Sum-Rate Maximization for D2D-Enabled UAV Networks with Seamless Coverage Constraint

Xiaolan Liu, Bin Yang, Jianming Liu, Lintao Xian, Xiaohong Jiang, and Tarik Taleb

***Abstract*—This paper investigates sum-rate maximization while achieving seamless coverage with the minimum number of UAVs in a device-to-device (D2D)-enabled unmanned aerial vehicle (UAV) network. Toward this end, we formulate it as a nonlinear and nonconvex optimization problem, and then propose a Max-Rate Min-Number (MRMN) scheme to solve this optimization problem. Firstly, we derive UAV's coverage radius which can depict the maximum coverage for user equipments, and then implement the optimal deployment for UAV swarm by exploiting the disk covering theory. Furthermore, we apply the coalitional game theory to design the cooperative strategy between UAV swarm and ground equipments. Finally, a coalition formation algorithm is presented for achieving maximum system sum-rate while reducing the number of UAVs under seamless coverage constraint. Extensive simulation results are provided to validate the effectiveness of our proposed MRMN scheme, and also illustrate that the scheme can improve the system sum-rate and reduce the number of deployed UAVs. Meanwhile, we further conduct a performance comparison between our scheme and the existing benchmark schemes.**

***Index Terms*—IoT network, UAV technology, D2D communication, seamless coverage, sum-rate.**

I. Introduction

Destructive natural disasters like earthquake, flood and tsunami can cause great loss of human life and infrastructure [1]. It is crucial to conduct rapid emergency response and recovery in the disaster areas. However, people in the area are usually unable to communicate with the outside world, which poses great difficulties for disaster relief. Therefore, deploying Internet of Things (IoT) networks are of significant importance for emergency communications. Since Unmanned Aerial Vehicles (UAVs) have many advantages such as precise flight control, flexible deployment and quick response [2], it is very attractive to construct UAV airborne networks to provide communication services for user equipments (UEs) in disaster areas. In UAV networks, frequent data transmissions between UEs and UAVs can consume a large amount of energy resources of UAVs. To conserve limited energy resources of UAVs and extend their service time for user equipments, a promising method is to utilize device-to-device (D2D) communications to achieve direct communications between nearby devices without the need of forwarding data through UAVs [3]. D2D communications can offload data from UAVs, improve data rate, and reduce transmission delay. By fully taking the advantages of D2D communications and UAVs, D2D-enabled UAV networks [4] are proposed to support various applications like emergency communications. Such networks have attracted much interest from both academia and industry.

Existing works have investigated cellular-connected UAV networks without the assistance of D2D communication, and D2D-enabled cellular networks without the assistance of UAV technology (Please refer to Related Works). Notice that these works focus on cellular networks, which are different from emergence communication scenarios without cellular infrastructures in disaster areas. Some initial works have been devoted to D2D-enabled UAV networks without the support of cellular communication [5]–[11]. Specifically, a sparse convolutional neural network and a deep reinforcement learning model were developed to optimize the data rate and latency performances of such networks in [5] and [6]. In [7], UAV swarm served as either relay devices or flying base stations (BSs) to improve throughput performance. The works in [8] and [9] investigated energy-efficient resource allocation problem in D2D-enabled UAV networks by jointly optimizing power control, UAV location and channel allocation. In natural disaster scenarios, the authors in [10] and [11] studied the IoT coverage problem, where a UAV serves as a flying BS to provide emergency communication, and UEs cooperate to construct D2D links to extend UAV coverage, aiming to achieve the performance improvement on the resource utilization and network throughput.

Note that these works in [5]–[11] employ both UAV and D2D communication technologies to enhance system performances. However, the problem of sum-rate maximization while achieving seamless coverage for the D2D-enabled UAV networks have not been comprehensively studied in disaster scenarios. In particular, seamless coverage of disaster areas is of fundamental importance to provide communication services for each user waiting for rescue. The data transmission rate in the networks is also another vital concern so as to provide timely assistance to users. Therefore, we investigate sum-

This work was supported by National Natural Science Foundation of China Grant 62372076, Natural Science Foundation of Anhui Province Grant KJ2021ZD0128, Anhui Talent Project Grant DTR2023051, Anhui Department of Human Resources and Social Security Grant 2020LCX020, and Anhui Education Department Grant gxyq2020056. This work was also conducted at ICTFICIAL Oy, Finland, and supported in part by the European Union's HE research and innovation program HORIZON-JUSNS-2023 under the 6G-Path project Grant 101139172. (Corresponding authors: Bin Yang, Jianming Liu)

X. Liu is with School of Basic Medicine, Shandong Second Medical University, Weifang, Shandong, China. E-mail: lxlchzu@126.com.

B. Yang is with School of Computer and Information Engineering, Chuzhou University, Chuzhou, Anhui, China. E-mail: yangbinchi@gmail.com.

J. Liu is with School of Basic Medicine, Shandong Second Medical University, Weifang, Shandong, China. E-mail: dwfljm@126.com.

L. Xian is with School of Basic Medicine, Shandong Second Medical University, Weifang, Shandong, China. E-mail: xianlintao@qq.com.

X. Jiang is with the School of Systems Information Science, Future University Hakodate, Hakodate, Japan. E-mail: jiang@fun.ac.jp.

T. Taleb is with the Faculty of Electrical Engineering and Information Technology, Ruhr University Bochum, Bochum, Germany. E-mail: tarik.taleb@rub.de.

rate maximization while achieving seamless coverage with the minimum number of UAVs in a D2D-enabled UAV network, where a swarm of UAVs is deployed as aerial BSs to provide wireless services for ground users, and UEs cooperate with each other to conduct D2D communications for direct data transmissions.

To address the above issues, we formulate it as a nonlinear and noncovex optimization problem, and further propose a Max-Rate Min-Number (MRMN) scheme to solve this optimization problem, which includes two stages, namely, UAV deployment and D2D cooperative strategy construction. The former one means how to achieve seamless coverage of disaster areas by deploying the minimum number of UAVs, while for the latter one, one basic issue is how to improve the data transmission rate performance through establishing a cooperative strategy between ground devices and UAVs. The main contributions of this paper are summarized as follows.

- We formulate sum-rate maximization as a nonlinear and noncovex optimization problem with the constraint of seamless coverage. We further propose a MRMN scheme to solve this optimization problem.
- Under such a scheme, we derive UAV's coverage radius associated with altitude of UAV, transmitted power of device and threshold of signal strength, which can depict the maximum coverage for user devices. Based on disk covering theory, we propose an efficient deployment method to determine the location and the number of UAVs achieving seamless coverage in the disaster area.
- We apply the coalitional game theory to design the cooperative strategy between UAV swarm and ground equipments. A coalition formation algorithm is proposed to maximize system sum-rate, while reducing the number of UAVs with the constraint of seamless coverage.
- Extensive simulation results are provided to validate the effectiveness of our proposed MRMN scheme, and also illustrate that the scheme can improve the system sum-rate and reduce the number of deployed UAVs. Meanwhile, we further conduct a performance comparison between our scheme and the existing benchmark schemes.

The remainder of this paper is organized as follows. Section II summarizes related works. The system model and the optimization problem are described in Section III. Section IV implements the deployment for UAV swarm and accomplishes D2D cooperative strategy construction. The experimental results are illustrated in Section V. Section VI concludes this paper.

II. Related Works

A. Cellular-connected UAV Networks without the Assistance of D2D Communication

The problem of three dimensional deployment of UAV swarm was investigated in UAV-assisted IoT networks [12], [13], where the authors in [12] designed a decentralized control strategy to improve the channel capacity of such system, and the authors in [13] provided both scheduling policies (e.g., a near-first policy and a far-first policy) to maximize sum-throughput. To enhance transmission performance such as energy efficiency and data rate of cellular-connected UAV networks, Li et al. [14] executed multi-objective slap swarm algorithm to formulate collaborative beamforming-based data harvesting and dissemination. Gao et al. [15] utilized the Leader-Follower topology model to design particle swarm optimization algorithm. Yang et al. [16] presented an iterative algorithm based on mmWave 3D directional antenna array model to solve the formulated performance optimization problem in terms of fairness, rate performance and their tradeoff.

Considering secure communication in cellular-connected UAV networks, the work in [17] proposed a deep learning-based UAV monitoring and tracking system, the work in [18] studied the covert communication issue for such network scenarios, and the work in [19] investigated mode selection and cooperative jamming for covert communication. Numerical results demonstrated a good network performance for the works in [17]–[19] in terms of covert capacity and detection error probability. To alleviate the task offloading burdens of mobile-edge computing, Li et al. [20] formulated a joint trajectory, energy and placement of UAV swarm as the three coupled multiagent stochastic games, and proposed a triple-learner-based reinforcement learning approach to maximize the long-term energy efficiency. Similarly, Shi et al. [21] constructed two-timescale resource management framework to strike the balance between task rerouting and service migration, and further developed two algorithms, i.e., the algorithm with Lyapunov method and the algorithm integrating Lagrange dual techniques and randomized rounding to control service delay and energy consumption.

B. D2D-enabled Cellular Networks without the Assistance of UAV Technology

There are a few works concentrating on the performance enhancement study for D2D-enabled cellular networks. The works in [22], [23] investigated the interference problem for D2D communication underlaid cellular networks, and then achieved sum-rate and fairness maximization by designing a deep reinforcement learning scheme. Apart from the performance such as sum-rate and fairness, the authors in work [24] presented a coverage analysis and interference-aware scheme to achieve coverage expansion and network throughput improvement. Considering natural disaster scenarios, UEs in [25] cooperated to construct multi-hop D2D links for extending the coverage of IoT emergency networks. Experimental results demonstrated the better performance on success probability. The issue of privacy protection in D2D communication underlaid cellular networks was studied by [26], [27], where the authors in [26] investigated the secrecy rate and the average covert rate of covert communications, and the authors in [27] formulated the covert rate of covert communications under both modes namely the full-duplex and half-duplex modes. Additionally, Yi et al. [28] investigated social-aware D2D content sharing and proactive caching, and designed the incentive mechanism integrating resource management to maximize the social welfare.

Different from the above works, we integrate D2D cooperation into UAV networks without the support of cellular

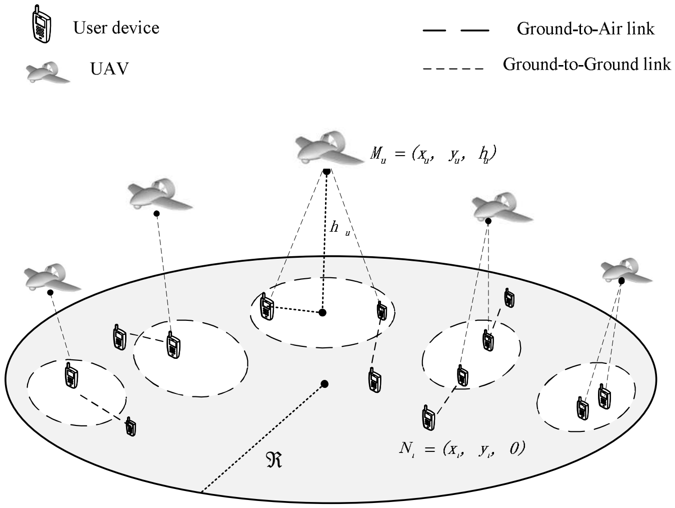


Fig. 1. Illustration of the D2D-enabled UAV airborne network structure.

communication, and investigate the fundamental issues of network performance, namely seamless coverage and sum-rate in such networks, aiming to maximize system sum-rate while achieving seamless coverage with the minimum number of UAVs. As a response, we make the deployment of UAV swarm by exploiting disk covering theory, and then apply the coalitional game theory to design the coalition formation algorithm for constructing D2D cooperative strategy.

III. System Model

A. Network Model

As depicted in Fig. 1, we focus on a round post-disaster area $\mathcal{D} \subset \mathbb{R}$ [29] with radius $\Re$, in which the BSs have been destroyed due to earthquake, flood, etc. Therefore, the trapped users cannot establish communication links with the ground BSs. In this area, a set of wireless users, labelled as $\mathcal{N} = \{1, 2, ..., N\}$, and mounted with wireless equipments, are independently deployed according to an arbitrary spatial distribution. In addition, a swarm of UAVs, denoted by $\mathcal{M} = \{1, 2, ..., M\}$, are dispatched to act as the aerial BSs to provide communication services for ground users. We assume that all UAVs are homogeneous and symmetric having the same flight altitude and equal coverage radius. Besides, each UAV is equipped with a rechargeable battery and can serve the users within a circle area. Let $\mathcal{M}_u = (x_u, y_u, h_u)$ be the three-dimensional (3D) coordinate of each UAV $u \subset \mathcal{M}$, and $\mathcal{N}_i = (x_i, y_i, 0)$ be 3D coordinate of ground user $i \subset \mathcal{N}$.

We consider an uplink network scenario, where the UAV allocates the resource to user devices from the set $\mathcal{N}$ by adopting orthogonal frequency division multiplexing (OFDM) technique [30], and then the user devices utilize the allocated individual frequency bands to transmit message. Without loss of generality, we assume that the available bandwidth and the transmitted power are sufficient to satisfy communication requirements of user devices. And also all user devices and the UAVs are equipped with omni-directional antennas, so that they can achieve information delivery and reception in highly mobile environments.

Under the service domain of the UAVs, the nearby devices can establish D2D communications to improve data rate and reduce transmission latency. It is notable that there are two modes [31] to formulate cooperative behaviors among user devices, i.e., the full-duplex and half-duplex mode. As for the half-duplex mode, it can avoid the negative effect of self-interference, however, it may waste the spectrum resources due to the different receiving and forwarding channel at the user device. Under the full-duplex mode, the user device can simultaneously receive and forward message on the same channel. Such a mode, although improving the availability of spectrum resources, can suffer from self-interference. Thus, we apply the half-duplex mode [32] to formulate cooperative behaviors among user devices, where the user devices may either receive data from the cooperators or transmit data to the UAVs. In the future study, we will take the advantages and disadvantage of two modes into consideration, and then explore a joint full-duplex and half-duplex mode that flexibly switches between both modes.

Currently, two classic relaying strategies [33] are used for formulating transmission behaviors of cooperative devices, i.e., decode-and-forward (DF) and amplify-and-forward (AF) protocol. In the former protocol, the relay decodes, re-modulates and retransmits the received signal, which improve the achievable rate of the delivery data on one hand and raise the complexity of data processing on the other hand. While for the latter protocol, the relay simply amplifies and retransmits the signal without decoding, which can lead to the enhancement of signal strength and the latency of data transmission. Consider our referred disaster relief scenarios, the latency and rate of delivery message are the primary two factors. Since DF protocol outperforms AF protocol in terms of the latency and rate of delivery message, and thus we exploit DF protocol [34] to formulate transmission behaviors of cooperative devices, where the cooperative devices can assist other user equipments to deliver data after completing their own data uploading.

B. Communication Model

In D2D-enabled UAV networks, there needs to construct two kinds of communication links, i.e., ground-to-air link and ground-to-ground (D2D) link. The former one corresponds to that user devices can directly upload data to the UAVs. The latter one represents that user devices in proximity can establish cooperative relationship to deliver data. Next, we briefly describe the two kinds of links, respectively.

Ground-to-air link: The UAV sends a frame regularly to search for ground equipments. If the ground equipment receives this frame, it will return a confirmation frame, which contains its own Ethernet/MAC address. A collision handling protocol is adopted to resolve multiple ACKs accepted by the UAVs. After receiving all confirmation frames, the UAVs will implement the bandwidth configurations according to channel quality of ground equipments. Finally, the ground-to-air communication links will be established between the UAVs and ground equipments.

Ground-to-ground link: For constructing ground-to-ground communication links, the peer discovery [35] is performed, in which the device periodically broadcasts a probing beacon containing its own Ethernet/MAC address. If the nearby device receives this probing beacon, it will send feedback message that attaches Ethernet/MAC address. Through this peer discovery, each device can obtain the list of candidate devices. Finally, ground-to-ground communication links will be constructed by cooperative devices.

C. Ground-to-Air Channel Model

Similar to the works [36] and [37], the UAVs can receive three groups of signals from the ground devices containing line-of-sight (LoS) signals, non-line-of-sight (NLoS) signals, and multipath fading signals. Mentioned by [36], the probability of the multipath fading is significantly lower compared to the LoS and NLoS groups, and thus the multipath fading signals can be neglected in our referred work. In addition, due to the ground devices' mobility, the shadowing impact and the signal reflection from obstacles can be weakened. Therefore, we only model ground-to-air channel of LoS components [37], and then the path loss model $L^s_{i,u}$ from user device i to UAV u can be expressed as

$$L^s_{i,u} = \hbar^s |d_{i,u}|^{-\alpha_s}, \tag{1}$$

where $\hbar^s$ is the channel coefficient of ground-to-air uplink, $d_{i,u}$ is the distance between UAV u and user device i, and α_s is the path loss exponent for the user-UAV link.

Considering the path loss for LoS connections, the power $P^s_{i,u}$ received by UAV u from user device i is calculated as

$$P^s_{i,u} = P^t \hbar^s |d_{i,u}|^{-\alpha_s}, \tag{2}$$

where P^t denotes the transmitted power of ground device i, which is assumed to be fixed and equal for all ground devices.

Finally, the signal to interference plus noise ratio (SINR) expression of UAV u that can connect to user device i is given as:

$$\gamma^s_{iu} = \frac{P^s_{i,u}}{N^s + I^d_u} = \frac{P^t \hbar^s |d_{i,u}|^{-\alpha_s}}{N^s + I^d_u}, \tag{3}$$

where N^s is the noise power in ground-to-air channel mode, I^d_u are the total interferences from the D2D transmitters. As user devices utilize the assigned individual frequency bands to deliver message, and hence we assume that they do not interfere with one another, i.e., $I^d_u = 0$.

D. Ground-to-Ground Channel Model

Under D2D channel model, we consider that device i transmits data to the UAV by device $j \in \mathcal{N}$. According to the free space propagation loss model [38], the path loss model $L^d_{i,j}$ received by D2D receiver j is written as

$$L^d_{i,j} = \hbar^d |d_{i,j}|^{-\alpha_d}, \tag{4}$$

where α_d is the path loss exponent between cooperative devices, $d_{i,j}$ is the distance between device i and j, and $\hbar^d$ is the channel coefficient of D2D link.

With the path loss model $L^d_{i,j}$, we then calculate the power P^d_{ij} received by relay device j on the link $i \to j$, which is posed as

$$P^d_{ij} = P^t L^d_{i,j} = P^t \hbar^d |d_{i,j}|^{-\alpha_d}. \tag{5}$$

Given the received power P^d_{ij}, the SINR expression for D2D receiver j can be formulated as follows

$$\gamma^d_{ij} = \frac{P^d_{ij}}{N^d + I^d_j + I^s_j} = \frac{P^t \hbar^d |d_{i,j}|^{-\alpha_d}}{N^d + I^d_j + I^s_j}, \tag{6}$$

where N^d is the thermal noise density level among D2D links, I^d_j and I^s_j are the interferences from the other D2D transmitters and direct transmitters, respectively. As the user devices utilize orthogonal frequency bands to deliver message, and hence we assume that they do not interfere with one another, i.e., $I^d_j = I^s_j = 0$.

E. Problem Formulation

In our work, we assume that the ground equipments deliver data to the UAVs by adopting both modes, namely direct delivery (transmission) mode and undirect delivery (transmission) mode. The former one represents that the data is directly delivered by the device to the UAV, while the latter one means that the data is relayed to the UAV by other devices. Thereinafter, we compute data rate of each device under the above two delivery modes.

For direct delivery mode, we assume that device i delivers its data to the UAV u, and then calculate data rate R^s_{iu} of device $i \in \mathcal{N}$, which is determined by Shannon's capacity formula [39] as follows

$$R^s_{iu} = B_i \log_2(1 + \gamma^s_{iu}) = B_i \log_2(1 + \frac{P^t \hbar^s |d_{i,u}|^{-\alpha_s}}{N^s}), \tag{7}$$

where B_i is the orthogonal resources of device i, which is allocated by the UAVs according to OFDM technique.

Considering undirect delivery mode, we assume that device i delivers data to the UAV u via relay device $j \in \mathcal{N}$. Similar to the data rate acquisition process in direct delivery mode, we first calculate the data rate R^d_{ij} of device i on the link between device i and j, say $i \to j$, and then calculate the data rate R^s_{ju} of device j on link $j \to u$. The expression of data rate of device i from link $i \to j \to u$, denoted by R^{ds}_{iju} , is finally given by

$$\begin{aligned} &R^{ds}_{iju} = R^d_{ij} + R^s_{ju} \\ &= B_i \log_2(1 + \gamma^d_{ij}) + B_j \log_2(1 + \gamma^s_{ju}) \\ &= B_i \log_2(1 + \frac{P^t \hbar^d |d_{i,j}|^{-\alpha_d}}{N^d}) + B_j \log_2(1 + \frac{P^t \hbar^s |d_{j,u}|^{-\alpha_s}}{N^s}). \end{aligned} \tag{8}$$

To calculate the system sum-rate of all user devices, we first classify the devices with attending data delivery into three patterns: source device, relay device and cooperative device. The source devices upload their own generated data to the UAVs by direct delivery mode. The relay devices are charge of receiving data from devices in the vicinity, and then relaying received data to the UAVs. All remaining ones are regarded as cooperative devices, which deliver data to the UAVs through relay devices. Then, we formulate the matrixes $\mathbf{a}= [a_{iu}]_{N \times M}$, $\mathbf{b}= [b_{ju}]_{N \times M}$, and $\mathbf{c}= [c_{ij}]_{N \times N}$ to represent link states between source devices and the UAVs, and between relay devices and the UAVs, and between relay devices and cooperative devices respectively, where $a_{iu}, b_{ju}, c_{ij} \in \{0, 1\}$.

Specifically, $a_{iu}=1$ implies that source device i is associated with UAV u, otherwise $a_{iu}=0$. $b_{ju}=1$ means that relay device j establishes a link with UAV u, otherwise $b_{ju}=0$. $c_{ij}=1$ indicates that cooperative device i builds D2D communication with relay device j, otherwise $c_{ij}=0$. Note that $\sum_{i=1}^{N}\sum_{j=1}^{N}c_{ij}=\sum_{j=1}^{N}\sum_{i=1}^{N}c_{ji}$. With these denotations, we formulate the utility function of the system sum-rate $\mathcal{R}_{sum}$, which consists of three parts, i.e., the data rate R_{iu}^{s} of source device $i\in\mathcal{N}$ with $u\in\mathcal{M}$, the data rate R_{ju}^{s} of relay device $j\in\mathcal{N}$ with $u\in\mathcal{M}$, and the data rate R_{ij}^{d} of cooperative device $i\in\mathcal{N}$ with $j\in\mathcal{N}$, and is described as follows

$$\begin{aligned}\mathcal{R}_{sum}=&\sum_{i=1}^{N}\sum_{u=1}^{M}a_{iu}R_{iu}^{s}+\sum_{i=1}^{N}\sum_{j=1}^{N}c_{ij}R_{ij}^{d}\\&+\sum_{j=1}^{N}(\sum_{i=1}^{N}c_{ij}\times\sum_{u=1}^{M}b_{ju})R_{ju}^{s}.\end{aligned}\tag{9}$$

We aim to maximize the system sum-rate while at the same time achieving seamless coverage with the minimum number of UAVs. Thus, apart from the system sum-rate calculation, we need to derive the expression of the number of required UAVs, which is denoted as

$$\mathcal{N}um=\sum_{u=1}^{M}(\sum_{i=1}^{N}a_{iu}\vee\sum_{j=1}^{N}b_{ju}).\tag{10}$$

Then, we formulate the following optimization problem, which is presented as

$$\max(\mathcal{R}_{\rm sum})\tag{11}$$

$$\begin{aligned}\text{s.t. }&\mathrm{C}_1: a_{iu},b_{ju},c_{ij}\in\{0,1\},\forall i,j\in\mathcal{N},\forall u\in\mathcal{M},\\&\mathrm{C}_2:\textstyle\sum_{u=1}^{M}a_{iu}\le 1,\forall i\in\mathcal{N},\\&\mathrm{C}_3:\textstyle\sum_{u=1}^{M}b_{ju}\le 1,\forall j\in\mathcal{N},\\&\mathrm{C}_4:\textstyle\sum_{j=1}^{N}c_{ij}\le 1,\forall i\in\mathcal{N},\\&\mathrm{C}_5:\gamma_{iu}^{s}\ge\gamma_{th},\forall i\in\mathcal{N},\forall u\in\mathcal{M},\\&\mathrm{C}_6:\textstyle\sum_{u=1}^{M}(\sum_{i=1}^{N}a_{iu}\vee\sum_{j=1}^{N}b_{ju})\le M,\\&\mathrm{C}_7:\textstyle\sum_{i=1}^{N}\sum_{u=1}^{M}a_{iu}+\sum_{i=1}^{N}\sum_{j=1}^{N}c_{ij}=N,\end{aligned}$$

where C_1 is the Boolean constraint for different link relationship. C_2 and C_3 indicate that a source device or a relay device can be served by at most one UAV. Through C_4, a cooperative device establishes D2D communication with at most a relay device. C_5 provides the minimum SINR threshold γ_{th} for establishing communication link between UAVs and devices, which is defined in advance. C_6 and C_7 guarantee the requirement of seamless coverage with the minimum number of UAVs. The optimization problem (11) is nonconvex and nonlinear due to constraints C_1-C_7, and thus employing traditional optimal methods are intractable to solve it efficiently [40].

IV. The MRMN scheme

In the section, we propose a MRMN scheme to solve the formulated optimization problem, which includes two stages, namely, UAV deployment and D2D cooperative strategy construction. In the first stage, we utilize the disk covering method to make the optimal deployment for UAV swarm, and a coalition formation algorithm based on coalitional game theory is presented to implement cooperative strategy between UAV swarm and ground equipments in the second stage.

TABLE I
COVERAGE RADIUS AND NUMBER OF DEPLOYED UAVS.

Coverage radius of UAV	Number of deployed UAVs
$\Re$	M=1,2
$\frac{\sqrt{3}}{2}\Re$	M=3
$\frac{\sqrt{2}}{2}\Re$	M=4
$0.61\Re$	M=5
$0.556\Re$	M=6
$0.5\Re$	M=7
$0.437\Re$	M=8
$0.422\Re$	M=9
$0.398\Re$	M=10
$0.38\Re$	M=11
$0.361\Re$	M=12

A. UAV Deployment

By adjusting the system parameters such as altitude of UAV, and transmitted power of device, we determinate the maximum coverage radius of UAV on the ground, and then exploit disk covering method to make the deployment of UAV swarm for covering the entire target area, where the number of deployed UAVs and the location of stop points are derived.

1) Coverage Radius Calculation: In our model, we assume the UAV builds a connection with the ground devices in a limited region. To derive the region range, the UAV sends a test signal to obtain the uplink signal strength of the ground devices. If the signal strength is greater than a given threshold γ_{th}, which is defined in advance, the connections can be established between the ground equipments and the UAVs. Thus, if a device i is covered by UAV u, we have

$$\gamma_{iu}^{s}=\frac{P^t\hbar^s|d_{i,u}|^{-\alpha_s}}{N^s}\ge\gamma_{th},\tag{12}$$

where $|d_{i,u}|=\sqrt{h_u^2+r_u^2}$ represents the distance between device i and UAV u. r_u is the coverage radius of UAV u, and h_u is the altitude of UAV u. Obviously, to find the maximum coverage radius of UAV u, we should have $\gamma_{iu}^{s}=\gamma_{th}$. Thus the following relationship holds

$$r_u=\sqrt{(\frac{P^t\hbar^s}{\gamma_{th}N^s})^{\frac{2}{\alpha_s}}-h_u^2}.\tag{13}$$

Similarly, with the acquisition of coverage radius r_u, the altitude h_u of UAV u is expressed as

$$h_u=\sqrt{(\frac{P^t\hbar^s}{\gamma_{th}N^s})^{\frac{2}{\alpha_s}}-r_u^2}.\tag{14}$$

Furthermore, when the altitude h_u and coverage radius r_u of UAV u are confirmed, the expression of transmitted power P^t is derived by

$$P^t=\frac{\gamma_{th}N^s}{\hbar^s}(h_u^2+r_u^2)^{\frac{\alpha_s}{2}}.\tag{15}$$

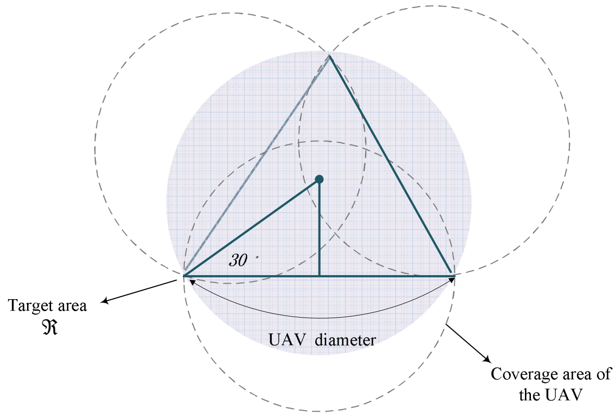


Fig. 2. Illustrative example for describing UAV deployment strategy.

Obviously, the coverage radius of UAV is dependent on the UAV's altitude and the device's transmitted power. According to the formula (13), (14), and (15), we can find that enlarging device's transmitted power always enhance the UAV coverage range. Additionally, we also see that UAV' coverage range decreases as its altitude increases.

2) Disk Covering Strategy: To provide the entire coverage of target area, we need to determinate the number of UAVs and the location of stop points. First, we utilize disk covering method [41] to obtain the number of deployed UAVs. In the disk covering problem, given a unit round area, we can find some smaller disks with the equal radius to cover the unit area completely. That is to say, for a given radius of small disks, the number of small disks to cover unit area is found. Thereby, utilizing the disk covering analysis, we can obtain the minimum number of deployed UAVs for the given coverage radius of the UAV, which is shown in Table I.

In general, the disk covering problem is intractable in a bounded region [42], and thus it is difficult to make the optimal deployment of UAV swarm. Then a specific deployment strategy requires to be provided. Fig.2 gives an illustrative example to make the description of the specific deployment strategy. In this figure, the radius of the disk is regarded as the coverage radius of UAV, and the center of the disk is seen as the stop location of the UAV. Consider a round target area with radius $\Re$ and UAV number $M = 3$, if it is completely covered by three equal disks, the following three requirements need to be satisfied. First, the target area can pass through all outer intersection points from any both disks. Second, the straight line connecting any two intersection point is the diameter of the disk. Finally, the formed three lines can construct the inscribed triangle of round area. Under the circumstances, it corresponds to the efficient placement of UAV swarm and the location of stop points is confirmed.

After finding the number of deployed UAVs and the location of stop points, we can reduce transmitted power of ground devices such that the coverage radius decreases to the minimum required radius, which ensures that less coverage overlap occurs. In this way, the transmitted power of ground devices can be minimized. Therefore, the minimum transmitted power leads to the minimum coverage radius of UAV.

B. D2D Cooperative Strategy

We first formulate cooperative communication among UAV swarms and ground equipments as a coalitional game, and then present coalition formation algorithm to implement the solution for the formulated coalitional game. Finally, the performance of coalition formation algorithm is investigated from the perspective of computational complexity.

1) Coalitional game formulation: Due to the fact that the number of cooperative links grows exponentially with the number of UAVs and devices, it is difficult to construct the optimal cooperative strategy for a large-scale deployment [43]. In particular, this problem is modeled as a coalitional game with the characteristic form. For the sake of completeness, we first give a brief definition to the coalitional game with the characteristic form [44] that will be needed in our analysis.

Definition 1: The coalitional game with the characteristic form $(\mathcal{N}, \mathcal{V})$ consists of a finite of players $\mathcal{N}$ and the coalition value $\mathcal{V}$ that associates with every nonempty coalition $S \subseteq \mathcal{N}$. For each coalition S, $\mathcal{V}(S)$ depends on the feasible cooperation among the players $i \in S$, without relationship of other devices out of coalition S.

In our concerned coalitional game, the players $\mathcal{N}$ correspond to all user equipments. To guarantee the maximum system sum-rate, each device $i \in \mathcal{N}$ can select the nearby devices $\mathcal{N}_i^d$ or the UAVs $\mathcal{N}_i^s$ within a given signal strength to construct a cooperative link S which can provide the maximum individual data rate, and thus device i joins the link S with the consideration of its own individual payoff. That is to say, the value $\mathcal{V}(S)$ of a coalition S is no longer the sum profits contributed by the entire coalition S, but a set of payoff vectors $\mathbf{x}(S)$ of all players in coalition S with $\mathcal{V}(S) \subseteq \mathbb{R}^{|S|}$, which cannot be transferred arbitrarily among players in coalition S, and thus the characteristic function is considered as a non-transferable utility (NTU).

Considering the basic concepts of the coalitional game with the characteristic form and the non-transferable utility, we model the optimization problem of cooperative communication among UAV swarms and ground equipments as a NTU coalitional game with characteristic form, which is represented by a tuple $(\mathcal{N}, \mathcal{X}_{\mathcal{N}}, \mathcal{V}, \succ_i)$.

- *Player*. The game players $\mathcal{N}$ consist of all user equipments.
- *Cooperative strategy*. The cooperative strategies $\mathcal{X}_{\mathcal{N}} = \{\mathcal{N}_i^d \cup \mathcal{N}_i^s : \forall i \in \mathcal{N}\}$ represents the possible candidate devices $\mathcal{N}_i^d$ and candidate UAVs $\mathcal{N}_i^s$ of device $i \in \mathcal{N}$.
- *Coalition value*. The value $\mathcal{V}(S)$ of a coalition S consists of device's payoff vectors $\mathbf{x}(S)$, where the payoff $x_i(S)$ of device $i \in S$ is measured as individual data rate from device i to the UAV-BS, which is determined as direct data rate R_{iu}^s by (7) or undirect data rate R_{iju}^{ds} by (8).
- *Preference order*. The preference order $\succ_i$ is defined as a complete, reflexive, and transitive binary relation over the coalitions that device i joins. If $S_1 \succ_i S_2$ implies that coalition S_1 can improve the individual payoff of device i compared to coalition S_2.

Our NTU coalitional game with characteristic form pertains to two mathematical properties. One is the superadditivity [45]

TABLE II
DESCRIPTION USED IN COALITIONAL FORMATION ALGORITHM.

Symbol	Denotation
$\mathcal{D}$	Circular target area
$\Re$	Radius of target area
$\mathcal{M} = \{1, 2, ..., M\}$	Set of UAV swarm
$\mathcal{M}_u = (x_u, y_u, h_u)$	3D coordinate of UAV u
$\mathcal{N} = \{1, 2, ..., N\}$	Set of ground equipments
$\mathcal{N}_i = (x_i, y_i, 0)$	3D coordinate of user device i
N^s	Noise power in ground-to-air channel
P^t	Transmitted power of user device
$\hbar^d$	Channel coefficient of D2D link
α_d	Path loss exponent for D2D link
N^d	Noise power in ground-to-ground channel
h_u	Flight altitude of UAV u
r_u	Coverage radius of UAV u
α_s	Path loss exponent for user-UAV link
$\hbar^s$	Channel coefficient of ground-to-air uplink
ω	D2D communication range
$\mathcal{N}_j^d$	Candidate devices of device i
$\mathcal{N}_i^s$	Candidate UAVs of device i
d_{ij}	Distance between device i and j
R_{ij}^d	D2D data rate of device i
R_{iu}^s	Direct data rate of device i
R_{iju}^{ds}	Undirect data rate of device i
γ_{iu}^s	SINR of device i on link $i \to u$
γ_{th}	The minimum SINR threshold
$\mathcal{N}um$	The number of required UAVs
R_{iu}^{max}	The maximum direct rate of $i \in \mathcal{N}$
R_{iju}^{max}	The maximum undirect rate of $i \in \mathcal{N}$
$\mathcal{R}_{sum}$	The system sum-rate
$\mathbf{a}= [a_{iu}]_{N\times M}$	Link states between source devices and UAVs
$\mathbf{b}= [b_{ju}]_{N\times M}$	Link states between relay devices and UAVs
$\mathbf{c}= [c_{ij}]_{N\times N}$	Link states between relay and cooperative devices
ς	Boolean value

to ensure the formation of the grand coalition, i.e, the coalition of all the players, and the other is core [45] which is directly related to the stability of grand coalition. In the following, we first give a definition of superadditivity.

Definition 2 (Superadditivity): Given any two coalitions $S_1, S_2 \subset \mathcal{N}$ and $S_1 \cap S_2 = \phi$, a NTU coalitional game with characteristic form $(\mathcal{N}, \mathcal{V})$ is said to be superadditive, which must satisfy the following condition.

$$\begin{aligned}\mathcal{V}(S_1 \cup S_2) \supset \{&\mathbf{x}(S_1 \cup S_2) \in \mathbb{R}^{|S_1 \cup S_2|} | \\ &x_i(S_1) \in \mathcal{V}(S_1), x_j(S_2) \in \mathcal{V}(S_2)\}.\end{aligned} \tag{16}$$

Superadditivity implies that cooperation is always beneficial, and the players have an incentive to form the grand coalition. Then we prove that the following theorem holds

Theorem 1: The proposed NTU coalitional game with characteristic form is superadditive.

Proof: Consider two coalitions S_1 and S_2 in IoT network with their corresponding payoff vectors $\mathbf{x}(S_1)$ and $\mathbf{x}(S_2)$. If coalition S_1 and S_2 can form coalition $S_1 \cup S_2$, we can obtain $x_i(S_1 \cup S_2)$ for $\forall i \in S_1$ and $x_j(S_1 \cup S_2)$ for $\forall j \in S_2$ according to (7) or (8). Assume that there exist $x_i(S_1 \cup S_2) < x_i(S_1)$ or $x_j(S_1 \cup S_2) < x_j(S_2)$, it is inconsistent with our formulated NTU coalitional game with characteristic form. Therefore, our proposed NTU coalitional game with characteristic form is superadditive.

Due to superadditvity, the grand coalition can form. We then focus on the stability of the grand coalition and define a core of NTU coalitional game with characteristic form, which is analogous to the Nash equilibrium of a noncooperative game.

Algorithm 1 Coalition formation algorithm for D2D-enabled UAV network

Deploy N devices in circular area $\mathcal{D}$ with radius $\Re$;
Initialize α_s, $\hbar^s$, N^s, $\hbar^d$, α_d, N^d, and γ_{th};
Obtain optimal r_u, P^t and h_u according to (13)(14)(15);
Determinate M and $\mathcal{M}_u = (x_u, y_u, h_u), \forall u \in \mathcal{M}$;
Set D2D range ω and $\mathcal{N}_i^s = \emptyset, \mathcal{N}_i^d = \emptyset$ with $i \in \mathcal{N}$;
Initialize $\mathbf{a} = \varnothing$, $\mathbf{b} = \varnothing$, $\mathbf{c} = \varnothing$, and $\varsigma = 0$;
for $i \in \mathcal{N}$ **do**
  for $u \in \mathcal{M}$ **do**
    Calculate SINR γ_{iu}^s according to (3);
    if $\gamma_{iu}^s \geq \gamma_{th}$ **then**
      Add UAV u to set $\mathcal{N}_i^s$;
      Search for maximum R_{iu}^s and set as R_{iu}^{max};
    end if
  end for
  for $j \in \mathcal{N}$ **do**
    Calculate distance d_{ij} between device i and j;
    if $d_{ij} \leq \omega$ **then**
      Add device j to set $\mathcal{N}_i^d$;
      Calculate data rate R_{ij}^d between device i, j;
    end if
    for $u \in \mathcal{N}_j^s$ **do**
      Calculate data rate R_{ju}^s of relay j;
      Search maximum R_{iju}^{ds} and set as R_{iju}^{max}.
    end for
  end for
  if $R_{iu}^{max} \geq R_{iju}^{max}$ **then**
    Set $a_{iu} = 1$;
  else
    Set $b_{ju} = 1$, $c_{ij} = 1$;
  end if
end for
for $u \in \mathcal{M}$ **do**
  for $i \in \mathcal{N}$ **do**
    if $a_{iu} = 1$ or $b_{iu} = 1$ **then**
      Set $\varsigma = 1$, break;
    end if
  end for
  if $\varsigma = 0$ **then**
    Delete an idle UAV u;
  end if
end for
Calculate the system sum-rate $\mathcal{R}_{sum}$ according to (9);
Calculate the number $\mathcal{N}um$ of UAVs according to (10).

Definition 3 (Core): For NTU coalitional game with characteristic form, the core $\mathcal{C}(\mathcal{N}, \mathcal{V})$ is the set of payoff vector $\mathbf{x}(\mathcal{N}) \in \mathcal{V}(\mathcal{N})$, which satisfies the following condition

$$\begin{aligned}\mathcal{C}(\mathcal{N}, \mathcal{V}) = &\{\mathbf{x}(\mathcal{N}) \in \mathcal{V}(\mathcal{N}) | \forall S, \nexists \mathbf{x}(S) \in \mathcal{V}(S), \\ &s.t., x_i(S) > x_i(\mathcal{N}), \forall i \in S)\}.\end{aligned} \tag{17}$$

The core guarantees that no deviation from the grand coalition $\mathcal{N}$ is profitable. Clearly, if we can find a payoff allocation that exists in the core, the formed grand coalition can be stabilized.

Theorem 2: Our formed grand coalition has a nonempty core.

Proof: To maximize the system sum-rate, each device select the most preferred helper which can provide the maximum individual payoff to construct the cooperative link. This implies that we can construct an unique grand coalition since each device has an out-degree of one on one hand, on the other hand, the formed grand coalition provide the best payoff allocation for each device, and no device deviates from the grand coalition and form other coalition instead. As a result, our formed grand coalition has a nonempty core.

2) Coalition Formation Algorithm Design: Based on the NTU coalitional game with characteristic form, we present a coalition formation algorithm to search for the grand coalition formed by user devices and UAV swarm. The basic idea of this algorithm is that we initially deploy enough candidate UAVs within obstacle avoidance area, where 'enough' represents that each device is covered by at least one UAV. By making a comparison between all direct and indirect data rates, each device establishes a cooperative link with the UAV which can satisfy the maximum data rate. Until all devices find the optimal cooperative links, a stable cooperative structure forms. Finally, we delete redundant UAVs that can not build communication relationships with ground devices. The denotations used in this algorithm are listed in Table II.

As shown in Algorithm 1, we first set a circular target area $\mathcal{D}$ with radius $\Re$, and randomly deploy N devices within the target area. After that, we initialize some parameters α_s, $\hbar^s$, N^s, $\hbar^d$, α_d, N^d, and γ_{th}, and obtain maximum coverage radius r_u by adjusting transmitted power P^t of the device and flight altitude h_u of UAV u. Furthermore, we determinate the number and the location of the UAVs by utilizing the disk covering method, and then make a deployment of UAV swarm for the entire target area.

For any device i, we first calculate its SINR γ_{iu}^s with the UAV u according to (3), and then make a comparison of SINR γ_{iu}^s and threshold γ_{th}. Under the condition of $\gamma_{iu}^s \geq \gamma_{th}$, we obtain a list of candidate UAVs $\mathcal{N}_i^s$ of device i, and search for maximum data rate R_{iu}^{max} of direct transmission. According to D2D communication range ω, we then obtain a list of candidate devices $\mathcal{N}_i^d$ of device i, and determinate maximum data rate R_{iju}^{max} of undirect transmission. To establish the optimal cooperative link, device i makes a comparison between R_{iu}^{max} and R_{iju}^{max}. If $R_{iu}^{max} \geq R_{iju}^{max}$, device i directly transmits data to the UAVs, i.e., $a_{iu} = 1$. Otherwise, device i achieves data uploading with the aid of the relay device j, i.e., $b_{ju} = 1$, $c_{ij} = 1$.

After obtaining all possible connections between UAV swarms and user devices, we delete all redundant UAVs from the set $\mathcal{M}$, and then a stable coalitional structure can form. By the formulated links, the ground devices will deliver data to the UAVs. Finally, we obtain the system sum-rate $\mathcal{R}_{sum}$ and the number $\mathcal{N}um$ of UAVs according to (9),(10).

For Algorithm 1, we nextly analyze its computational complexity. Firstly, we initialize the performance parameters and deploy UAV swarm and user devices, and thus the complexity is $O(0)$. To establish the optimal cooperative link, the execution process consists of two parts, i.e., direct and undirect rate calculation. The former operation is executed at most $O(M \times N)$, while the latter one is iterated at most $O(N \times N \times \mathcal{N}_j^s)$ times. Since we consider that less coverage overlap occurs between any two UAVs, and thus $O(N \times N \times \mathcal{N}_j^s)$ converge within $O(N^2)$ iterations theoretically. To delete all redundant UAVs, each UAV needs to make the $O(M \times N)$ attempts. Finally, the computational complexity of our proposed algorithm is at most $O(N^2 + 2MN)$.

TABLE III
SIMULATION PARAMETERS

Description	Parameter	Value
Radius of area ($\mathcal{D}$)	$\Re$	500m
The transmitted power of user device	P^t	$0 \sim 100$mW
The altitude of UAV u	h_u	$0 \sim 1000$m
Path loss exponent for user-UAV link	α_s	3
Path loss exponent for D2D link	α_d	2
SINR threshold value	γ_{th}	$-10 \sim 10$dB
Noise power in ground to air channel	N_s	-174 dbm/Hz
The thermal noise density level of D2D	N_d	-120 dBm/Hz
Carrier frequency	f_c	2GHz
Channel bandwidth	$\mathcal{B}$	10 MHz
Number of user devices	N	$0 \sim 100$
D2D communication range	ω	$0 \sim 200$ m
Channel coefficient of ground-to-air uplink	$\hbar^s$	-50dB
Channel coefficient of D2D link	$\hbar^d$	-30dB
# of Runs	$-$	500

V. PERFORMANCE EVALUATIONS

Extensive simulation results provided by this section evaluate the performance gains that can be achieved by our proposed scheme. Firstly, the evaluating settings are presented. We then determinate the optimal coverage radius of UAV by adjusting system parameters. Furthermore, a sample scenario of D2D cooperative structure is provided. Finally, we compare our simulation results in terms of the system sum-rate and the number of UAVs with the existing schemes.

A. Evaluating Settings

We carry out the simulations in a circular post-disaster area, where user devices are distributed randomly within the coverage of UAV swarms. In Table III, we summarize the values of environmental parameters to analyze the simulation and numerical results. These parameters are set based on typical values from [1] and [36]. In addition, we assume that the locations of all devices fix after deployment, and the default parameter values are set as follows: $P^t = 30mW$, $\omega = 200m$ and $h_u = 300m$ for any UAV u.

To evaluate the efficiency of our proposed Max-Rate Min-Number scheme denoted by MRMN, we compare the performance under our proposed MRMN, with that under the direct data uploading scheme (DDUS) proposed in [46], [47], and the centralized deployment scheme with heuristic method (CDHM) proposed by [48]. Meanwhile, we consider three different resource allocation policies to evaluate our simulation results, namely, Maximum Throughput (MT) [49], Round Robin (RR) [50] and Proportional Fair (PF) [51]. The first case means that resources are allocated in advance to user devices with good channel quality for improving system rate. In the second case, all user devices have the same opportunity

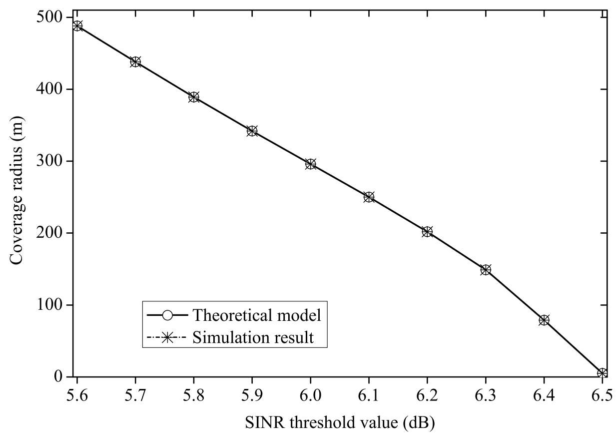


Fig. 3. Coverage radius vs. SINR threshold value.

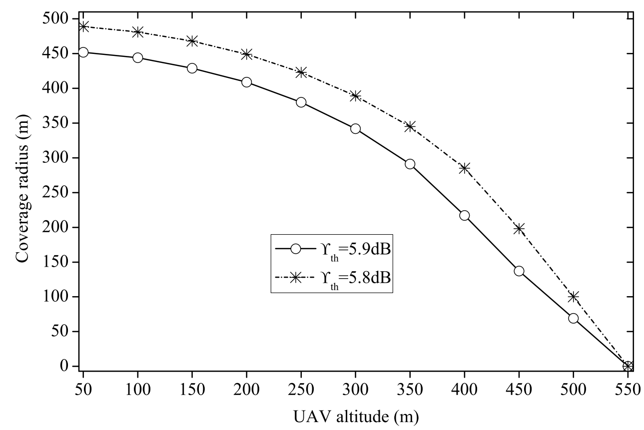


Fig. 4. Coverage radius vs. UAV altitude.

to obtain system resources, so this policy has high fairness. Different from the former two policies, the third case take throughput and fairness into account, which makes full use of the time-frequency characteristics of the channel to schedule user devices with better channel conditions as fairness as possible. Additionally, we set the default resource allocation policy as MT policy.

B. Determination of Optimal Coverage Radius

To derive the optimal coverage radius of UAV, we conduct a series of sensitivity experiments by properly adjusting the various control parameters such as flight altitude, SINR threshold and transmitted power.

Fig.3 summarizes the corresponding theoretical models and simulation results on coverage radius for different SINR thresholds. From Fig.3, we can observe that the theoretical and simulation results for coverage radius match perfectly. Therefore, our theoretical formula can accurately predict the relationship of coverage radius and SINR threshold. Another interesting observation from Fig.3, by increasing SINR threshold values, the coverage radius for UAV will decrease and tend to zero with $\gamma_{th} \to \infty$, which is consistent with our theoretical analysis. This is due to the fact that the UAV reduces its coverage radius to cope with the high SINR value.

Fig.4 shows the UAV coverage radius as a function of UAV altitude for changeable SINR threshold. As expected, coverage radius decreases as the altitude increases. This is because higher altitude can enhance the distance and the path loss between UAVs and devices. In fact, due to a low probability and high shadowing of LoS connections [36], the UAVs can not be deployed at very low altitudes. As a result, we should carefully adjust UAV altitude to obtain the optimal coverage radius of UAV. In our performance evaluation, the feasible altitude of UAV is set as $300m$. Additionally, we also notice that bigger SINR threshold can lead to smaller coverage radius.

Fig.5 illustrates the impact of the transmitted power of device on UAV's coverage radius for different SINR threshold values. Note that, in Fig.5, UAV's coverage radius will become bigger with the increment of the transmitted power, which can be explained as below. The transmitted power of device that we consider is relatively small, which can not cause interference on the uplink. Without interference, a higher power of user device creates bigger coverage radius under the condition of fixed SINR threshold, which result is proved by (13). In reality, as the transmitted power becomes more and more bigger, higher interference can be produced, thereby reducing SINR value on the uplink [52]. As a result, the UAVs will reduce the coverage radius to cope with SINR threshold. In our performance evaluation, $P^t = 30mW$ is regarded as the optimal transmitted power. We can also see from Fig.5 that, by reducing the SINR threshold, the UAV can provide a larger coverage radius. For instance, under the fixed $P^t = 30mW$, reducing γ_{th} from $6dB$ to $5.9dB$ increases UAV coverage radius from $296m$ to $343m$.

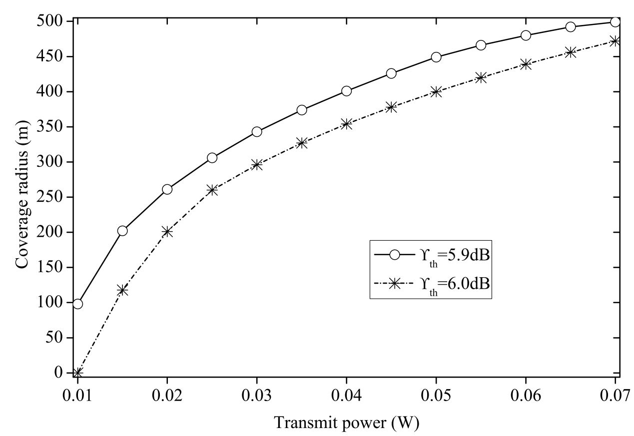


Fig. 5. Coverage radius vs. Transmitted power.

C. Performance Gain by D2D and UAV Cooperation

We show a sample scenario of cooperative structure constructed by user devices and UAV swarms, which arms to analyze cooperative link formation process, and at the same time compare the individual rate under the direct and undirect transmission mode.

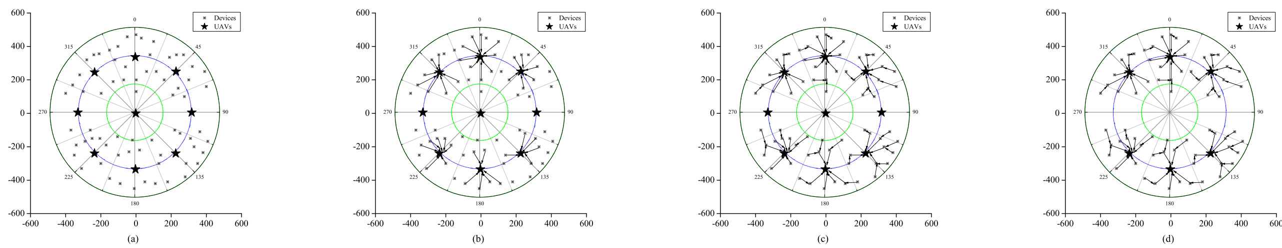


Fig. 6. Cooperative link formation process (N = 60, M = 9).

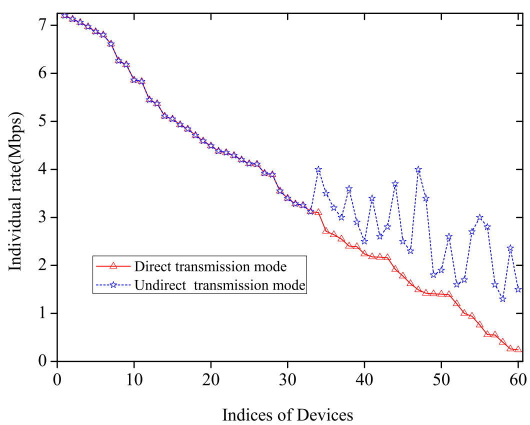


Fig. 7. Individual rate under direct and undirect transmission mode.

Fig.6 focuses on the iteration process and the final cooperative results when we apply the coalition formation algorithm, in which user devices and UAVs are labelled as solid circle, solid star, respectively. Fig.6(a) describes a random distribution of 60 initial devices and 9 candidate UAVs, and UAV coverage radius is set to $200m$.

As depicted in Fig.6(b), partial devices upload data to the UAVs according to the direct transmission mode, where each formed line is connected by arrow line. The dynamic process of D2D cooperation is shown in Fig.6(c), where the data is relayed to the UAVs by the undirect transmission mode. After multiple iterations, the algorithm stops and consequently outputs the final cooperative results, as displayed in Fig.6(d). In this figure, redundant UAVs have been deleted, and every device is associated with a UAV or cooperator.

For each device in Fig.6, the individual rate is derived according to the direct and undirect transmission mode in Fig.7. We can observe that the individual rate is maximum under the undirect transmission mode. This is due to the fact that the undirect transmission mode can make more devices attend cooperative link construction for improving individual data rate.

D. Comparison with Different Resource Allocation

As shown in Fig.8, we consider three different resource allocation policies (i.e., MT, RR, and PF) to evaluate our performance results in terms of the system sum-rate, the number of required UAVs and the number of cooperative devices. In the performance comparison, the coverage radius of UAV is set as $150m$.

Fig.8(a) displays how the system sum-rate varies with the number of devices for three different resource allocation policies. One can observe from Fig.8, the sum-rate increases with the increase of number of devices. Such behaviors can be explained as below, with the increase of the number of user devices, the total resource keeps unchanged, while more devices are inclined to attend D2D cooperation for improving the individual rate, which is further careful observation from Fig.8(c). What's more, we can note that the system sum-rate is maximum under the MT policy. It is due to the fact that, compared to other two policies, MT allocates resources to user devices with good channel quality.

In Fig.8(b), curves of the number of required UAVs varying with the number of devices for three different resource allocation policies are depicted. From the curves in Fig.8(b), we can note that UAV number increases slowly as the number of devices increases, which can be attributed to the reason. As the number of devices become more, more UAVs are deployed for satisfying the requirement of seamless coverage, meanwhile more devices are willing to construct cooperative links for obtaining bigger individual rate. Additionally, we also note from Fig.8(b) that the number of required UAVs is less under the MT policy. Similar explanation holds with the curves of Fig.8(a).

E. Impact of D2D Communication Range

Fig.9 displays the impact of D2D communication range on the system sum-rate and the number of required UAVs under the scheme of MRMN, CDHM and DDUS, where coverage radius of any UAV u is set as $r_u = 150m$, and the number of devices is set as $N = 100$.

From Fig.9(a), we can observe that, with the increase of communication range, the sum-rate from cooperative schemes (i.e., MRMN and CDHM) increases and saturates to a maximum constant value, whereas that in noncooperative scheme (i.e., DDUS) keeps unchanged. This is because that, the DDUS scheme only focuses on direct transmission mode, and thus the sum-rate is not related to the value of D2D communication range. While under the MRMN and CDHM scheme, bigger communication range can lead to more devices participate in D2D cooperation for the individual rate improvement, and thus the sum-rate from cooperative schemes increases, as observed from Fig.9(c). Moreover, we also observe that cooperative

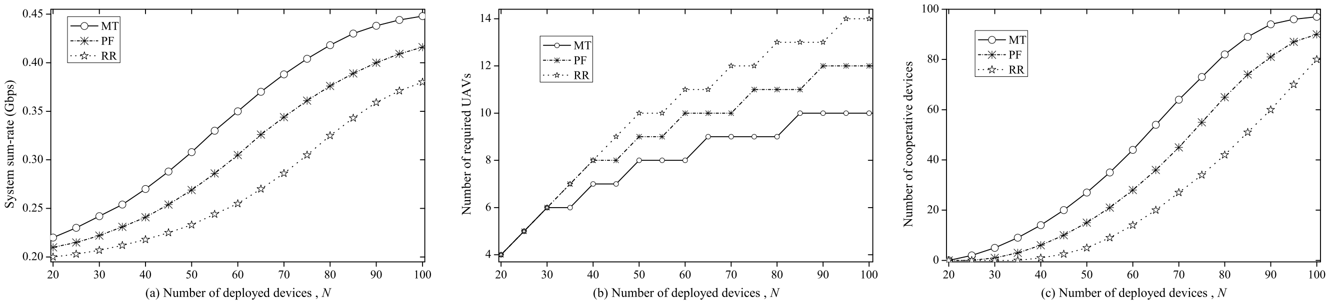


Fig. 8. Impact of three different resource allocation (MT, PF, and RR).

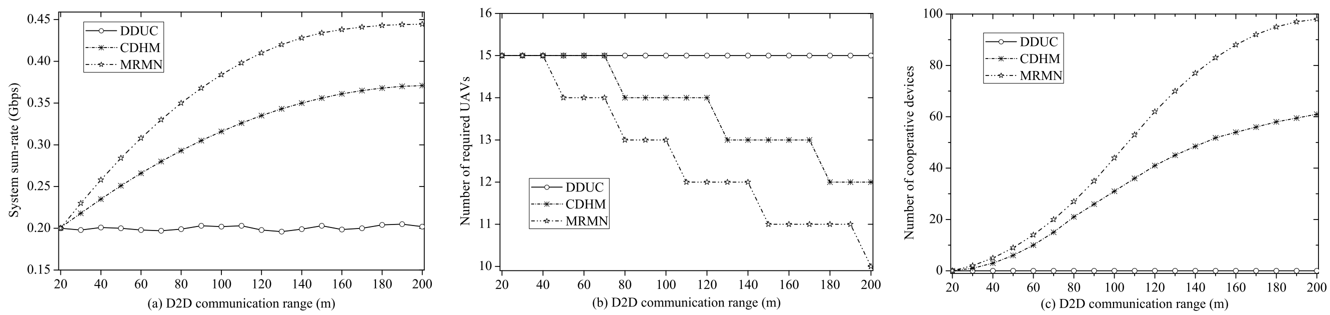


Fig. 9. Impact of D2D communication range under DDUS, CDHM and MRMN.

schemes outperform non-cooperative scheme, and the sum-rate is highest under our proposed MRMN. This is due to the fact that the establishment of cooperative behaviors is decided by the maximization of individual data rate in our scheme.

As shown in Fig.9(b), the number of required UAVs from both schemes (i.e., MRMN and CDHM) decreases and reaches a minimum value (i.e., 10 under MRMN, and 12 under CDHM) when D2D communication range increases, whereas that for DDUS remains unchanged during the increase of communication range. This is due to the reason, as D2D communication range increases, more and more devices select the undirect transmission mode for the improvement of individual rate, and thus employing MRMN and CDHM scheme can appear more and more redundant UAVs. However, in DDUS, user devices only build communication relationship with UAV swarms, and no cooperative relationship appears among user devices. Therefore, the number of required UAVs keeps fixed with the change of D2D communication range, as explained from Fig.9(c). Besides, we also see that the number of required UAVs is least under our proposed MRMN. Due to the fact that our scheme can search for the optimal cooperators with the consideration of the entire communication area, and thus there is more opportunity for devices to select the undirect transmission mode with the increase of communication range.

F. Performance Gain of Our Scheme

To prove the efficiency of our scheme, we compare the performance gains of the schemes of MRMN, CDHM and DDUS on the system sum-rate and the number of required UAVs in terms of the number of deployed devices. In the performance comparison, the default coverage radius of UAV is set as $150m$.

We plot Fig.10 to illustrate the impact of the number of deployed devices N on the system sum-rate for DDUS, CDHM and MRMN. From Fig.10, we can see that, the sum-rate of cooperative schemes (i.e., MRMN and CDHM) monotonically increases and reaches a maximum value (i.e., 0.38Gbps for the CDHM, and 0.45Gbps for the MRMN) with the increase of N, while the sum-rate of noncooperative scheme (i.e., DDUS) keeps unchanged when the number of devices increases, which can be explained as below. The total resource keeps unchanged with the increase of N, and thus the sum-rate of the DDUS can not change. However, as N increases, more devices are inclined to establish cooperative relationship to obtain bigger individual rate, so that the sum-rate of the cooperative schemes can be increased. Moreover, we also see that cooperative scheme is better than noncooperative scheme, and the sum-rate is highest under our proposed MRMN. This is due to the fact in our proposed MRMN, to maximize the system sum-rate, each device can select the most preferred cooperator which can provide the maximum individual rate to construct a cooperative link.

We show in Fig.11 that how the number of required UAVs changes with the number of deployed devices for the scheme of DDUS, CDHM and MRMN. One can easily observe from Fig.11, as the number of devices N increases, the number of required UAVs for both schemes (i.e., MRMN and CDHM) increases slowly, whereas the number of required UAVs for the DDUS increases sharply. This is due to the fact that more devices in DDUS need more UAVs for satisfying the requirement of seamless coverage. While the MRMN and

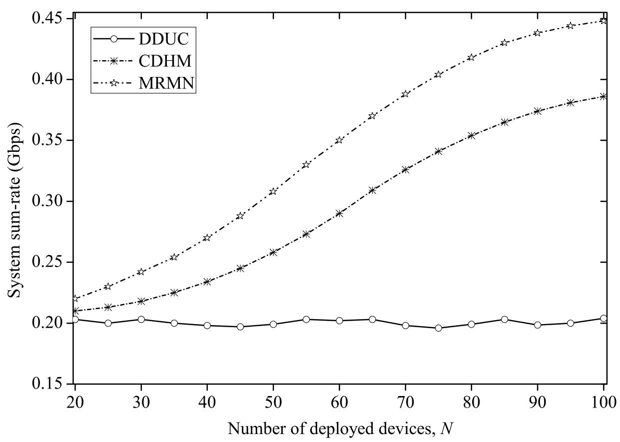


Fig. 10. System sum-rate versus number of deployed devices using DDUS, CDHM and MRMN.

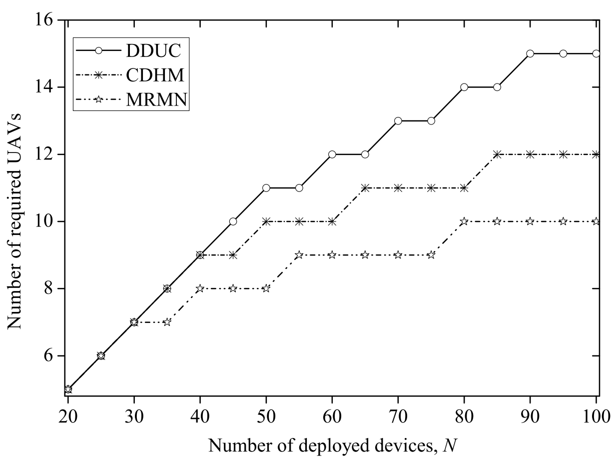


Fig. 11. Number of required UAVs versus number of deployed devices using DDUS, CDHM and MRMN.

CDHM scheme can reduce the number of deployed UAVs by selecting the undirect delivery mode with the increase of number of deployed devices, which makes the MRMN and CDHM outperform the DDUS. Additionally, we could observe that our scheme is better than the CDHM scheme. That is because our scheme searches the entire communication area for establishing cooperative links, while the CDHM scheme limits to the local search to build communication connections.

Fig.12 illustrates how the number of cooperative devices varies with the number of deployed devices for different schemes, i.e., MRMN, CDHM and DDUS. One can see from Fig.12, during the change of N, the number of cooperative devices for DDUS remains zero, while the number of cooperative devices for the schemes of MRMN and CDHM increases, and the number of cooperative devices of the MRMN scheme is always higher than one of the CDHM scheme. This is because, in the scheme of MRMN and CDHM, the increment of the device number enhances cooperative opportunities among the devices and makes more devices construct cooperative links. Additionally, the MRMN scheme considers the cooperative behaviors within the entire communication area, while the

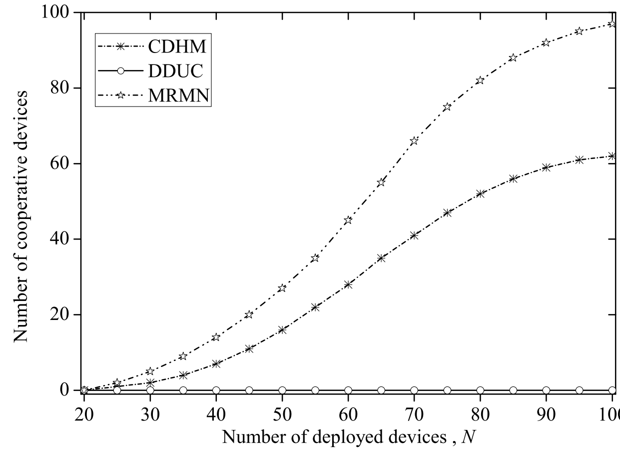


Fig. 12. Number of cooperative devices versus number of deployed devices using DDUS, CDHM and MRMN.

CDHM scheme focuses on the communication cooperation of local search area. Consider DDUS scheme, the data is directly uploaded to the UAVs and no devices attends D2D cooperation. Under the circumstances, the increment of device number does not work effectively.

To further demonstrate the efficiency of our proposed MRMN scheme, Table IV summarizes the performance results obtained from different schemes (i.e., MRMN, CDHM and DDUS) in previous figures, and shows the performance improvement of our scheme on system sum-rate, the number of required UAVs and the number of cooperative devices for different ω and N. From Table IV, we can see that our scheme outperforms the other schemes (i.e., CDHM and DDUS). Such behavior can be attributed to the utilization of coalitional game, which can guarantee completely cooperation among devices, and thus lead to the maximum system sum-rate and the minimum the number of required UAVs.

VI. Conclusion

This paper investigated UAV-based wireless network with consideration of D2D cooperation for establishing IoT-enabled emergency communication, and then proposed MRMN scheme to achieve sum-rate maximization while guaranteeing seamless coverage with the minimum number of UAVs. In this scheme, we first calculated the optimal coverage radius of UAV by adjusting the system parameters such as flight altitude and transmitted power. Using the disk covering theory, we then proposed an efficient deployment method to determine the location and the number of UAV swarm. Finally, a coalition formation algorithm based on coalitional game theory was presented to implement cooperative strategy between user devices and UAV swarm. Through extensive simulations, we indicated the impacts of some system parameters on coverage radius of UAV, and demonstrated the effectiveness of our proposed MRMN on system sum-rate and number of UAVs.

TABLE IV
PERFORMANCE COMPARISON UNDER DDUS, CDHM AND MRMN FOR DIFFERENT ω AND N

Performance parameter	$\omega = 0 \sim 200, N = 100$	$\omega = 200, N = 100$	$\omega = 200, N = 0 \sim 100$
System sum-rate (DDUS)	$0 \sim 125\%$	125%	$0 \sim 125\%$
System sum-rate (CDHM)	$0 \sim 18\%$	18%	$0 \sim 18\%$
Number of required UAVs (DDUS)	$0 \sim 33\%$	33%	$0 \sim 33\%$
Number of required UAVs (CDHM)	$0 \sim 20\%$	20%	$0 \sim 20\%$
Number of cooperative devices (DDUS)	–	–	–
Number of cooperative devices (CDHM)	$0 \sim 67\%$	67%	$0 \sim 67\%$

REFERENCES

[1] S. Zhang and J. Liu, "Analysis and Optimization of Multiple Unmanned Aerial Vehicle-Assisted Communications in Post-Disaster Areas," *IEEE Transactions on Vehicular Technology*, vol. 67, no. 12, pp. 12 049–12 060, 2018.

[2] Y. Qu, H. Sun, C. Dong, J. Kang, H. Dai, Q. Wu, and S. Guo, "Elastic Collaborative Edge Intelligence for UAV Swarm: architecture, Challenges, and Opportunities," *IEEE Communications Magazine*, vol. 62, no. 1, pp. 62–68, Jan. 2024.

[3] S. A. Gbadamosi, G. P. Hancke, and A. M. Abu-Mahfouz, "Adaptive Interference Avoidance and Mode Selection Scheme for D2D-Enabled Small Cells in 5G-IIoT Networks," *IEEE Transactions on Industrial Informatics*, vol. 20, no. 2, pp. 2408–2419, Feb. 2024.

[4] Y. Han, L. Liu, L. Duan, and R. Zhang, "Towards Reliable UAV Swarm Communication in D2D-Enhanced Cellular Networks," *IEEE Transactions on Wireless Communications*, vol. 20, no. 3, pp. 1567–1581, Mar. 2021.

[5] V. T. Tuong, W. Noh, and S. Cho, "Sparse CNN and Deep Reinforcement Learning-Based D2D Scheduling in UAV-Assisted Industrial IoT Networks," *IEEE Transactions on Industrial Informatics*, vol. 20, no. 1, pp. 213–223, Jan. 2024.

[6] B. Lea, D. Shome, O. Waqar, and J. Tomal, "Sum Rate Maximization of D2D Networks with Energy Constrained UAVs through Deep Unsupervised Learning," in *Proceedings of IEEE UEMCON*, 2021, pp. 0453–0459.

[7] A. Alsharoa and M. Yuksel, "Energy Efficient D2D Communications Using Multiple UAV Relays," *IEEE Transactions on Communication*, vol. 69, no. 8, p. 5337—5351, May 2021.

[8] Z. Su, W. Feng, J. Tang, Z. Chen, Y. Fu, N. Zhao, and K. K. Wong, "Energy-Efficiency Optimization for D2D Communications Underlaying UAV-Assisted Industrial IoT Networks With SWIPT," *IEEE Internet of Things Journal*, vol. 10, no. 3, pp. 1990–2002, Oct. 2023.

[9] P. Chen, X. Zhou, J. Zhao, F. Shen, and S. Sun, "Energy-Efficient Resource Allocation for Secure D2D Communications Underlaying UAV-Enabled Networks," *IEEE Transactions on Vehicular Technology*, vol. 71, no. 7, pp. 7519–7531, Jul. 2022.

[10] X. Liu, Z. Li, N. Zhao, W. Meng, G. Gui, Y. Chen, and F. Adachi, "Transceiver Design and Multihop D2D for UAV IoT Coverage in Disasters," *IEEE Internet of Things Journal*, vol. 6, no. 2, pp. 1803–1815, Apr. 2019.

[11] S. Ghosh, A. Bhowmick, S. Roy, D. Sanjay, and S. Kundu, "A UAV based Multi-hop D2D Network for Disaster Management," in *Proceedings of IEEE INFOCOM*, 2021, pp. 1–6.

[12] N. Gao, X. Li, S. Jin, and M. Matthaiou, "3-D Deployment of UAV Swarm for Massive MIMO Communications," *IEEE Journal on Selected Areas in Communications*, vol. 39, no. 10, pp. 3022–3034, Oct. 2021.

[13] H. Ye, X. Kang, J. Joung, and Y. Liang, "Joint Uplink-and-Downlink Optimization of 3-D UAV Swarm Deployment for Wireless-Powered IoT Networks," *IEEE Internet of Things Journal*, vol. 8, no. 17, pp. 13 397–13 413, Sep. 2021.

[14] J. Li, G. Sun, J. Duan, and Q. Wu, "Multi-Objective Optimization for UAV Swarm-Assisted IoT With Virtual Antenna Arrays," *IEEE Transactions on Mobile Computing*, vol. 23, no. 5, pp. 4890–4907, May 2024.

[15] H. Gao, B. Jiang, H. Xu, and S. Chen, "The Low Latency Networking Method for Task-driven MEC-enabled UAV Swarm," *Computer Communications*, vol. 211, pp. 104–118, Nov. 2023.

[16] B. Yang, T. Taleb, Y. Shen, X. Jiang, and W. Yang, "Performance, Fairness, and Tradeoff in UAV Swarm Underlaid mmWave Cellular Networks With Directional Antennas," *IEEE Transactions on Wireless Communications*, vol. 20, no. 4, pp. 2383–2397, Apr. 2021.

[17] Y. Dong, C. Benzaïd, B. Yang, T. Taleb, and Y. Shen, "Deep-Ensemble-Learning-Based GPS Spoofing Detection for Cellular-Connected UAVs," *IEEE Internet of Things Journal*, vol. 9, no. 24, pp. 25 068–25 085, Dec. 2022.

[18] B. Yang, T. Taleb, G. Chen, and S. Shen, "Covert Communication for Cellular and X2U-Enabled UAV Networks with Active and Passive Wardens," *IEEE Network*, vol. 36, no. 1, pp. 166–173, Feb. 2022.

[19] B. Yang, T. Taleb, Y. Fan, and S. Shen, "Mode Selection and Cooperative Jamming for Covert Communication in D2D Underlaid UAV Networks," *IEEE Network*, vol. 35, no. 2, pp. 104–111, Mar. 2021.

[20] J. Li, C. Yi, J. Chen, K. Zhu, and J. Cai, "Joint Trajectory Planning, Application Placement, and Energy Renewal for UAV-Assisted MEC: A Triple-Learner-Based Approach," *IEEE Internet of Things Journal*, vol. 10, no. 15, pp. 13 622–13 636, Aug. 2023.

[21] Y. Shi, C. Yi, R. Wang, Q. Wu, B. Chen, and J. Cai, "Service Migration or Task Rerouting: A Two-Timescale Online Resource Optimization for MEC," *IEEE Transactions on Wireless Communications*, vol. 23, no. 2, pp. 1503–1519, Feb. 2024.

[22] V. Vishnoi, I. Budhiraja, S. Gupta, and N. Kumar, "A Deep Reinforcement Learning Scheme for Sum Rate and Fairness Maximization Among D2D Pairs Underlaying Cellular Network With NOMA," *IEEE Transactions on Vehicular Technology*, vol. 72, no. 10, pp. 13 506–13 522, Oct. 2023.

[23] D. Ron and J. Lee, "DRL-Based Sum-Rate Maximization in D2D Communication Underlaid Uplink Cellular Networks," *IEEE Transactions on Vehicular Technology*, vol. 70, no. 10, pp. 11 121–11 126, Oct. 2021.

[24] S. Gbadamosi, G. Hancke, and A. Abu-Mahfouz, "Interference-Aware and Coverage Analysis Scheme for 5G NB-IoT D2D Relaying Strategy for Cell Edge QoS Improvement," *IEEE Internet of Things Journal*, vol. 11, no. 2, pp. 2224–2235, Jan. 2024.

[25] N. Kamiyama, K. Ishibashi, and Y. Hoshiai, "Reachability Analysis of Multi-Hop D2D Communications at Disaster," *IEICE Transactions on Communication*, vol. 101-B, no. 8, pp. 1833–1844, Apr. 2018.

[26] R. Sun, B. Yang, Y. Shen, X. Jiang, and T. Taleb, "Covertness and Secrecy Study in Untrusted Relay-Assisted D2D Networks," *IEEE Internet of Things Journal*, vol. 10, no. 1, pp. 17–30, Jan. 2023.

[27] Y. Yang, B. Yang, S. Shen, Y. Shi, and T. Taleb, "Covert Rate Study for Full-Duplex D2D Communications Underlaid Cellular Networks," *IEEE Internet of Things Journal*, vol. 10, no. 17, pp. 15 223–15 237, Sep. 2023.

[28] C. Yi, S. Huang, and J. Cai, "An Incentive Mechanism Integrating Joint Power,Channel and Link Management for Social-Aware D2D Content Sharing and Proactive Caching," *IEEE Transactions on Mobile Computing*, vol. 17, no. 4, pp. 789–802, Apr. 2018.

[29] Z. Lu, G. Cao, and T. L. Porta, "TeamPhone: Networking Smartphones for Disaster Recovery," *IEEE Transactions on Mobile Computing*, vol. 16, no. 12, pp. 3554–3567, Dec. 2017.

[30] M. Neinavaie and Z. M. Kassas, "Cognitive Sensing and Navigation With Unknown OFDM Signals With Application to Terrestrial 5G and Starlink LEO Satellites," *IEEE Journal on Selected Areas in Communications*, vol. 42, no. 1, pp. 146–160, Jan. 2024.

[31] R. Sun, B. Yang, S. Ma, Y. Shen, and X. Jiang, "Covert Rate Maximization in Wireless Full-Duplex Relaying Systems With Power Control," *IEEE Transactions on Communications*, vol. 69, no. 9, pp. 6198–6212, Sep. 2021.

[32] T. Ji, M. Hua, C. Li, Y. Huang, and L. Yang, "Exploiting Intelligent Reflecting Surface for Enhancing Full-Duplex Wireless-Powered Communication Networks," *IEEE Transactions on Communication*, vol. 72, no. 1, pp. 553–569, Feb. 2024.

[33] G. Farhadi and N. C. Beaulieu, "On the Ergodic Capacity of Multi-hop Wireless Relaying Systems," *IEEE Transactions on Wireless Communication*, vol. 8, no. 5, pp. 2286–2291, May 2009.

[34] X. Wang, P. Zhang, F. Shu, W. Shi, and J. Wang, "Power Allocation for IRS-Aided Two-Way Decode-and-Forward Relay Wireless Network," *IEEE Transactions on Vehicular Technology*, vol. 72, no. 1, pp. 1337–1342, Jan. 2023.

[35] M. Ashraf, S. Kang, and I. Lee, "Harvested Energy Maximization in Wireless Peer Discovery Systems," *IEEE Communication Letter*, vol. 23, no. 5, pp. 934–937, Mar. 2019.

[36] M. Mozaffari, W. Saad, M. Bennis, and M. Debbah, "Unmanned Aerial Vehicle With Underlaid Device-to-Device Communications: performance and Tradeoffs," *IEEE Transactions on Wireless Communications*, vol. 15, no. 6, pp. 3949–3963, Jun. 2016.

[37] J. Lyu, Y. Zeng, and R. Zhang, "Spectrum Sharing and Cyclical Multiple Access in UAV-Aided Cellular Offloading," in *Proceedings of IEEE GLOBECOM*, 2017, pp. 1–6.

[38] 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 Transactions on Wireless Communications*, vol. 21, no. 2, pp. 976–990, Feb. 2022.

[39] A. Alexiou, M. Debbah, M. D. Renzo, E. C. Strinati, and H. Viswanathan, "Guest Editorial Beyond Shannon Communications - A Paradigm Shift to Catalyze 6G," *IEEE Journal on Selected Areas in Communications*, vol. 41, no. 8, pp. 2299–2305, Aug. 2023.

[40] A. Alsharoa and M. Yuksel, "UAV-Direct: Facilitating D2D Communications for Dynamic and Infrastructure-less Networking," in *Proceedings of the 4th ACM Workshop on MobiSys*, 2018, pp. 57–62.

[41] G. F. Toth, "Thinnest Covering of A Circle by Eight, Nine, or Ten Congruent Circles," *Combinatorial and computational geometry*, vol. 52, no. 361, pp. 50–59, 2005.

[42] J. J. Yang, J. R. Jiang, and Y. L. Lai, "A Decreasing k-means algorithm for the Disk Covering Tour Problem in wireless sensor networks," in *Proceedings of IEEE ICPADS*, 2014, pp. 906–910.

[43] F. Lagum, I. Bor-Yaliniz, and H. Yanikomeroglu, "Strategic Densification With UAV-BSs in Cellular Networks," *IEEE Wireless Communication Letter*, vol. 7, no. 3, pp. 384–387, Dec. 2018.

[44] Z.Han, D. NIYATO, W. Saad, T. Basar, and A. HjØrungnes, *Game Theory in Wireless and Communication Networks: Theory, Models, and Applications*. Cambridge university press, 2012.

[45] W. Saad, Z. Han, M. Debbah, A. Hjørungnes, and T. Basar, "Coalitional game theory for communication networks," *IEEE Signal Processing Magazine*, vol. 26, no. 5, pp. 77–97, May 2009.

[46] N. Nouri, F. Fazel, J. Abouei, and K. N. Plataniotis, "Multi-UAV Placement and User Association in Uplink MIMO Ultra-Dense Wireless Networks," *IEEE Transactions on Mobile Computing*, vol. 22, no. 3, pp. 1615–1632, Mar. 2023.

[47] Z. Yin, N. Cheng, Y. Song, Y. Hui, Y. Li, T. H. Luan, and S. Yu, "UAV-Assisted Secure Uplink Communications in Satellite-Supported IoT: Secrecy Fairness Approach," *IEEE Internet of Things Journal*, vol. 11, no. 4, pp. 6904–6915, Feb. 2024.

[48] H. Zhao, H. Wang, W. Wu, and J. Wei, "Deployment Algorithms for UAV Airborne Networks Toward On-Demand Coverage," *IEEE Journal on Selected Areas in Communications*, vol. 36, no. 9, pp. 2015–2031, Sep. 2018.

[49] L. Militano, A. Orsino, G. Araniti, A. Molinaro, and A. Iera, "A Constrained Coalition Formation Game for Multihop D2D Content Uploading," *IEEE Transactions on Wireless Communications*, vol. 15, no. 3, pp. 2012–2024, Mar. 2016.

[50] S. P. S and T. Rajendran, "Improved Round Robin Rule Learning for Optimal Load Balancing in Distributed Cloud Systems," *Journal of Systems Science And Systems Engineering*, vol. 13, no. 1, Nov. 2023.

[51] N. Akar and E. Karasan, "Is Proportional Fair scheduling Fuitable for Age-sensitive Traffic?" *Compute Networks*, vol. 226, pp. 109 661–109 668, Apr. 2023.

[52] H. Liu, R. Chen, S. Ding, Z. Jiang, F. Liu, and J. Zhang, "An Energy Efficiency Routing Protocol for UAV-aided WSNs Data Collection," *Ad Hoc Networks*, vol. 154, pp. 103 371–103 378, Feb. 2024.

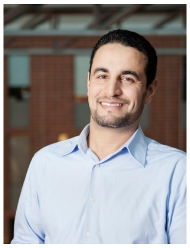
Xiaolan Liu received her B.S. and M.S. degrees in electronic and information engineering form Naval Aeronautical University, China in 2007 and in information and communication engineering from Dalian Maritime University, China in 2009, and Ph.D. degree in systems information science from Future University Hakodate, Japan in 2019, respectively. She is currently an associate professor at the School of Basic Medicine, Shandong Second Medical University, China. Her research interests include D2D communication and machine learning.

Bin Yang received his Ph.D. degree in systems information science from Future University Hakodate, Japan in 2015. He was a research fellow with the School of Electrical Engineering, Aalto University, Finland, from Nov. 2019 to Nov. 2021. He is currently a professor with the School of Computer and Information Engineering, Chuzhou University, China. His research interests include unmanned aerial vehicle networks, cyber security, edge computing and Internet of Things.

Jianming Liu received her B.S. and M.S. degrees in physics education form Shandong Normal University, China in 2001 and in computer application technology from Tianjin Normal University, China in 2006, respectively. He is currently a professor at the School of Basic Medicine, Shandong Second Medical University, China. His research interests include machine learning and artificial intelligence.

Lintao Xian received his B.S. and M.S. degrees both in computer science from Qingdao University, China, in 2012 and from Ocean University of China, China, in 2015, and Ph.D. degree in computer science and technology from Ocean University of China, China, in 2021, respectively. He is currently an faculty member at the School of Basic Medicine, Shandong Second Medical University, China. His research interests include machine learning, internet of things technology and parallel computing.

Xiaohong Jiang received his B.S., M.S. and Ph.D degrees in 1989, 1992, and 1999 respectively, all from Xidian University, China. He is currently a full professor of Future University Hakodate, Japan. Before joining Future University, Dr. Jiang was an Associate professor, Tohoku University, from Feb. 2005 to Mar. 2010. Pro. Jiang's research interests include computer communications networks, mainly wireless networks and optical networks, network security, routers/switches design, etc. He has published over 300 technical papers at premium international journals and conferences, which include over 70 papers published in top IEEE journals and top IEEE conferences, like IEEE/ACM Transactions on Networking, IEEE Journal of Selected Areas on Communications, IEEE Transactions on Parallel and Distributed Systems, IEEE INFOCOM.



Tarik Taleb received the B.E. degree Information Engineering with distinction and the M.Sc. and Ph.D. degrees in Information Sciences from Tohoku University, Sendai, Japan, in 2001, 2003, and 2005, respectively. He is currently a Full Professor with the Faculty of Electrical Engineering and Information Technology, Ruhr University Bochum. He is the founder and director of the MOSAIC Lab (www.mosaic-lab.org). Between Oct. 2014 and Dec. 2021, he was a Professor at the School of Electrical Engineering, Aalto University, Finland. Prior to that, he was working as Senior Researcher and 3GPP Standards Expert at NEC Europe Ltd, Heidelberg, Germany. Before joining NEC and till Mar. 2009, he worked as assistant professor at the Graduate School of Information Sciences, Tohoku University, Japan, in a lab fully funded by KDDI, the second largest mobile operator in Japan. From Oct. 2005 till Mar. 2006, he worked as research fellow at the Intelligent Cosmos Research Institute, Sendai, Japan. His research interests lie in the field of telco cloud, network softwarization & network slicing, AI-based software defined security, immersive communications, mobile multimedia streaming, and next generation mobile networking. He has been also directly engaged in the development and standardization of the Evolved Packet System as a member of 3GPP's System Architecture working group. He served as the general chair of the 2019 edition of the IEEE Wireless Communications and Networking Conference (WCNC'19) held in Marrakech, Morocco. He was the guest editor in chief of the IEEE JSAC Series on Network Softwarization & Enablers. He was on the editorial board of the IEEE Transactions on Wireless Communications, IEEE Wireless Communications Magazine, IEEE Journal on Internet of Things, IEEE Transactions on Vehicular Technology, IEEE Communications Surveys & Tutorials, and a number of Wiley journals. Till Dec. 2016, he served as chair of the Wireless Communications Technical Committee.