENT IN OFDMA-D2D MODEL

The problem of resource allocation and power control in OFDMA-D2D model is formulated as follows:

$$
\begin{aligned}
\max_{p_c^n, \beta_i^n, \rho_m^n} \sum_{n\in\mathcal{S}} \sum_{m\in\mathcal{D}} \sum_{i\in\mathcal{C}} \rho_m^n \beta_i^n &\left(\log\left(1 + \frac{p_d h_{dd_m}^n}{1 + p_c^n h_{d_m}^n}\right)\right.\\
&\left. + \log\left(1 + \frac{p_c^n h_{c_i}^n}{1 + p_d h_{c_i d_m}^n}\right)\right)\\
&\mathcal{C}_1 : \sum_{m\in\mathcal{D}} \rho_m^n = 1 \;\; \forall n \in \mathcal{S}, \;\; \sum_{n\in\mathcal{S}} \rho_m^n = 1 \;\; \forall m \in \mathcal{D},\\
&\rho_m^n \in \{0, 1\}\\
&\mathcal{C}_2 : \sum_{i\in\mathcal{C}} \beta_i^n = 1 \;\; \forall n \in \mathcal{S}, \;\; \sum_{n\in\mathcal{S}} \beta_i^n \leq 1 \;\; \forall i \in \mathcal{C},\\
&\beta_i^n \in \{0, 1\}\\
&\mathcal{C}_3 : \sum_{n\in\mathcal{S}} p_c^n \leq P_B
\end{aligned} \tag{11}
$$

$\mathcal{C}_2$ indicates that each RB is occupied by a CU and each CU can utilize at most one RB.

We face a MINLP the optimal solution of which is computationally expensive to achieve. Therefore, we proceed with a low-complexity heuristic approach. The objective function of the problem can be re-expressed in the form of $f_1(X, Z) + f_2(X, Y, Z)$, where X and Y are vectors of binary variables indicating RB assignments for D2D pairs and CUs, respectively. Z is a power vector, each element of which is the transmit power of the BS in a RB. f_1 is the sum rate of D2D pairs and f_2 is the sum rate of CUs. We assume a vector $\hat{Z}$ complying with $\mathcal{C}_3$ is given. The problem is turned into $\max_{X,Y}\left(f_1(X, \hat{Z}) + f_2(X, Y, \hat{Z})\right)$. The first term in the objective is now a function of X and the second term is a function of X and Y. This structure motivates maximizing the D2D sum rate through RB assignment for D2D pairs in the first step. Obtaining the RB policy for the D2D pair, the sum rate of CUs is maximized via RB assignment for CUs in the next step. This heuristic approach leads to a sub-optimal solution and prioritizes D2D pairs over CUs. However, it can reduce the complexity of RB assignment.

We choose the equal power allocation. This power control is the optimal strategy for maximizing the sum rate of CUs under certain conditions. CUs which are given less priority in RB allocations are now privileged by the power control strategy.

Proposition 1: The equal power allocation policy achieves the maximum sum rate of CUs as far as CUs have high SINR, i.e., $\log(1 + \text{SINR}) \approx \log(\text{SINR})$ is applicable to CUs.

Proof: Assuming that the binary variables indicating RB assignments, e.g., β_i^n and ρ_m^n have been set and the CUs have high SINR, i.e., the logarithmic approximation is held, the sum rate maximization of CUs can be stated as follows:

$$\max_{p_c^n} \sum_{n\in\mathcal{S}} \sum_{i\in\mathcal{C}} \sum_{m\in\mathcal{D}} \beta_i^n \rho_m^n \log\left(\frac{p_c^n h_{c_i}^n}{1 + p_d h_{c_i d_m}^n}\right)$$
$$\mathcal{C}_3 : \sum_{n\in\mathcal{S}} p_c^n \le P_B \tag{12}$$

After removing the ineffective terms in (12), the Lagrangian function $l(\lambda, P)$ is defined as follows:

$$l(\lambda, p_c^1, p_c^2, \dots p_c^N) = \sum_{n\in\mathcal{S}} \log p_c^n + \lambda\left(P_B - \sum_{n\in\mathcal{S}} p_c^n\right), \tag{13}$$

where λ is the Lagrange multiplier. Taking derivatives of the Lagrangian leads us to the optimal point of the problem, which is $p_c^n = \frac{P_B}{N}$.

The equal power allocation policy is not the optimal power control for (11) in general conditions. It is straightforward to verify that the water-filling algorithm maximizes CU's sum rate [26]. The whole objective in (11), composing the sum rates of CUs and D2D pairs, has a D.C. optimization structure in terms of power levels [27] and the SCALE algorithm presented in [28] can reach its suboptimal solution. Despite this, we proceed with equal power allocation, which has a low implementation complexity.

Another issue is that the power control and RB allocation are coupled optimization problems. Some research works, e.g., [8] and [29], optimize the objective versus power levels and RBs iteratively. Their approach is based on the coordinate descent methods, which successively optimize a convex multi-variable function along a direction while all other coordinates are fixed [30]. We did not choose such an approach due to its high complexity. Moreover, the convergence of this method in MINLP and yielding suboptimal solutions need extensive investigation. We take advantage of the structure of the problem and decompose it into three sub-problems. First, we set the power levels of the BS based on 1. Next, we determine the RB assignment for D2D pairs and CUs consecutively. We obtain a lower bound for the maximum sum rate of primary CUs and D2D pairs through this low-complexity approach.

Proposition 2: The RB assignment for the D2D pairs can be expressed as an assignment problem in a weighted bipartite graph.

Proof: According to (11), the D2D RB assignment can be formulated as follows:

$$\max_{\rho_m^n} \sum_{n\in\mathcal{S}} \sum_{m\in\mathcal{D}} \rho_m^n \log\left(1 + \frac{p_d h_{dd_m}^n}{1 + p_c^n h_{d_m}^n}\right)$$
$$\mathcal{C}_1 : \sum_{m\in\mathcal{D}} \rho_m^n = 1 \;\; \forall n \in \mathcal{S}, \sum_{n\in\mathcal{S}} \rho_m^n = 1 \;\; \forall m \in \mathcal{D},$$
$$\rho_m^n \in \{0, 1\} \tag{14}$$

A bipartite graph, denoted by $G(V, U, E)$, can be divided into two disjoint and independent sets of vertices, i.e., V and U. Every edge in the graph connects a vertex in U to a vertex in V. This means that none of the two vertices in U or V are adjacent. The set of RBs and the set of D2D pairs indicate independent sets. Each RB is connected to all D2D pairs through weighted edges. The set of edges is denoted by E. The weight of the edge connecting the RB n to the D2D pair m is defined by $w_{n,m} = \log\left(1 + \frac{p_d h_{dd_m}^n}{1+p_c^n h_{d_m}^n}\right)$. A matching in a bipartite graph is a set of graph edges that do not share endpoints. A maximum matching is a matching having the maximum number of edges. $\mathcal{C}_1$ expresses a maximum matching whose sum-weight must be maximized, as the objective in problem (14) shows. This is an assignment problem and can be solved by the Hungarian algorithm [31] with the complexity of $\mathcal{O}(N^3)$.

Proposition 3: The RB assignment for the CUs can be expressed as an assignment problem in a weighted bipartite graph.

$$\max_{p_{c_i}^n, p_{c_j}^n, \beta_i^n, \beta_j^n, \rho_m^n} \sum_{n\in\mathcal{S}} \sum_{m\in\mathcal{D}} \sum_{i\in\mathcal{C}} \sum_{j\in\mathcal{C}-\{i\}} \rho_m^n \beta_i^n \beta_j^n \left(\log\left(1 + \frac{p_d h_{dd_m}^n}{1 + \left(p_{c_i}^n + p_{c_j}^n\right) h_{d_m}^n}\right) + \log\left(1 + \frac{p_{c_i}^n h_{c_i}^n}{1 + p_d h_{c_i d_m}^n}\right)\right)$$
$$\mathcal{C}_1 : \sum_{m\in\mathcal{D}} \rho_m^n = 1 \;\; \forall n \in \mathcal{S}, \;\; \sum_{n\in\mathcal{S}} \rho_m^n = 1 \;\; \forall m \in \mathcal{D}, \;\; \rho_m^n \in \{0, 1\}$$
$$\mathcal{C}_2 : \sum_{i\in\mathcal{C}} \beta_i^n = 2 \;\; \forall n \in \mathcal{S}, \;\; \sum_{n\in\mathcal{S}} \beta_i^n = 1 \;\; \forall i \in \mathcal{C}, \;\; \beta_i^n \in \{0, 1\}$$
$$\mathcal{C}_3 : \beta_i^n \beta_j^n \rho_m^n \log\left(1 + \frac{p_{c_j}^n h_{c_j}^n}{1 + p_{c_i}^n h_{c_j}^n + p_d h_{c_j d_m}^n}\right) \ge \beta_i^n \beta_j^n \rho_m^n R_{th}$$
$$\forall i, j : i \in \mathcal{C}, j \in \mathcal{C} - \{i\} \;\; \forall n, m : n \in \mathcal{S}, m \in \mathcal{D}$$
$$\mathcal{C}_4 : \sum_{n\in\mathcal{S}} \sum_{i\in\mathcal{C}} \sum_{j\in\mathcal{C}-\{i\}} \beta_i^n p_{c_i}^n + \beta_j^n p_{c_j}^n \le P_B \tag{10}$$

Algorithm 1 Resource Management for OFDMA-D2D and NOMA-D2D Models

1: Apply equal power allocation policy, i.e., $\forall n \;\; p_n = \frac{P_B}{N}$.
2: Perform the D2D RB allocation based on Proposition 2.
3: Perform the RB allocation for the primary CUs based on Proposition 3.
OFDMA-D2D resource management has been accomplished.
4: Perform the RB allocation for the secondary CUs based on Proposition 4.
5: Set a threshold for the rate of secondary CUs based on (20).
6: Update the power levels of the Primary CUs based on equal power allocation policy and the total power budget for primary CUs obtained in (19).
7: Allocate power to secondary CUs based on (17).
NOMA-D2D resource management has been accomplished.

Proof: According to (11), the RB assignment for the CUs can be formulated as follows:

$$\max_{\beta_i^n} \sum_{n\in\mathcal{S}} \sum_{i\in\mathcal{C}} \beta_i^n \log\left(1+\frac{p_c^n h_{c_i}^n}{1+\sum_{m\in\mathcal{D}} \rho_m^n p_d h_{c_i d_m}^n}\right)$$
$$\mathcal{C}_2: \sum_{i\in\mathcal{C}} \beta_i^n = 1 \;\forall n\in\mathcal{S}, \quad \sum_{n\in\mathcal{S}} \beta_i^n <= 1 \;\; \forall i\in\mathcal{C},$$
$$\beta_i^n \in \{0,1\} \tag{15}$$

Here, the binary variables indicating RB assignment for D2D pairs have been set based on Proposition (2). The sets of RBs and CUs are the two independent sets of a bipartite graph. Each RB, which represents a vertex of the graph, is occupied by a D2D pair and is connected to all CUs through weighted edges. We assume that RB n has been allocated to the D2D pair m. The edge connecting the RB n to the CU i has the weight $w_{i,n} = \log\left(1+\frac{p_c^n h_{c_i}^n}{1+p_d h_{c_i d_m}^n}\right)$. The Hungarian algorithm can find the maximum matching expressed in (15) with a complexity of $\mathcal{O}(N^3)$.

IV. RESOURCE MANAGEMENT IN NOMA-D2D MODEL

The Primary CUs and D2D pairs have been admitted to the system based on the power control and RB allocation developed for an OFDMA-D2D model. Now, the secondary CUs are admitted to the system to meet a target rate. We set a SINR threshold γ_t for the secondary CUs based on the rate requirement expressed in (10) and employ (7) as follows:

$$\frac{p_{c_j}^n \gamma_{c_j}^n}{1+p_{c_i}^n \gamma_{c_j}^n} \geq \gamma_t \tag{16}$$

After some manipulation (16) can be reformulated as follows:

$$p_{c_j}^n \geq \gamma_t \left(\frac{1}{\gamma_{c_j}^n} + p_{c_i}^n\right) \tag{17}$$

TABLE 2. Simulation parameters.

Parameter	Value
Path-loss (BS-User device)	$15.3 + 37.6\log_{10} distance_{BS-Device}$
Path-loss (CU-D2D, D2D pairs)	$28 + 40\log_{10} distance_{CU-D2D}$
Fading	Rayleigh flat fading
Noise power	-100 dBm
$N = 10$	
User device maximum power	-5dBm
Cell radius	500 m
Proximity of D2D pairs	random in (20,30)
CU distance from the BS	random in (30, 500)
$N = 5$	
User device maximum power	-7dBm
Cell radius	200 m
Proximity of D2D pairs	random in (8,20)
CU distance from the BS	random in (30, 200)

Based on (17), the BS power budget constraint $\mathcal{C}_4$ of problem (10) can be reformulated as follows:

$$\sum_{n\in\mathcal{S}} \sum_{j\in\left(\mathcal{C}-\hat{\mathcal{C}}\right)} \sum_{i\in\hat{\mathcal{C}}} p_{c_i}^n + \gamma_t^n p_{c_i}^n + \frac{\gamma_t}{\gamma_{c_j}^n} \leq P_B, \tag{18}$$

where $\hat{\mathcal{C}}$ and $(\mathcal{C}-\hat{\mathcal{C}})$ indicate the set of primary CUs and the set of secondary CUs, respectively.

This leads to

$$\sum_{n\in\mathcal{S}} \sum_{i\in\hat{\mathcal{C}}} p_{c_i}^n \leq \frac{1}{1+\gamma_t}\left(P_B - \sum_{n\in\mathcal{S}} \sum_{j\in\left(\mathcal{C}-\hat{\mathcal{C}}\right)} \frac{\gamma_t}{\gamma_{c_j}^n}\right) \tag{19}$$

Based on (19) an upper bound for γ_t can be obtained as follows:

$$\gamma_t < \frac{P_B}{\sum_{n\in\mathcal{S}} \sum_{j\in(\mathcal{C}-\hat{\mathcal{C}})} \frac{1}{\gamma_{c_j}^n}} \tag{20}$$

To maximize the upper bound, the term $\sum_{n\in\mathcal{S}} \sum_{j\in(\mathcal{C}-\hat{\mathcal{C}})} \frac{1}{\gamma_{c_j}^n}$ in the denominator should be minimized. This fact can be employed for devising a strategy in admitting secondary CUs.

Proposition 4: The RB assignment for the secondary CUs can be expressed as an assignment problem in a weighted bipartite graph.

Proof: Based on (20), the RB assignment for the secondary CUs can be formulated as:

$$\min_{\theta_j} \sum_{n\in\mathcal{S}} \sum_{j\in(\mathcal{C}-\hat{\mathcal{C}})} \frac{\theta_j^n}{\gamma_{c_j}^n},$$
$$\mathcal{C}_4: \sum_{n=1}^{N} \theta_j^n = 1 \;\forall j\in(\mathcal{C}-\hat{\mathcal{C}}), \; \sum_{j=1}^{N} \theta_j^n = 1 \;\forall n\in\mathcal{S}, \; \theta_j^n \in \{0,1\} \tag{21}$$

Here, $\theta_j^n = 1$ indicates that RB n is reused by the secondary CU j. The set of RBs and the set of secondary CUs are the two independent sets of a bipartite graph. Each RB is occupied by a D2D pair and a primary CU based on Proposition 2 and Proposition 3, respectively. The weight of

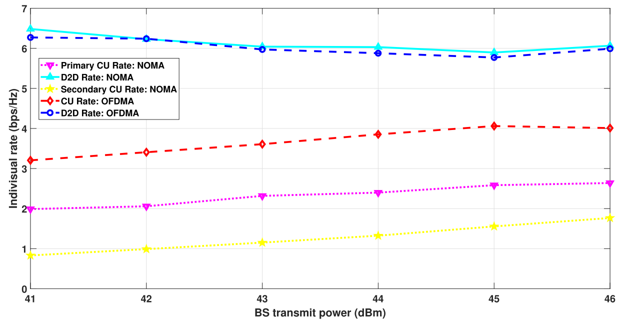

FIGURE 2. **Individual rates of users in OFDMA-D2D and NOMA-D2D models ($N = 10$).**

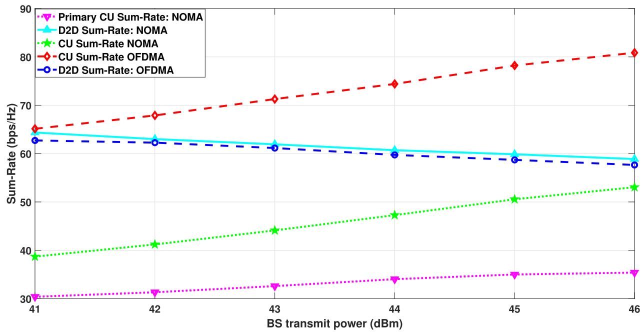

FIGURE 3. **Users sum rate in OFDMA-D2D model and NOMA-D2D models ($N = 10$).**

the edge connecting RB n to the secondary CU j is $\frac{1}{\gamma_{c_j}^n}$. The problem can be solved by the Hungarian algorithm with the complexity of $\mathcal{O}(N^3)$. Obtaining the solution by exhaustive search requires trying $N!$ possible strategies.

CUs that are admitted in the first and second stages have been receptively called primary CUs and secondary CUs. The following proposition verifies the order of interference cancellation between primaries and secondaries.

Proposition 5: A primary CU can cancel the interference of its co-channel secondary CU.

Proof: Assume CU i and CU j are admitted in the first and second stages, respectively, and are paired on RB n. It can be concluded that $\gamma_{C_i}^n > \gamma_{C_j}^n$. If this is not the case, i.e., $\gamma_{C_i}^n < \gamma_{C_j}^n$, then, CU j has a higher OFDMA-D2D rate compared to CU i and must have been selected in the first stage to maximize the sum rate. As we explained in Sec. (II) when the condition $\gamma_{C_i}^n > \gamma_{C_j}^n$ is held, CU i can cancel the interference of CU j.

In the last step, we upgrade the power allocation strategy. The BS power budget is now divided among primary and secondary CUs. The portion of the power budget for the primary CUs is determined based on (19), where each CU is allocated an equal amount of this budget. The power level for each secondary CU is determined according to (17). The secondary CU having a better OFDMA-D2D SINR requires less power to reach the target SINR. The proposed power allocation is not the optimal strategy but has a low complexity. Alg. 1 summarizes the proposed resource allocation and power control strategy.

V. SIMULATION RESULTS

In this section, we evaluate the performance of the proposed schemes. We perform simulations for two network size cases, i.e., $N = 10$ and $N = 5$. In both cases, the BS is located at the center of the cell. CUs and D2D pairs are randomly located within the cell. The channel gain includes path loss and Rayleigh flat fading. The path-loss model has been adopted from [32]. The target SINR for the secondary CU in the NOMA-D2D model is set to 0.9 of the upper bound obtained based on (20). The results are averaged over 1000 channel realizations. The simulation parameters for both network sizes have been summarized in Table 2.

Fig. 2 illustrates the performance of OFDMA-D2D and NOMA-D2D models in terms of average rates of users as the BS power budget increases for N = 10. The average rate of D2D links has a downward trend. The reason is that D2D receivers collect a higher level of interference as the BS transmit power level rises. The D2D average rates in both OFDMA-D2D and NOMA-D2D models are close. This behavior is consistent with the theoretical results expressed in (8). Fig. 2 also indicates that the average rate of a CU in OFDMA-D2D model is higher than the average rate of a CU in NOMA-D2D model. The reason behind such behavior is that each CU in the NOMA-D2D model is provided with less power. In the NOMA-D2D model, the average rate of a primary CU is higher than that of a secondary CU since primary CUs are given priority in RB allocation.The higher average rate of D2D pairs compared to that of CUs stems from multiple factors, including the proximity of D2D transmitters and receivers and prioritizing D2D users in RB allocation over CUs. Moreover, each D2D pair is assigned a RB in each chan- nel realization, whereas a CU in the OFDMA-D2D model may not be allocated a RB in some channel realizations. This result motivates the usage of D2D communication for data-intensive applications in the proposed scenario.

Fig. 3 illustrates the cellular and D2D sum rates in both OFDMA-D2D and NOMA-D2D models for $N = 10$. As expected, the sum rate of CUs and that of D2D pairs increases and declines, respectively, with the increments of the transmit power level of the BS. Fig. 3 also indicates that CUs in the OFDMA-D2D model can achieve higher sum rates compared to D2D pairs, whereas the average rate of a D2D pair is higher than that of a CU in the OFDMA-D2D model according to Fig. 2. The reason is that the number of CUs is twice the number of RBs in the OFDMA-D2D model. This fact provides user diversity that can be exploited in sum rate maximization. The sum rate of NOMA CUs (including primary CUs and secondary CUs) is significantly lower than that of OFDMA CUs due to the reduced power portion for each CU in the NOMA-D2D model.

Fig. 4 demonstrates the cellular and D2D sum rates for the network size of N = 5 in both models. For this network size, we have added the graphs of the optimal achievable sum

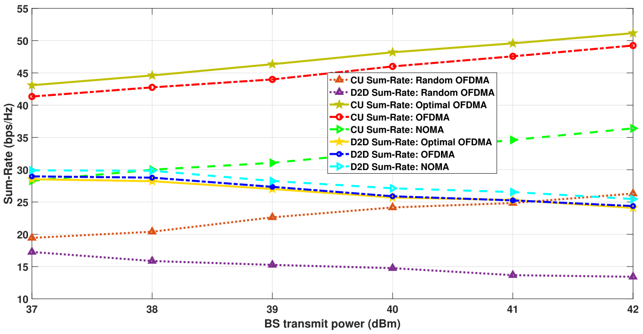

FIGURE 4. **Users' sum rate in OFDMA-D2D and NOMA-D2D models ($N = 5$) .**

rates of CUs and D2D pairs in the OFDMA-D2D model. The RB allocation for this scheme has been performed by exhaustive search. We have selected this network size and only the OFDMA-D2D model for applying the exhaustive search to reduce the computational load. Moreover, the optimal achievable cellular sum rate in the OFDMA-D2D model can be considered an upper bound for the optimal achievable cellular sum rate in the NOMA-D2D model based on the discussion in Sec. II. To show the effectiveness of the proposed scheme, we have also depicted the sum rates of CUs and D2D pairs in the OFDMA-D2D model when RB allocation has been performed randomly. As the results indicate, the proposed RB allocation for the OFDMA-D2D model has a close performance to that of the optimal case and superior performance over that of random resource allocation. The cellular sum rate in the NOMA-D2D model is lower than that of the OFDMA-D2D model, whereas D2D sum rates in both models have close values. These results are aligned with those presented in Fig.3.

There is a discrepancy between our results and those reported in [14] and [15]. While we have demonstrated that the OFDMA-D2D model outperforms the NOMA-D2D model, the mentioned works have reported superior performance of the NOMA-D2D model over OMA-D2D models. In TDMA-D2D and FDMA-D2D scenarios, respectively considered in [14] and [15], the number of CUs equals the number of serving CUs in the NOMA-D2D model. The increased number of CUs in OMA penalizes the rate of CUs since less portion of resources can be used by each user. In our work, the number of CUs in the OFDMA-D2D model is half of that in the NOMA-D2D model. Moreover, we have considered the same power budget for both schemes. This strategy has affected the rate of NOMA CUs. Our work clarifies that comparing the performance of NOMA and OFDMA schemes entails the scenario settings, i.e. the number of users and the available resources, to be considered.

VI. CONCLUSION

The research provided deeper insights into mutual interference between NOMA CUs and D2D links to construct a resource allocation framework for a NOMA-D2D model, considering mutual interference. Our objective was to maximize the system sum-rate, while ensuring a minimum rate for CUs. The problem, formulated as a MINLP, seemed highly complex at the outset. However, our two-stage heuristic sub-optimal resource management solution efficiently addressed the issue. The first stage was devoted to resource allocation for an OFDMA-D2D model in which half of the cellular users and D2D pairs are admitted into the system. In the next stage, the model was extended to a NOMA-D2D model, where the rest of cellular users were admitted into the system. The proposed two-stage procedure provided insights on the trade-off between OFDMA-D2D and NOMA-D2D systems. The OFDMA-D2D model boasted higher sum-rates and individual rates than the NOMA-D2D model when both models have the same power budget at the BS, while the NOMA-D2D model serves twice the number of available resource blocks in the system. An open problem which needs further investigation is deriving the required power budget at the BS that can lead to superior performance of NOMA-D2D model over OFDMA-D2D model. It remains to be investigated if this power budget can meet the regulatory obligations and hardware restrictions. Studying the performance of NOMA-D2D model with various numbers of cellular users, especially for mixed NOMA/OFDMA-D2D scenarios are worth further consideration. Moreover, investigating the integration of NOMA and D2D communication presents a promising path for interference management and resource allocation in heterogeneous networks.

REFERENCES

[1] A. Benjebbour, Y. Saito, Y. Kishiyama, A. Li, A. Harada, and T. Nakamura, "Concept and practical considerations of non-orthogonal multiple access (NOMA) for future radio access," in *Proc. Int. Symp. Intell. Signal Process. Commun. Syst.*, Naha-Shi, Japan, Nov. 2013, pp. 770–774.

[2] Z. Ding, Z. Yang, P. Fan, and H. V. Poor, "On the performance of non-orthogonal multiple access in 5G systems with randomly deployed users," *IEEE Signal Process. Lett.*, vol. 21, no. 12, pp. 1501–1505, Dec. 2014.

[3] Y. Sun, D. W. K. Ng, Z. Ding, and R. Schober, "Optimal joint power and subcarrier allocation for full-duplex multicarrier non-orthogonal multiple access systems," *IEEE Trans. Commun.*, vol. 65, no. 3, pp. 1077–1091, Mar. 2017.

[4] Z. Yang, Z. Ding, P. Fan, and N. Al-Dhahir, "A general power allocation scheme to guarantee quality of service in downlink and uplink NOMA systems," *IEEE Trans. Wireless Commun.*, vol. 15, no. 11, pp. 7244–7257, Nov. 2016.

[5] M. Vaezi, R. Schober, Z. Ding, and H. V. Poor, "Non-orthogonal multiple access: Common myths and critical questions," *IEEE Wireless Commun.*, vol. 26, no. 5, pp. 174–180, Oct. 2019.

[6] R. Kotaba, C. N. Manchón, T. Balercia, and P. Popovski, "How URLLC can benefit from NOMA-based retransmissions," *IEEE Trans. Wireless Commun.*, vol. 20, no. 3, pp. 1684–1699, Mar. 2021.

[7] P. Popovski, K. F. Trillingsgaard, O. Simeone, and G. Durisi, "5G wireless network slicing for eMBB, URLLC, and mMTC: A communication-theoretic view," *IEEE Access*, vol. 6, pp. 55765–55779, 2018.

[8] J. Zhao, Y. Liu, K. K. Chai, Y. Chen, and M. Elkashlan, "Joint subchannel and power allocation for NOMA enhanced D2D communications," *IEEE Trans. Commun.*, vol. 65, no. 11, pp. 5081–5094, Nov. 2017.

[9] T. Yoon, T. H. Nguyen, X. T. Nguyen, D. Yoo, B. Jang, and V. D. Nguyen, "Resource allocation for NOMA-based D2D systems coexisting with cellular networks," *IEEE Access*, vol. 6, pp. 66293–66304, 2018.

[10] I. Budhiraja, N. Kumar, and S. Tyagi, "Cross-layer interference management scheme for D2D mobile users using NOMA," *IEEE Syst. J.*, vol. 15, no. 2, pp. 3109–3120, Jun. 2021.

[11] R. Gupta and S. Tanwar, "A zero-sum game-based secure and interference mitigation scheme for socially aware D2D communication with imperfect CSI," *IEEE Trans. Netw. Service Manage.*, vol. 19, no. 3, pp. 3478–3486, Sep. 2022.

[12] M. Sun, X. Xu, X. Tao, P. Zhang, and V. C. M. Leung, "NOMA-based D2D-enabled traffic offloading for 5G and beyond networks employing licensed and unlicensed access," *IEEE Trans. Wireless Commun.*, vol. 19, no. 6, pp. 4109–4124, Jun. 2020.

[13] R. Li, P. Hong, K. Xue, M. Zhang, and T. Yang, "Resource allocation for uplink NOMA-based D2D communication in energy harvesting scenario: A two-stage game approach," *IEEE Trans. Wireless Commun.*, vol. 21, no. 2, pp. 976–990, Feb. 2022.

[14] N. Madani and S. Sodagari, "Performance analysis of non-orthogonal multiple access with underlaid device-to-device communications," *IEEE Access*, vol. 6, pp. 39820–39826, 2018.

[15] Y. Pan, C. Pan, Z. Yang, and M. Chen, "Resource allocation for D2D communications underlaying a NOMA-based cellular network," *IEEE Wireless Commun. Lett.*, vol. 7, no. 1, pp. 130–133, Feb. 2018.

[16] K. Doppler, M. Rinne, C. Wijting, C. B. Ribeiro, and K. Hugl, "Device-to-device communication as an underlay to LTE-advanced networks," *IEEE Commun. Mag.*, vol. 47, no. 12, pp. 42–49, Dec. 2009.

[17] Z. Zhang, Z. Ma, M. Xiao, Z. Ding, and P. Fan, "Full-duplex device-to-device-aided cooperative nonorthogonal multiple access," *IEEE Trans. Veh. Technol.*, vol. 66, no. 5, pp. 4467–4471, May 2017.

[18] Y. Xu, G. Wang, B. Li, and S. Jia, "Performance of D2D aided uplink coordinated direct and relay transmission using NOMA," *IEEE Access*, vol. 7, pp. 151090–151102, 2019.

[19] Md. F. Kader, S. M. R. Islam, and O. A. Dobre, "Device-to-device aided cooperative NOMA transmission exploiting overheard signal," *IEEE Trans. Wireless Commun.*, vol. 21, no. 2, pp. 1304–1318, Feb. 2022.

[20] D. Zhai, R. Zhang, Y. Wang, H. Sun, L. Cai, and Z. Ding, "Joint user pairing, mode selection, and power control for D2D-capable cellular networks enhanced by nonorthogonal multiple access," *IEEE Internet Things J.*, vol. 6, no. 5, pp. 8919–8932, Oct. 2019.

[21] Y. Xu, J. Tang, B. Li, N. Zhao, D. Niyato, and K. Wong, "Adaptive aggregate transmission for device-to-multi-device aided cooperative NOMA networks," *IEEE J. Sel. Areas Commun.*, vol. 40, no. 4, pp. 1355–1370, Apr. 2022.

[22] L. Pei, Z. Yang, C. Pan, W. Huang, M. Chen, M. Elkashlan, and A. Nallanathan, "Energy-efficient D2D communications underlaying NOMA-based networks with energy harvesting," *IEEE Commun. Lett.*, vol. 22, no. 5, pp. 914–917, May 2018.

[23] K. Z. Shen, D. K. C. So, J. Tang, and Z. Ding, "Power allocation for NOMA with cache-aided D2D communication," *IEEE Trans. Wireless Commun.*, vol. 23, no. 1, pp. 529–542, Jan. 2024.

[24] T. M. Cover and J. A. Thomas, *Elements of Information Theory*. Hoboken, NJ, USA: Wiley, 2006.

[25] C. A. Floudas, *Mixed-Integer Nonlinear Optimization*. London, U.K.: Oxford Univ. Press, Nov. 1995.

[26] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge, U.K.: Cambridge Univ. Press, 2004.

[27] H. Tuy, "DC optimization: Theory, methods and algorithms," in *Handbook of Global Optimization*. New York, NY, USA: Springer, 1995, pp. 149–216.

[28] J. Papandriopoulos and J. S. Evans, "SCALE: A low-complexity distributed protocol for spectrum balancing in multiuser DSL networks," *IEEE Trans. Inf. Theory*, vol. 55, no. 8, pp. 3711–3724, Aug. 2009.

[29] D. T. Ngo, S. Khakurel, and T. Le-Ngoc, "Joint subchannel assignment and power allocation for OFDMA femtocell networks," *IEEE Trans. Wireless Commun.*, vol. 13, no. 1, pp. 342–355, Jan. 2014.

[30] P. Tseng, "Convergence of a block coordinate descent method for nondifferentiable minimization," *J. Optim. Theory Appl.*, vol. 109, no. 3, pp. 475–494, Jun. 2001.

[31] M. Grötschel, L. Lovász, and A. Schrijver, *Geometric Algorithms and Combinatorial Optimization* (Algorithms and Combinatorics), vol. 2. Berlin, Germany: Springer, 1988.

[32] Y. Huang, A. A. Nasir, S. Durrani, and X. Zhou, "Mode selection, resource allocation, and power control for D2D-enabled two-tier cellular network," *IEEE Trans. Commun.*, vol. 64, no. 8, pp. 3534–3547, Aug. 2016.

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