An Efficient Energy Harvesting and Optimal Clustering Technique for Sustainable Postdisaster Emergency Communication Systems

ABDU SAIF[1] (Member, IEEE), KAHARUDIN DIMYATI[1] (Member, IEEE),
KAMARUL ARIFFIN NOORDIN[1] (Senior Member, IEEE), DEEPAK G C[2] (Member, IEEE),
NOR SHAHIDA MOHD SHAH[3] (Member, IEEE), QAZWAN ABDULLAH[3] (Member, IEEE),
AND MAHATHIR MOHAMAD[4]

[1]Department of Electrical Engineering, Faculty of Engineering, University of Malaya, Kuala Lumpur 50603, Malaysia
[2]School of Computer Science and Mathematics, Kingston University, London KT1 2EE, U.K.
[3]Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia , Johor 86400, Malaysia
[4]Faculty of Applied Science and Technology, Universiti Tun Hussein Onn Malaysia, Johor 86400, Malaysia

Corresponding authors: Kaharudin Dimyati (kaharudin@um.edu.my) and Kamarul Ariffin Noordin (kamarul@um.edu.my)

ABSTRACT The energy consumption and coverage range of unmanned aerial vehicles (UAVs) are major challenges in UAV-based postdisaster communications. To address these challenges, energy harvesting is employed to power communication devices and prolong the lifetime of the wireless communication network during a disaster. In addition, clustering techniques and device-to-device (D2D) communication are needed to increase the overall network coverage and provide sustainable connectivity during the disaster and postdisaster phases. We have proposed a novel emergency communication system (ECS) using the optimal cluster head (CH) technique to improve the energy transfer efficiency for sustainable network connectivity. We have developed a UAV deployment model assisted by the clustering technique and D2D links that is capable of harvesting energy to increase the network lifetime. This new approach is expected to enhance the reliability of the network in disaster situations. The proposed methods have been evaluated by measuring the energy efficiency performance and the network outage probability. The simulation results demonstrate improved performance with the deployment of optimal CHs, while the outage probability has been effectively reduced. Moreover, the proposed approach has been proven to reduce the computational complexity. In conclusion, UAV deployment with the optimal CH algorithm is a suitable network design to recover from natural disasters and potentially save many lives.

INDEX TERMS UAVs, energy harvesting, cluster heads, D2D communication, 5G.

I. INTRODUCTION

Natural disasters, such as earthquakes, hurricanes, tornadoes, and severe snowstorms, frequently devastate the telecommunication infrastructure. In such circumstances, existing wireless communication networks can be damaged, partially unavailable, or significantly overloaded, as demonstrated by the aftermath of recent hurricanes *Sandy* and *Irma* and the 2017 earthquake in central Mexico. This hinders the effective functioning of search and rescue operations between emergency personnel and victims. More than two million people have died since 1995 due to natural disasters alone [1]. Therefore, it is critical to obtain first-hand knowledge to assess the severity of the destruction in postdisaster scenarios. The wireless technologies currently used for public safety coordination include fourth-generation (4G) long-term evolution (LTE), wireless local area networks (WLANs), satellite communications, and dedicated public safety systems such

The associate editor coordinating the review of this manuscript and approving it for publication was Mostafa Zaman Chowdhury.

as terrestrial trunked radio (TETRA) and the Association of Public Safety Communications Officials (APCO) Project 25 (P25) [2], [3].

Fifth-generation (5G) systems, on the other hand, promise an increase in user data rates and connection density by 100 times, a 10-fold increase in energy efficiency and sub-millisecond latency compared to the previous generations [4]. The available systems may not offer the required flexibility or address the need for rapid responses to environmental disruption due to natural disasters. Thus, an unmanned aerial vehicle (UAV) could be the best alternative to ensure continuous and reliable network connectivity in the event of a natural disaster; i.e., the UAV can be deployed to provide temporary wireless coverage to replace the network infrastructure failure [4], [5].

However, UAVs have limited battery power, and therefore, energy harvesting is a possible way to satisfy the energy requirements for an emergency communication system during the postdisaster phase. Due to this limitation, user devices that are out of the UAV coverage range cannot obtain wireless access from UAVs during natural disasters.

Here, the integration of device-to-device (D2D) communication plays a vital role in improving the coverage performance of UAV-supported networks. In addition, D2D communication and clustering techniques can be efficiently used in a wireless network to improve energy efficiency and in turn extend the communication range [6]. Clustering allows cluster heads (CHs) to share wireless services across the network based on energy harvesting capabilities to maintain network functions during its operations [7]. Therefore, it is inevitable that communication in disaster events needs efficient power-saving techniques and reliable connectivity to keep the network services running seamlessly so that disaster relief activities are conducted effectively and more lives are saved [8].

A. ENERGY HARVESTING
The cause of unreliable communication networks during catastrophic circumstances originates from the failure of the network's ground base station (GBS) power supply. Therefore, replacing the GBS with a UAV is a viable option, but the primary drawback is that UAVs run on battery power that can run out very quickly. The same situation occurs with user devices. Consequently, prolonging battery life is critical for postdisaster communications. At the same time, tethered UAV deployment is one potential solution for the power supply problem in disaster scenarios [9], [10]. Furthermore, problems could occur with its ground base station power source. Therefore, we further investigate and propose energy harvesting (EH) techniques for postdisaster communications.

Here, EH can eliminate the battery power barriers of UAVs and user devices and provide a sustainable solution to extend the network lifetime. In EH, energy is harvested from radio signals that convert the wireless signals received into a usable energy source [11], [12]. The harvested energy can increase the flight time of the UAV and provides the extra power

needed to serve its connected user devices. Note that the energy harvesting performance for the UAV link in our proposed approach is affected by altitudes, large-scale path loss, user distances, network bandwidth, and so on [13].

The CH uses simultaneous wireless information and power transfer (SWIPT) technology to harvest energy from radio frequency wireless signaling to enhance energy efficiency (EE) [14]. CHs are wirelessly powered by harvesting a portion of the received signal power from the UAV based on the time switching protocol and SWIPT. As a relay, CH assumes the role of transmitting the obtained information signal and energy harvesting to the associated user devices [15], [16].

B. USER DEVICE CLUSTERING
Clustering is among the techniques used to provide efficient and stable routes for data dissemination. Clustering establishes links between a group of user devices through direct communication to improve the performance of the network for sharing data and radio resources [17]. However, rapid changes in network topology, such as in disaster situations, create frequent cluster reorganization, which can seriously impact the network route stability. The clustering of nodes and nominations of CHs was investigated to reach cluster stability in a wireless network [18]. Here, the CH is a node that is responsible for collecting data from the cluster members (CMs) and forwards the data to UAVs. However, managing this clustering network is challenging due to the signaling traffic load on each CH [19].

C. CLUSTER HEAD SELECTION
Cluster head selection is crucial and can be critical if we aim to establish efficient communication links with the network and minimize the outage probability. User devices distributed at the optimal location, i.e., nearer the UAV path, could be selected as the CH. In this paper, the chosen CHs, i.e., the optimal CHs, are those with more residual energy, and more neighborhood nodes based on the metrics of intra-user device distance, relative speed, and residual energy [20]. In addition, the load on the CH should be reduced to ensure effective and stable routes, finally lengthening the lifetime of postdisaster communication [21].

D. CONTRIBUTIONS OF THE PAPER
In this paper, we proposed a system model for a UAV-assisted emergency communication network that is stable and reliable to manage disaster scenarios. The critical aspect of our approach is to select user devices that should be performing as the optimal CH and at the same time extending the wireless coverage. We then investigated the energy harvesting techniques with the intent of prolonging the network lifetime. Finally, we analyzed the power consumption of the optimal CH and enable reliable connectivity for the UAV and D2D communication range. The system model is expected to perform with better outage probability and efficiency for sustainable operations during disasters.

The remainder of the paper is organized as follows. Section II discusses existing research in this area. Section III presents the system model for further analysis of the energy harvesting technique and D2D with clustering and evaluates the outage probability. Section IV presents the computational complexity analysis. Section V presents the simulation results and discusses the obtained results, and finally, Section VI concludes the paper.

II. RELATED WORK

The common goal in any disaster management research is to design a ubiquitous network architecture capable of working continuously and serving effectively in search and rescue missions. Various solutions have been proposed in the literature. For example, a UAV-powered energy harvesting wireless communication system was proposed in [22] to transfer energy and improve network connectivity duration during a natural disaster. In emergency communications, energy management is a significant concern for the network infrastructure. Here, UAVs increase wireless coverage and reduce the channel access delay. Moreover, UAVs are integrated with an emergency communication system to assist terrestrial networks for fast response and reliable connectivity in disaster scenarios [23], [24].

Efficient resource distribution is critical to improve the channel link quality and thus maximize the downlink coverage services. The strategies of power allocation based on RF energy harvesting were investigated in [25], in which a UAV carries a pico-base station to increase wireless coverage and reduce network congestion and traffic overload. They adopted several clustering approaches in wireless networks to tackle the energy harvesting issues, catering to the power supply limitation. The energy harvesting technique presented in this paper could increase the battery life and keep the network running during disasters. The clustering technique and D2D communication in UAV networks can sustain communication services when the cellular infrastructure becomes partially or fully dysfunctional. *Haider et al.* [26] proposed an optimum CH selection strategy to maximize the lifetime of wireless sensor networks. The CH was selected based on the average residual energy, link quality and distance of each sensor node from the UAV [27].

In [28], a SWIPT method was proposed to harvest energy from the radio frequency signals and subsequently improve the energy efficiency (EE) performance within the limited battery capacity. In this work, a stable matching algorithm of EH was used to solve the resource allocation problem under spectrum reuse and transmit power constraints. Nevertheless, this work does not include optimizing of the power splitting ratio, power transfer and CH selection to improve the EE for cellular networks and D2D communications.

Energy harvesting-powered D2D communications were investigated to maximize the energy efficiency of D2D communications based on time slot allocation and transmit power control to overcome the constraint on energy performance [29]. Additionally, efficient resource distribution was used to improve the channel link quality based on D2D energy harvesting (D2D-EH) to decrease the communication outage probability in postdisaster situations.

In [12], [30], UAVs with multiple antennas serve as relay nodes to transfer wireless information and power among the D2D user devices located outside the coverage area and the core network. Here, an integrated method (i.e., UAV, CHs, and D2D communications) was used to optimize the energy harvesting time and power control between functional and dysfunctional areas. The communication in the cluster through the D2D communication utilizes the unlicensed spectrum for the communication link between the CH and CMs to improve the system spectrum efficiency [31]. However, there is difficulty underlying the use of the CHs to transfer the wireless signals from the UAV to the CM nodes during disaster phases.

In [32], the power control strategies proposed to guarantee the quality of service were investigated for D2D pair communications underlying UAV coverage in postdisaster recovery. In [22], [33], a multihop clustering algorithm was employed to transfer wireless services from the UAV to the CM nodes via CHs to enhance cluster coverage and user device connectivity.

In this paper, we have considered the optimal CH selection approach to minimize the outage probability during and after disaster events. In addition, we have developed a model of UAV deployment to address the optimal CHs with clustering and D2D communication that are utilized to harvest energy. The selection approach improves the network lifetime, reliability and coverage in disaster situations.

III. SYSTEM MODEL

Fig. 1 illustrates the system model for the proposed UAV-assisted postdisaster communication, where the UAV provides immediate coverage to the disaster area while simultaneously executing wireless power transfer to user devices. We assume that the UAV coverage diameter is circular, and the user devices are distributed according to a Poisson cluster process (PCP) with a spatial density of λ_{UDs}.

User devices within the UAV coverage range receive wireless services through the LoS link, and selected user devices are located at the edge of the UAV coverage range as CHs to extend the network links between the inside and the outside of the UAV coverage area. The CHs will be the primary distribution nodes for the cluster members (CMs). CMs must have sufficient residual energy to establish D2D communication with the CH.

A. TIME SWITCHING PROTOCOL

The time switching protocol has been implemented at the CH to forward the information and power to CMs. A block of information is transmitted from the source to destination nodes via channel propagation. The time slot ratio (TSR) of the transmission is denoted in the transmit nodes as e_1, e_2 at the channel propagation, and e_3 at the receiver node, where $e_1 + e_2 + e_3 = 1$. Therefore, the duration of the first time slot
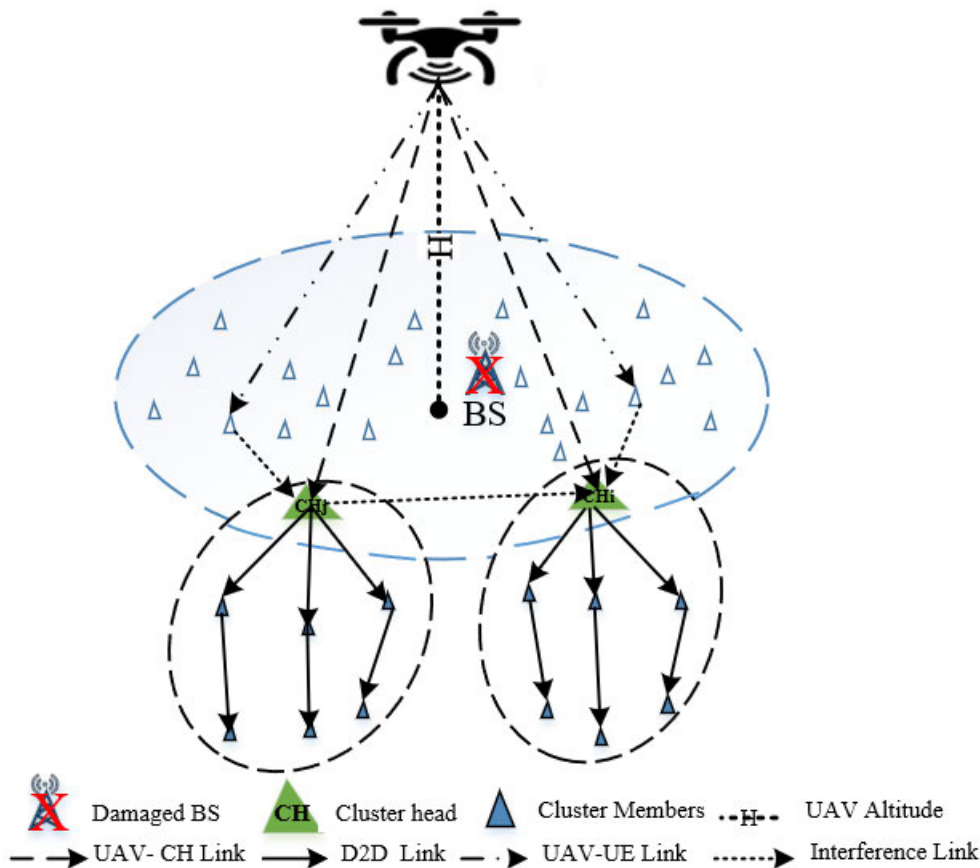
FIGURE 1. The architecture of the proposed system model.

e_1T consists of the wireless coverage energy signals handled in source nodes.

Furthermore, the wireless coverage signals are sent to the CHs in the second time slot, e_2T, while the CHs send it to the destination CMs in the third time slot, e_3T. We assume that the total bandwidth is divided into N orthogonal subcarriers, $n \in \{1, 2, \ldots, N\}$, and the network has two wireless coverage links, which are the UAV to CHs and the CH to CMs when the user devices are outside of the UAV coverage area. The nonlinearity in the energy harvesting circuit during the first time slot at the CHs is denoted as follows [11], [34].

$$E = e_1 T \zeta \sum_{n=1}^{N} p_n^{S,1} \left| h_n^{S-CH} \right|^2, \qquad (1)$$

where $p_n^{S,1}$ represents the transmission power from the UAV source in the first time slot over the nth subcarrier for energy transfer, while ζ denotes the EH efficiency that accounts for the loss in the energy transducer. In contrast, h_n^{S-CH} denotes the channel gain between the UAV source node and the CHs. Therefore, the source node should allocate all available power over the subcarrier with an entire channel gain to optimize the

energy harvest at the CH node. As a consequence, we obtain the following equation:

$$E = e_1 G, \qquad (2)$$

where

$$G = T \zeta P \max_n | h_n^{S-CH} |^2 . \qquad (3)$$

Here, P denotes the maximum UAV transmit power and $P \geq \sum_{n=1}^{N} p_n^{S,1}$ through the UAV source node to the CH node over the nth subcarrier in the first time slot. Therefore, the maximum data rate that can be achieved directly from the CH to CMs is obtained as follows [35].

$$R = \min \left\{ e_2 \sum_{n=1}^{N} \log_2(1 + p_n^{S,2} \gamma_n^{S-CH}), \right.$$

$$\left. e_3 \sum_{n=1}^{N} \log_2(1 + p_n^{CH} \gamma_n^{CH-CM}) \right\}, \qquad (4)$$

where $p_n^{S,2}$ and p_n^{CH} denote the UAV transmit power in the second time slot and the CHs in the third time slot over the nth subcarrier for information transmission, respectively.
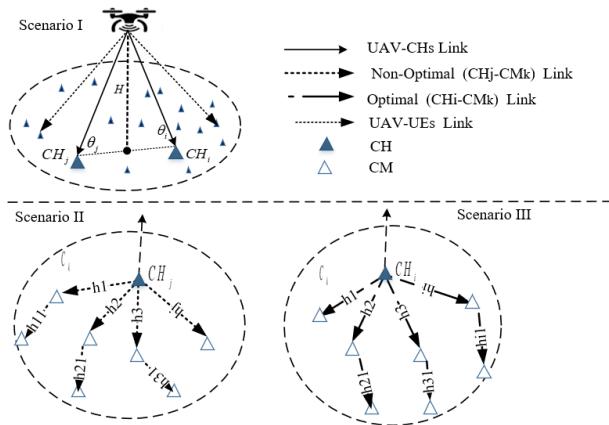
FIGURE 2. Three different communication network scenarios for energy harvesting.

Furthermore, $\gamma_n^{S-CH} = \left|h_n^{S-CH}\right|^2/\sigma_{CH}^2$ and $\gamma_n^{CH-CM} = \left|h_n^{CH-CM}\right|^2/\sigma_{CM}^2$, where σ_{CH}^2 and σ_{CM}^2 denote noise power over each subcarrier at the CH and CMs respectively. According to [36], [37], the energy obtained in the first time slot should be greater than or equal to the energy consumed to transmit information to the CHs, which is denoted as follows.

$$E \geq e_3 T \sum_{n=1}^{N} p_n^{CH}. \qquad (5)$$

Note that there are likely many user devices within the UAV coverage range that are possible candidates to perform as CHs. An essential step is then to select the CHs before information and energy can be transferred. The selected CHs are on the edge of the coverage area, and they should have an SNR higher than a predefined threshold.

We have considered the UAV coverage range with the radius of R_{ha} centered at the UAV coverage source, as shown in Fig. 1. R_{ha} is denoted as follows.

$$R_{ha} = \left(\frac{\zeta p_{UAV}}{EH_{thr}}\right)^{1/\alpha}, \qquad (6)$$

where $\zeta \in (0, 1)$, p_{UAV} is the UAV transmitted power, EH_{thr} is the threshold of the energy harvesting, and α is the path-loss exponent. The Doppler Effect resulting from the relatively higher velocity of UAVs is not taken into consideration in this paper.

IV. POWER TRANSFER FOR THE CLUSTERING NETWORK
In this section, we elaborate on the mechanism of control signals transmitted by the UAV to CHs and the CH to CMs. The D2D communication is implemented between the CH and CMs to extend the UAV coverage range and improve the energy efficiency. The performance of the energy harvesting is evaluated on the clustering within D2D communication links. We have considered three different scenarios, as shown in Fig. 2, i.e., (I) UAV to user devices that are in the range of its coverage, (II) nonoptimal CH to CMs and (III) optimal CH to CMs. In these scenarios, the UAV transmits the main

beam to the optimal CH nodes to maximize throughput in the optimal user nodes. CHs can harvest the received energy and forward it to CMs within the cluster through D2D communication. We expect that the optimal CH will provide more efficient and stable route solutions to the network during postdisaster situations, which is crucial for the search and rescue teams to save lives.

A. PERFORMANCE ANALYSIS OF D2D IN CLUSTERING
The time needed to transmit energy with a data packet content of size S_T bits on the ith optimal CH_i and the jth nonoptimal CH_j to the kth cluster member CM_k links that have an achievable rate of $R_{i,k}$ and $R_{j,k}$ bps are given by $S_T/R_{i,k}$ and $S_T/R_{j,k}$, respectively. The CM_k battery power will be drained for receiving data from nodes CH_i and CH_j by $P_{Rx,i,k}$ and $P_{Rx,j,k}$; then, the CM_k consumes energy to receive the data from CH_i and CH_j, which are given by $S_T P_{Rx,i,k}/R_{i,k}$ and $S_T P_{Rx,j,k}/R_{j,k}$ respectively. Similarly, denoting $P_{Tx,i,k}$ and $P_{Tx,j,k}$ as the power drained by the battery of CH_i and CH_j to transmit the data to CM_k, respectively, then the consumption of energy by CH_i and CH_j to transmit the content to CM_k is given by $S_T P_{Tx,i,k}/R_{i,k}$ and $S_T P_{Tx,j,k}/R_{j,k}$ respectively [11], [38].

It should be noted that P_{Tx} derivations for both CH_i and CH_j are expressed as follows.

$$P_{Tx} = \begin{cases} P_{Tx_{i,k}} = P_{Tx_{ref,i,k}} + P_{t,i,k} \\ P_{Tx_{j,k}} = P_{Tx_{ref,j,k}} + P_{t,j,k}, \end{cases} \qquad (7)$$

where $P_{Txref,i,k}$ and $P_{Txref,j,k}$ correspond to the consumed power by the source circuitry nodes of the ith optimal CH_i and the jth nonoptimal CH_j through transmission on the communication link with the kth CM, i.e., CM_k, nodes. On the other hand, $P_{t,i,k}$ and $P_{t,j,k}$ correspond to the transmitted power over the air interface on (CH_i, CH_j) to CM_k links. We assume the communication links occur from the optimal CH_i to CM_k through a number of clusters C_l. Subsequently, the total energy consumed E_{C_l} is expressed as follows:

$$E_{C_l} = S_T \sum_{\substack{i \neq k, \\ i=1,2,...,|C_l|, \\ k \in C_l}} \left(\frac{\Gamma_l P_{Tx_{i,k}} + P_{Rx,i,k}}{R_{i,k}} + \frac{P_{Rx,i}}{R_i}\right). \qquad (8)$$

The consumed energy is used by the ith CH, i.e., optimal CH_i to receive data from the UAV in the first-term links and in D2D communication in the second-term links. The distinguishing variable Γ_l is applied from unicasting to multicasting. Moreover, each user device has specific data to transmit in the unicasting uplink. The CMs have residual energy to establish the link with CH, which is able to deliver collected singles to the UAV in the uplink and improve the energy transfer efficiency with shorter-distance connectivity. The same data are forwarded to CMs in the downlink for each coalition, and consequently, the unicasting or multicasting on long-range and short-range connections is adopted. In the case of D2D communication from the CH_i to CM_k with short-range unicasting, $\Gamma_l = 1$. Meanwhile, in the case of

short-range multicasting, $(\Gamma_l = 1/|C_l| - 1)$ compensates for the effect of the summation in (8) since transmission occurs only once. In the single cluster, the harvested energy calculated in (1) must not be lower than the energy consumption in (8). Therefore, we can rewrite those equations as follows.

$$E \geq E_{C_l}$$

$$e_1 T \zeta \sum_{n=1}^{N} p_n^{S,1} \mid h_n^{S-CH} \mid^2 \geq E_{C_l}$$

$$\sum_{n=1}^{N} p_n^{S,1} \mid h_n^{S-CH} \mid^2 \geq \frac{E_{C_l}}{e_1 T \zeta}. \tag{9}$$

Assuming that each subcarrier has equal power, i.e., $p_1^{S,1} = p_2^{S,1} = p_N^{S,1}$, we obtain the following.

$$p^{S,1} \geq \frac{E_{C_l}}{e_1 T \zeta \sum_{n=1}^{N} \mid h_n^{S-CH} \mid^2}, \tag{10}$$

where $p^{S,1}$ is a single subcarrier power as a function of the user devices. Hence, the transmission energy harvested at the CHs is greater than or equal to the energy consumed for the wireless transfer signal between the CH and CMs. Therefore, in the multiple cluster case, the CHs transfer energy to the next cluster through the cluster gateway in a serial multihop manner.

B. OUTAGE PROBABILITY

Clustering techniques and D2D communication have received a great deal of attention because of their ability to enhance network coverage and improve connectivity during disaster scenarios. In this section, the outage probability for user devices is investigated. First, the outage probability for the first-hop link between the UAV and CHs is determined. Second, the outage probability for the second hop between the CH and CMs is determined. The distance between the UAV and CHs is $d_{u,i,j}$, while the distance between CH and an intended CM is $d_{i,j,k}$, where $i, j \in CHs$ and $k \in CMs$.

According to [11], the outage probability of D2D communication between CH and CMs can be expressed as follows.

$$P_{out}$$
$$= 1 - \exp\left\{-\xi(\theta_d, \alpha)\left(\rho_{UAV}\lambda_{UAV}d_1^2 + \frac{p_{CH}\lambda_{CH}}{N}d_2^2\right)\right\}, \tag{11}$$

where $d_1 = d_{u,i,j}$, $d_2 = d_{i,j,k}$, α is the path-loss exponent, and θ_d is the SINR threshold for the D2D-assisted link.

In addition, $\xi(\theta_d, \alpha)$ is set as follows:

$$\xi(\theta_d, \alpha) = \frac{2\pi^2}{\sin\left(\frac{2\pi}{\alpha}\right)\theta_d^2} \tag{12}$$

In the second hop link between CH and CMs in D2D communication, the network outage occurs when one of the two links, i.e., UAV to CHs and CH to CMs, is not successful in achieving the SINR target of $SINR_{\theta_d}$. Therefore, the UAV is located at (x_u, y_u, z_u), the nonoptimal CH_i is located at

(x_j^o, y_j^o), while the kth CM is located at (x_k, y_k) out of UAV coverage. Subsequently, the distance in the first hop from the UAV and the jth nonoptimal CH are denoted as $d_{u,j}^2 = (x_u - x_j)^2 + (y_u - y_j)^2 + (z_u - 0)^2$. In the same context, the distance in the next hop from the jth nonoptimal CH and the kth CM is denoted as $d_{j,k}^2 = (x_j - x_k)^2 + (y_j - y_k)^2$. Therefore, the outage probability in (11) can be rewritten as follows.

$$P_{out} = 1 - \exp\left\{-\rho_{UAV}\lambda_{UAV}\xi(\theta_d, \alpha)f(x_{u,j,k}, y_{u,j,k})\right\}, \tag{13}$$

where,

$$f(x_{u,j,k}, y_{u,j,k}) = \|(x_u - x_j)\|^2 + \|(y_u - y_j)\|^2 + \|(z_u - 0)\|^2$$
$$+ \Lambda\|(x_j - x_k)\|^2 + \Lambda\|(y_j - y_k)\|^2 \tag{14}$$

and Λ is given as

$$\Lambda = \frac{p_{CH}\lambda_{CH}}{N\rho_{UAV}\lambda_{UAV}}, \tag{15}$$

where p_{CH} is the power transmitted by the CHs, λ_{CH} is the density of CHs, ρ_{UAV} is the UAV load and λ_{UAV} is the density of UAVs. Therefore, the rotation of the CH function among members is selected as the optimal CH based on the efficient distribution for the selected CHs in the network to balance the energy consumption and minimize the outage probability. Subsequently, the aim of finding an optimal solution such that the feasible solution will mitigate P_{out} can be formulated as follows:

$$(x_j^o, y_j^o) = \operatorname{argmin}_{\{x_j, y_j\}} P_{out}$$
$$= \operatorname{argmin}_{\{x_j, y_j\}} f(x_{u,j,k}, y_{u,j,k}). \tag{16}$$

When we take the partial derivatives of $f(x_{u,j,k}, y_{u,j,k})$ in (14) with respect to x_j and y_j and equate them to zero, we obtain the optimal locations of CHs that will achieve the minimum energy consumption and outage probability as follows:

$$x_j^o = \frac{\Lambda x_k + x_u}{1 + \Lambda}, \quad y_j^o = \frac{\Lambda y_k + y_u}{1 + \Lambda}. \tag{17}$$

Due to the communication through the optimal CH, the energy consumption and outage probability will be minimized. As a result, the optimal cluster head (CH) nodes are distributed between the UAV nodes and cluster member (CM) nodes at the edge of the UAV coverage area, as shown in Fig. 3. The CHs move to their optimal locations and enable communication with the UAV and the kth user device out of their coverage area. We obtain the optimal location of CHs as follows:

$$(x_j^o, y_j^o) = \left(\frac{x_u + \Lambda x_k}{1 + \Lambda}, \frac{y_u + \Lambda y_k}{1 + \Lambda}\right). \tag{18}$$

We assume that the locations of nonoptimal CHs are at (x_j, y_j), while the optimal CHs are at (x_j^o, y_j^o), where $(x_j^o, y_j^o) = (x_i, y_i)$. We then determine the distance between the nonoptimal CHs and the optimal CHs as follows.

$$d_{j,i}^2 = \left(x_j - \frac{x_u + \Lambda x_k}{1 + \Lambda}\right)^2 + \left(y_j - \frac{y_u + \Lambda y_k}{1 + \Lambda}\right)^2. \tag{19}$$

Similarly, we determine the distance between the optimal CH and the CMs (x_k, y_k) as follows.

$$d_{i,k}^2 = \left(\frac{x_u + \Lambda x_k}{1 + \Lambda} - x_k\right)^2 + \left(\frac{y_u + \Lambda y_k}{1 + \Lambda} - y_k\right)^2. \quad (20)$$

In addition, the distance between the UAV and the optimal CHs is determined as follows.

$$d_{u,i}^2 = \left(x_u - \frac{x_u + \Lambda x_k}{1 + \Lambda}\right)^2 + \left(y_u - \frac{y_u + \Lambda y_k}{1 + \Lambda}\right)^2 + (z_u - 0)^2. \quad (21)$$

The CHs are located at the intermediate level between the UAV and CMs. Therefore, the optimal elevation angle of the optimal CH from (17) can be achieved as follows:

$$\theta_i^0 = \arctan\left(\frac{\Lambda y_k + y_u}{\Lambda x_k + x_u}\right). \quad (22)$$

Based on the optimal location of CHs, the outage probability of the link between the UAV and optimal CHs and the optimal CH and CMs in (11) can be rewritten as follows.

$$P_{out} = 1 - e^{\left\{-\xi(\theta_d, \alpha)\left(\rho_{\text{UAV}} \lambda_{UAV} d_{u,i}^2 + \frac{p_{CH}\lambda_{CH}}{N} d_{i,k}^2\right)\right\}}, \quad (23)$$

where $d_{u,i}^2$ is the distance from the UAV to the optimal CH, while $d_{i,k}^2$ is the distance from the optimal CH to the kth CM.

C. OUTAGE PROBABILITY OF D2D WITHIN CLUSTERING

To ensure the decoding correctness in the network receivers, the SNR received by CMs should exceed the threshold value γ_{min} [39]. Therefore, the kth CM establishes link communication with the optimal CH through D2D pair communication. According to the above definitions, when the ith optimal CH transmits wireless signals to CMs, the desired received signals by the kth CM can be expressed as $y_{i,k} = d_{i,k}^{-\alpha}\sqrt{h_{i,k}}\,p_{CH} + \sigma^2$, where $y_{i,k}$ is the received wireless signal from the optimal CH, and p_{CH} is the transmit power for the optimal CH. The instantaneous SINR received by the kth CM is $\gamma_{i,k} = \frac{p_{CH}\,h_{i,k}\,d_{i,k}^{-\alpha}}{\sigma^2 B_0}$, where $h_{i,k}$ denotes the channel gain between the optimal CH and the kth CMs and B_0 is the total bandwidth. Consequently, the outage probability of the link between the optimal CH and the kth CM is expressed as follows.

$$P_{out} = \mathbb{P}\left(\gamma_k < \gamma_{min}\right) = \mathbb{P}\left(h_{i,k} < \frac{\sigma^2 B_0 \gamma_{min}}{p_{CH}\,d_{i,k}^{-\alpha}}\right)$$

$$= \int_0^{\left(-\frac{\sigma^2 B_0 \gamma_{min}}{p_{CH}\,d_{i,k}^{-\alpha}}\right)} \exp(-x)\,dx$$

$$= 1 - \exp\left(-\frac{\sigma^2 B_0 \gamma_{min}}{p_{CH}\,d_{i,k}^{-\alpha}}\right). \quad (24)$$

The outage probability of D2D communication within a cluster will be archived through the link from the optimal CH to CMs in full-duplex communication mode. Then, the maximum data rate that can be achieved without any outage is
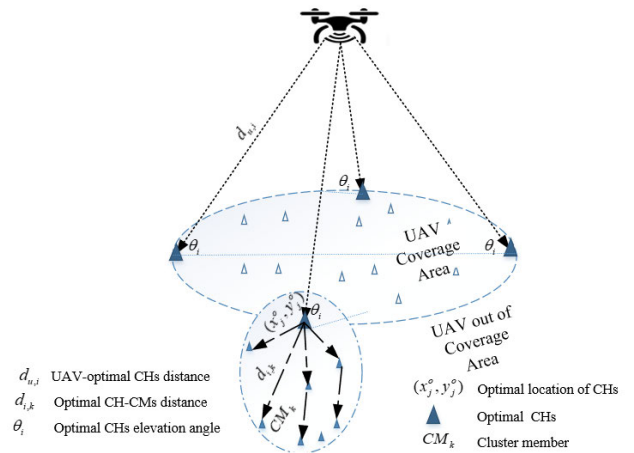

FIGURE 3. Distribution of UAVs, optimal CHs and CMs in the postdisaster scenario.

denoted as the outage capacity. The outage capacity of D2D communication in the cluster is represented as follows.

$$C_{out,i,k} = (1 - p_{out,i,k})B_0 \log_2(1 + \gamma_{min})$$

$$= e^{\frac{-\sigma^2 B_0 \gamma_{min}}{p_{CH}\,d_{i,k}^{-\alpha}}} B_0 \log_2(1 + \gamma_{\min}), \quad (25)$$

where the outage capacity $C_{out,i,k}$ for D2D communication is based on the bandwidth B_0 and distance from the optimal CH to the kth CM. We assume that the kth CM receives the multicast signals from the ith optimal CH in the same time slot. The outage capacity of the multicast channel depends on the transmission rate for every k^{th} CM. Therefore,

$$C_{out} = \min\{C_{out_1}, C_{out_2}, \ldots, C_{out_k}\} \quad (26)$$

According to Fig. 3, user devices are distributed inside and outside of the UAV coverage area. The user devices within the radio coverage range acquire wireless services from the UAV, while those outside of the UAV coverage range obtain wireless services from the ith optimal CH. In this paper, the UAV is deployed in the disaster area at an altitude of H_n and a static location (x_u, y_u, z_u). The CHs extend the coverage area to provide services to more CMs. The optimal elevation angle of the user devices in the disaster area is denoted as θ_i for the ith CH. The downlink air-to-ground (ATG) channel can be either an LoS link or an NLoS link. Therefore, the probability of LoS and NLoS on the optimal CH served by the UAV can be represented as follows [40].

$$P_{\text{LoS}_{u,i}} = \left(1 + a\,e^{-b\,(\theta_i - a)}\right)^{-1}. \quad (27)$$

We exploit the ATG channel model for the optimal CHs and their associated CMs in UAV-assisted communication during disaster recovery. The channel power gain from the UAV to the optimal CHs that are located at (x_i, y_i) under the LoS link is given as follows [30].

$$\bar{h}_{u,i} = P_{\text{LoS}_{u,i}}\left(\sqrt{h^2 + x^2 + y^2}\right)^{-\alpha}$$

$$+ (1 - P_{\text{LoS}_{u,i}})\eta\left(\sqrt{h^2 + x^2 + y^2}\right)^{-\alpha}. \quad (28)$$

The network link quality, communication performance and path loss are highly affected by LoS and NLoS probabilities and other environmental parameters. Furthermore, the path loss between the UAV and optimal CH nodes is obtained as

$$PL(dB) = FSP_{u,i} + APL_{u,i}, \qquad (29)$$

where $FSP_{u,i} = \frac{4\pi f_c d_{u,i}}{c}$ is the free space path loss between the UAV and the ith optimal CH, f_c is the carrier frequency, c is the speed of light, and $d_{u,i}$ is the distance between the UAV and the ith optimal CH. Moreover, $APL_{u,i} = \eta_{\text{LoS}u,i}P_{\text{LoS}u,i} + \eta_{\text{NLoS}u,i}P_{\text{NLoS}u,i}$ is the propagation of free space additional loss that depends on the specific radio environment.

D. OPTIMAL CH POWER CONTROL ANALYSIS

In the case of CHs that change their locations to the optimal location, the user devices are affected by interference based on the new optimal location. Thus, the cluster formation will be reconfigured to minimize the outage probability. Therefore, the optimal CHs are incorporated to minimize the transmit power to reduce the interference for user devices and minimize the power consumption. The power iteration is applied in optimal CHs to adjust the desired received signals at CMs and eliminate the interference of D2D pair communication. We assume that there are $m = 1, 2, \ldots, M$ interfering D2D pair communications. Therefore, the power to transmit vector for D2D pair communication is denoted as $[p_1, p_2, \ldots, p_m, \ldots, p_M]^T$. The SINRs for the UAV to optimal CHs and the optimal CH to CMs are further analyzed to minimize energy consumption and reduce the interference. According to [32], [41], the SINR at the UAV link with the jth nonoptimal CH can be defined as follows:

$$\gamma_j = \frac{p_j h_j}{\sum_{m=1}^{M} p_m h_{m,j} + \sigma^2}, \qquad (30)$$

The SINR at the UAV link to the ith optimal CH that is affected by D2D pair communication is given as follows:

$$\gamma_i = \frac{p_i h_i}{\sum_{m=1}^{M} p_m h_{m,i} + p_j h_j + \sigma^2}, \qquad (31)$$

Finally, the SINR at the receiver of the kth CM as D2D pair communication is given by:

$$\gamma_k = \frac{p_k h_{k,m}}{\sum_{\substack{m=1 \\ m \neq k}}^{M} p_k h_{m,k} + (p_j + p_i)h_{m,j,i} + \sigma^2}, \quad \forall m \in \mathcal{M}, \quad (32)$$

Furthermore, the kth CMs will select the optimal CH based on the maximum residual energy, EH and the number of neighbors that satisfy the SINR threshold. Then, the achievable sum rate of all i^{th} optimal CHs is given as follows.

$$\begin{aligned} R_i &= \log_2 (1 + \gamma_i) \\ &= \log_2 \left(1 + \frac{p_i h_i}{\sum_{m=1}^{M} p_m h_{m,i} + p_j h_j + \sigma^2} \right). \end{aligned} \qquad (33)$$

E. COMPUTATIONAL COMPLEXITY ANALYSIS

In this section, the computational complexity of the proposed algorithm is determined and compared with the results in [32]. In this algorithm, the iteration loop applies to all user devices, including nonoptimal CHs, optimal CHs and the kth CMs in lines 8 to 23. The first loop (lines 8 to 13) has been designated to locate the optimal CH based on (18). The algorithm will find the distance between the UAV and optimal CH and optimal CH and CMs and calculate EH_i at the optimal CH nodes based on (1). In each round, the computational complexity is dominated by matrix inversion and multiplication operations according to (1),(18). The computational complexity for those analyses are $\mathcal{O}(t * N_{(CH_j)})$ where t represents the number of iterations for each CH rotation nodes.

In the second loop (lines 14 to 18), the CM will choose its optimal CH. Additionally, CMs can decide to communicate with the optimal CH based on the residual energy, maximum EH and neighbor nodes. In this case, D2D pair communications and outage capacity inside the cluster are calculated based on (24) and (25). The computational complexity for those analyses is found to be $\mathcal{O}(t * N_{CM_k})$. The third loop (lines 19 to 22) is intended to minimize the optimal CH power consumption based on the following power control condition $p_n^{CH} \leqslant \frac{e_1}{Ne_3}\zeta \sum_{n=1}^{N} p_n^{S,1} \left| h_n^{S-CH} \right|^2$.

Here, the UAV is configured to control the transmit power by sending the maximum transmit power over n-subcarriers to an optimal CH and the minimum transmit power to UEs in its coverage range to reduce interference that affects the optimal CH nodes. In addition, the optimal CHs apply control strategies to forward transmit power with its associated CMs through D2D pair communication to minimize the interference and power consumption. Here, the computational complexity based on the power control iteration is $\mathcal{O}(t * N_{(CH_i)})$. Therefore, the computational complexity of the algorithm is $\mathcal{O}(t * N_{(CH_j)}) + \mathcal{O}(t * N_{(CM_k)}) + \mathcal{O}(t * N_{(CH_i)}))$ Therefore, when we assume that the N user devices distributed in the system model include (CH_j, CH_i, CM_k), then the total computational complexity for the proposed method's solution is on the order of $\mathcal{O}(3 * t * N)$.

Furthermore, the complexity of the proposed scheme is mainly determined by the complexity of solving the linear program at each iteration of the search where the linear program is solvable in polynomial time [42]. The number of iterations is limited to $t = t_{max}$ to guarantee the convergence of the proposed algorithm. The complexity of the related work presented in [32] is on the order of $\mathcal{O}(LM^c)$. Thus, low complexity is the ultimate benefit of the proposed algorithm used in the emergency communication system for disaster management.

V. SIMULATION RESULTS AND DISCUSSION

In this section, the simulation results are presented to demonstrate the performance of the proposed methods. Energy consumption, energy harvesting and outage probability will be analyzed for several user devices in disaster scenarios.

TABLE 1. Simulation parameters.

Parameters	Values
Bandwidth	B_0=5 MHz
Number of clusters	6
UAV maximum transmit power	p_u^{max} = 5 W
Transmission block time	T=1 s - 3 s
UAV-user devices vertical distance	d= 500 m
Time slot ratios	$\{e_1, e_2, e_3\} = (0 - 1)$
CH spatial density	$\lambda_{CH} = \{1^{-8}, 2^{-8}, 3^{-8}\}$
Threshold (SNR)	γ_{min}=30 dB
D2D transmission distance	R_d=1 m - 50 m
Noise power spectral density	σ^2=-174 dBm/Hz
Carrier frequency	f_c=3.5 GHz
Path-loss exponent (PLE)	α=2-4
EH efficiency	ζ = 0.1-0.9
α_{D2D}	3
Excess-loss encountered	η=0.5
UAV altitude range	H=100 m - 250 m
Urban environment	a=9.6, b=0.16 η_{LoS}=1, η_{NLoS}=20

The simulation parameters used are shown in Table 1, while Algorithm 1 shows the proposed method used to select the optimal CHs.

A. ENERGY HARVESTING PERFORMANCE FOR UAV

Fig. 4 shows the energy harvesting for various user device distances when the deployed UAVs change their altitudes. UAV altitudes are affected by the probability of LoS based on the change of elevation angle of user devices when the vertical distance of the UAV to user devices varies by up to 500 m. Thus, the UAV can adjust its altitude to provide improved network coverage for user devices. However, EH is affected by UAV altitudes when the large-scale path loss is considered for user distances when the bandwidth is fixed. In addition, the UAV altitude affects the EH performance because it needs a higher transmit power to compensate for the increasing user distance and more hops between UAV-CH and CH-CMs at higher altitudes. This is demonstrated in Fig. 4, which shows that EH decreases as a function of the user device distance. Therefore, the UAV moves up in altitude, which will increase the probability of LoS and increase path loss. For $100 \ m \leq H \leq 200 \ m$, Fig. 4 shows that EH deceased from 1.2 joules to 0.1 joules with an increase in distance from 100 m to 500 m respectively. Furthermore, UAV altitudes affect the EH because a higher transmit power will be needed with an increasing distance and an increasing number of hops between CH and D2D at higher altitudes.

In Fig. 5, EH performance versus ζ is simulated for UAV and D2D communication. As shown in the figure, EH is equal to 1.5 joules at $\zeta = 0$ in the UAV scenario, while in the D2D scenario, it is equal to 0.6 joules. Hence, EH maximizes the UAV direct link scenario at approximately 50% for the UAV link scenario through CHs as D2D communication. Thus, it can be concluded that EH performance in the UAV scenario is better than that in the D2D communication. This

---

Algorithm 1: Hybrid Optimal CH, EH and PC

1 t! t_{max}: Maximum number of iterations
2 P_{max}: Maximum transmission power of the UAV
3 CH_j: Nonoptimal CH_j nodes
4 CH_i: Optimal CH_i nodes
5 CM_K: Out of coverage CM_k nodes
6 $d_{u,i}$: The distance from the UAV to the optimal CH_i
7 $d_{i,k}$: The distance from the optimal CH_i to CM_k
8 **for** $t = 1$ to t_{max} **do**
9   Cluster is formed with its proximity devices based on PCP distribution
10   **for** $i = 1$ to CH_j **do**
11   Find optimal CH_i location (x_j^o, y_j^o) according to (18)
12   Calculate EH_i based on (1)
13   **end**
14   **for** $k = 1$ to CM_k **do**
15   k^{th} CM chooses optimal CH_i based on maximum residual energy, EH and number of the neighborhood
16   Calculate $p_{out,k}$ of D2D according to (24)
17   Calculate $C_{out,k}$ of D2D according to (25)
18   **end**
19   **for** $j = 1$ to CH_i **do**
20   The power that satisfies
$$p_j^{CH} \leqslant \frac{e_1}{Ne_3} \zeta \sum_{j=1}^{N} p_j^{S,1} \left| h_j^{S-CH} \right|^2$$
21   to minimize energy consumption
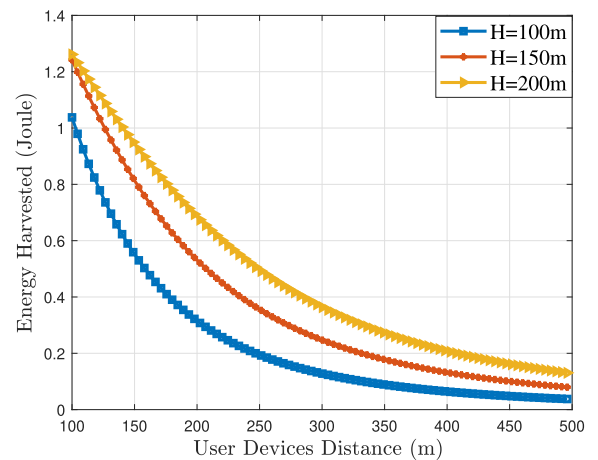22   **end**
23 **end**

FIGURE 4. Energy harvested *vs.* distance at different UAV altitudes.

is attributed to the substantial LoS propagation path gain between the UAV and CHs and the slight loss of received signals at the user device receivers. Additionally, EH in D2D communication is lower than that with UAVs due to the lower amount of power needed for the CH to forward the wireless signal to CMs.
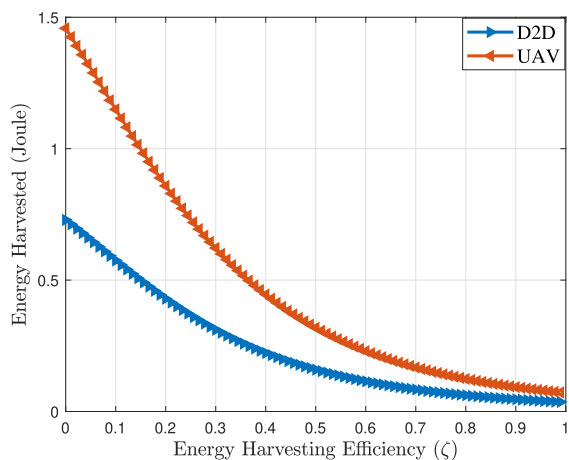
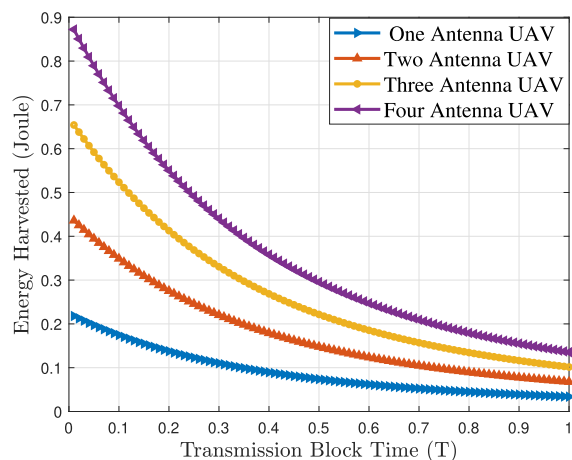**FIGURE 5.** EH performance *vs.* ζ for UAV and D2D.

FIGURE 7. Analysis of the energy harvesting *vs.* time interval with multiantenna UAVs.
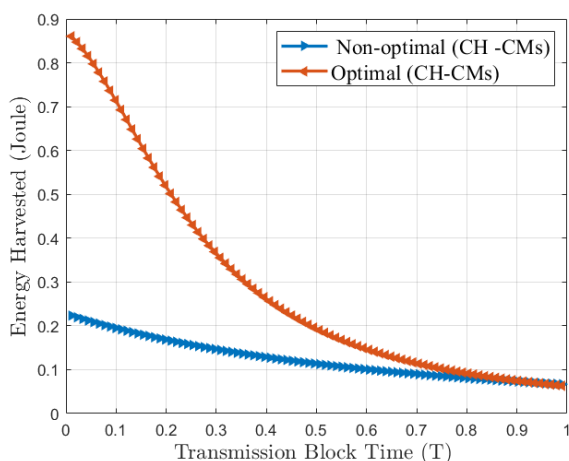

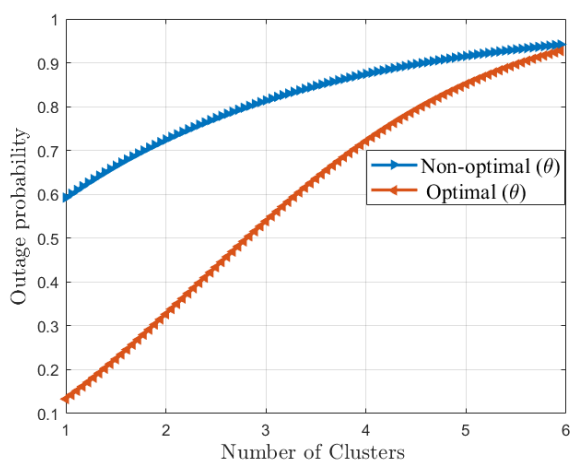**FIGURE 6.** Energy harvested *vs.* transmission block time with the CHs.

FIGURE 8. Outage probability *vs* number of clusters for optimal and nonoptimal CHs.

B. ENERGY HARVESTING BASED ON D2D

Fig. 6 presents the energy harvesting capability for the nonoptimal CH and optimal CH. It is evident from the figure that the D2D communication between the optimal CH and CMs harvests more energy than that between the nonoptimal CH and CMs. Therefore, determining the optimal location of CH is crucial because it reduces the transmission power between the UAV and user devices; thus, it improves the harvested energy. Furthermore, the optimal CH will also reduce the communication latency between CH and CMs due to the shorter communication range.

It is understood that more energy is required to increase the UAV coverage range. Thus, the next step is to analyze the energy harvested by multiantenna UAVs. As anticipated, the amount of energy harvested through multiantenna UAVs is more than that of a single-antenna UAV, as shown in Fig. 7. For example, at transmission block time 0.3, the amount of energy harvested is 0.1 joule for a single-antenna UAV, while for a four-antenna UAV, it is 0.45 joules. Therefore, energy harvesting using multiantenna UAV will increase energy efficiency and thus serve a larger coverage area.

C. OUTAGE PROBABILITY PERFORMANCE

Fig. 8 shows that the outage probability is improved when the elevation angle of the CHs is at its optimal value. The outage probability with an elevation angle based on nonoptimal CHs ranges from 0.6 to 0.95, whereas the outage probability for the optimal elevation angle is in the range of 0.1 to 0.95. Therefore, the optimal elevation angle of CHs provides more sustainable connectivity during a disaster scenario. The optimal location of the CH can effectively increase the coverage probability and decrease the outage probability.

Further analysis of the overall outage probability for the UAV and D2D user devices versus the transmission block time (T) as two different postdisaster scenarios is shown in Fig. 9. As the number of retransmissions (transmission block time) increases, the overall outage probability also increases. In other words, for the higher number of (T), the possibility that a failure happens during retransmissions increases. Furthermore, the UAV is an interference source for the D2D user devices, and the higher number of stop points leads to a higher outage probability. As a result, the outage probability of the UAV is lower than that of D2D due to the
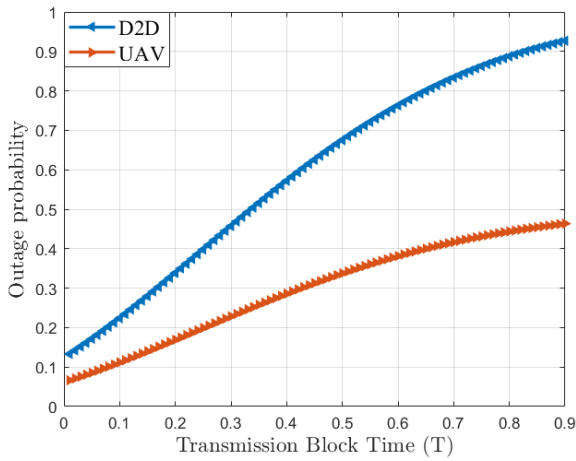
FIGURE 9. Performance of outage probability *vs.* transmission block time for the UAV link and D2D link.
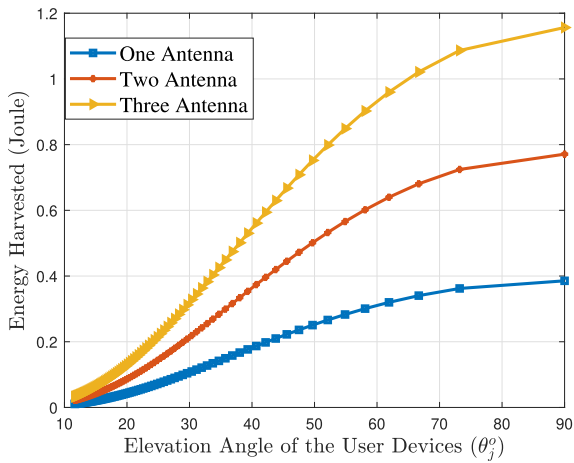

FIGURE 10. Energy harvested (joule) *vs.* the elevation angle with three UAV antenna.

strong LoS link between the source and destination and the slight loss of the received signals at the user device receivers. Moreover, the outage probability of the UAV while communicating with user devices is much better than the outage performance of the D2D communication mode, primarily due to the higher channel quality associated with the UAV scenario. Hence, the LoS propagation gain of the UAV outage probability performance is better than that of D2D, which maintains short distance connectivity and distance between the end nodes, which is greater than the UAV coverage radius.

A higher number of antennas eventually increases the transmission power that improves wireless coverage services. Fig. 10 shows the EH performance when the elevation angle of user devices varies for up to three UAV transmission antenna. As expected, EH increases when user device elevation angles are raised for the same level of coverage in multiantenna UAV. Moreover, the maximum EH of 1.1 joules is achieved at a maximum elevation angle of 90° in the case of three UAV antennas. However, the minimum EH performance is 0.4 joule, which is achieved at a maximum elevation
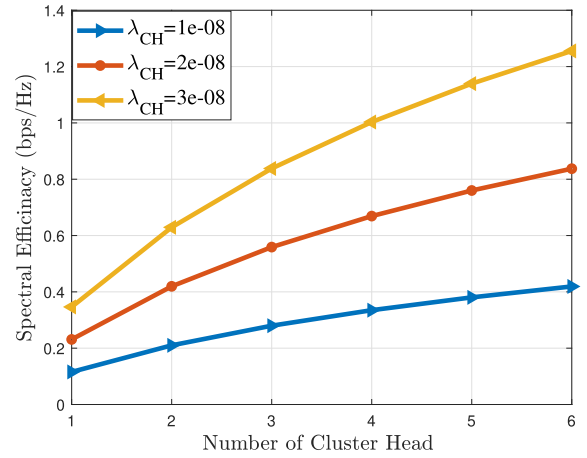

FIGURE 11. Spectral efficiency *vs.* number of CHs with different densities.

angle of 90° in the case of one UAV antenna. Thus, the EH efficiency of UAVs can be improved to enable flying for a longer duration and operating optimally within the receiver's LoS range using multiple antennas.

D. SPECTRAL EFFICIENCY PERFORMANCE
As previously mentioned, a UAV is deployed to ensure uninterrupted wireless coverage in the disaster area while D2D communication increases the coverage area and improves the spectral efficiency.

Fig. 11 shows the performance of spectral efficiency with various CH densities. The spectral efficiency increases when the number of CHs increases because the optimal reuse of radio resources and densities directly affects the energy of the network coverage. The wideband channel for the link between the UAV and optimal/nonoptimal CHs acts for widely deployed user devices with low-power channel sounding solutions. In addition to the system model's wideband, it helps to increase the system efficiency based on the optimal CH approach that integrates EH and PC in the emergency communication system.

It has been further investigated that the higher CH densities will improve the spectral efficiency in the considered network scenario. For instance, when the CHs are increased from 1 to 6 at CH density $\lambda_{CH} = 10^{-8}$, the spectral efficiency increases from 0.1 bps/Hz to 0.4 bps/Hz. Similarly, spectral efficiency improves from 0.2 bps/Hz to 0.8 bps/Hz and from 0.4 bps/Hz to 1.3 bps/Hz at CH densities of $\lambda_{CH} = 2 \times 10^{-8}$ and $\lambda_{CH} = 3 \times 10^{-8}$, respectively. A higher spatial density of CHs can serve more CMs based on the formation of the cluster and D2D communication pairs to achieve the same level of system spectral efficiency. The clustering technique is applied to reduce the computational complexity, trim the data and expand the connectivity. However, a further increase in the number of clusters may disrupt the performance of the post-disaster communication system due to the limitation of the transmission power and the distance of the wireless coverage. Fig. 12 shows EH performance for various transmission time slots with optimal power allocation for two-hop EH systems,
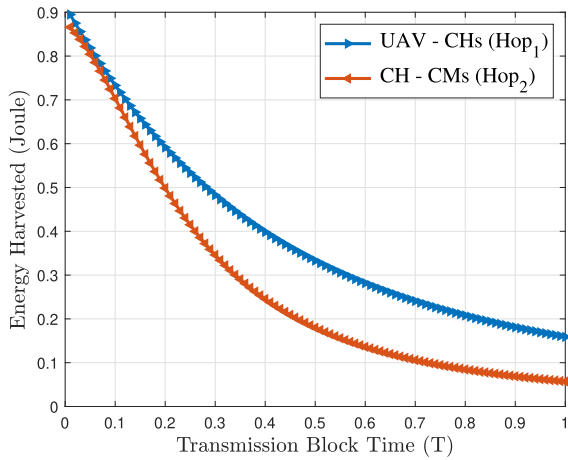
FIGURE 12. Energy harvested *vs.* transmission block time in a two-hop network.
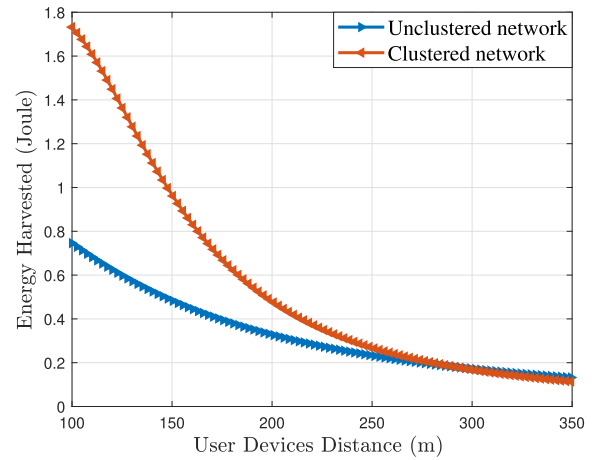

FIGURE 14. Energy harvested *vs.* user device distance with clustering and unclustered networks.
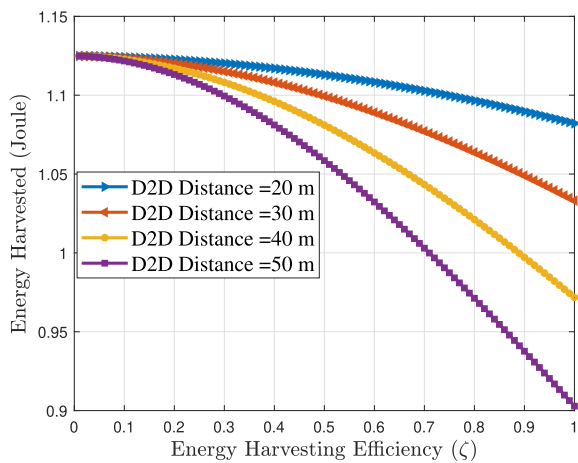

FIGURE 13. Energy harvested *vs.* energy harvesting efficiency at different D2D distances.

FIGURE 15. Comparison of outage probability of best CHs selection approach based on the optimal location for CHs and CMs.

i.e., UAV – CHs and CH – CMs. Based on these results, it is apparent that the LoS in the first-hop communication, i.e., UAV – CHs, is better than that in the second-hop link, i.e., CH – CMs.

Next, we set the D2D distance to 20 m, 30 m, 40 m and 50 m apart and measured the harvested energy versus the energy harvesting efficiency. Fig. 13 shows that the harvested energy decreases as the sparsity distance increases. This is attributed to lower user density as the sparsity distance increases and lesser D2D link interference. Moreover, when the distance between CH and CMs increases by more than 20 m, the EH performance is stably degraded because of a higher path loss or a lower received SINR when the distance is increased.

Fig. 14 shows an analysis of EH for various user device distances with a clustering network and an unclustered network. The clustering network contributes more to increasing EH due to the decentralized control and the low path loss of received signals based on the communication distance. The clustering network decreases harvested energy from 1.8 joule to 0.2 joule when user device distances increase from 100 m
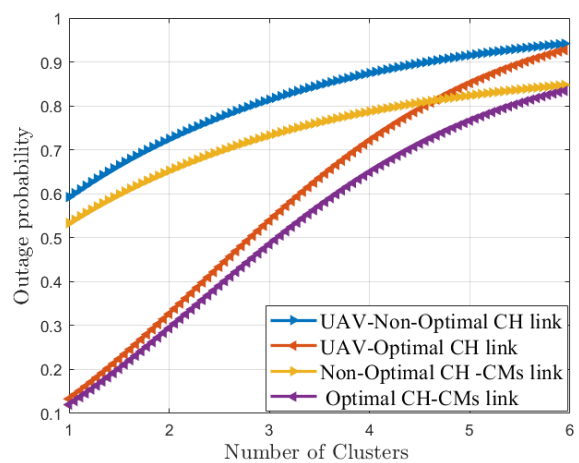
to 350 m. However, the unclustered network decreases from 0.8 joule to 0.2 joule. Therefore, clustering is an appropriate approach for wireless communication in postdisaster scenarios as it will be able to prolong the network energy lifetime. Furthermore, the EH with the clustered network will be scalable to overcome challenges in disaster events, e.g., limited resources and network capacity.

Fig. 15 demonstrates the outage probability of the CH for a different number of clusters. Similar to the findings depicted in Fig. 8, the optimal CH also achieves a lower outage probability than the nonoptimal CH in both UAV–CHs and CH–CMs links, which will improve the stability of the networks. Another important observation in this figure is that with CH, communication latency between CH and CMs is reduced due to the shorter propagation distance; hence, the outage probability is reduced while maintaining the superiority of the optimal CH with respect to the nonoptimal CH.

Fig. 16 compares the D2D outage probability of the proposed solution, i.e., the UAV connected to optimal CHs, with the work presented in [32]. It can be observed that the outage
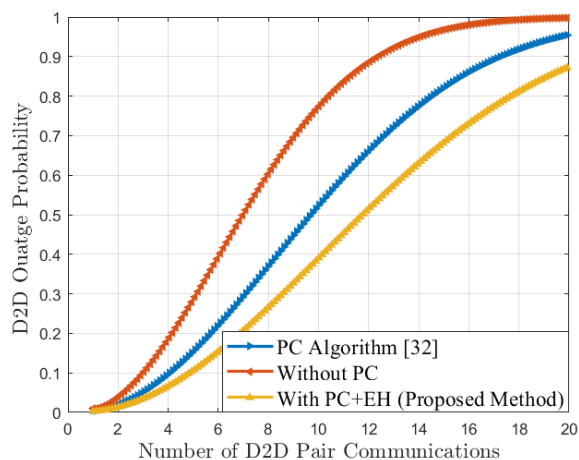
FIGURE 16. Comparison of D2D outage probability versus number of D2D pair communications based on the PC and EH performance.
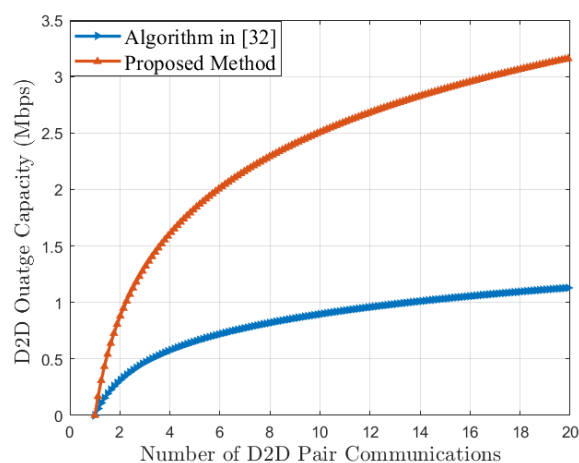

FIGURE 17. Comparison of D2D outage capacity versus number of D2D pair communications based on the PC and EH performance.

probability of the proposed solution is approximately 10% higher than the work in [32]. It can be seen that, for example, when the D2D pair communications are 20, the outage probability of the proposed solution is 0.86%, while it is 0.95% in [32]. This is attributed to the higher channel quality associated with optimal CHs.

Fig. 17 shows the performance of the outage capacity versus the number of D2D pair communications. It can be seen that when the number of D2D links is equal to 10, the outage capacity of the proposed solution is 2.5 Mbps, while it is at 0.9 Mbps in [32], a whopping increase of approximately 90%. This can be credited to eliminating the battery power barriers and interference of UAVs and user devices through a combination of EH and PC. This will guarantee the communication link quality between the optimal CH-CMs as D2D communication pairs.

VI. CONCLUSION

In this paper, we addressed the difficulty of maintaining continuous wireless communication activities when disaster strikes. An efficient UAV-assisted emergency communication with clustering techniques was adopted. An optimal CH was introduced and utilized to harvest energy for stable networks that enhanced the network coverage and reliability. It was also proven that the EH of the optimal CH links is better than that of the nonoptimal CH links. Therefore, the optimal CH can reduce the transmission power needed for the UAV and user devices leading to a better outage probability for optimal links. Establishing links between the CH and CMs is also crucial in disaster scenarios, as it increases the coverage services provided to the disaster victims, i.e., more victims can be reached by the search and rescue teams, potentially saving many lives. Emergency communication systems have limitations when minimizing the UAV outage probability during disaster recovery with the cluster-based channel model. A multipath clustering approach for the channel model between the UAV and user devices will be further investigated to enable increasing the accuracy of clustering and the reliability of communication in postdisaster scenarios.

REFERENCES

[1] S. Voigt, F. Giulio-Tonolo, J. Lyons, J. Kučera, B. Jones, T. Schneiderhan, G. Platzeck, K. Kaku, M. K. Hazarika, L. Czaran, S. Li, W. Pedersen, G. K. James, C. Proy, D. M. Muthike, J. Bequignon, and D. Guha-Sapir, "Global trends in satellite-based emergency mapping," *Science*, vol. 353, no. 6296, pp. 247–252, Jul. 2016.

[2] F. Bader, L. Martinod, G. Baldini, F. Frantz, S. Kandeepan, and O. Sallent, "Future evolution of public safety communications in the 5G era," *Trans. Emerg. Telecommun. Technol.*, vol. 28, no. 3, Mar. 2017, Art. no. e3101.

[3] G. Baldini, S. Karanasios, D. Allen, and F. Vergari, "Survey of wireless communication technologies for public safety," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 2, pp. 619–641, 2nd Quart., 2014.

[4] Q. Wu, J. Xu, Y. Zeng, D. W. K. Ng, N. Al-Dhahir, R. Schober, and A. L. Swindlehurst, "5G-and-beyond networks with UAVs: From communications to sensing and intelligence," 2020, *arXiv:2010.09317*. [Online]. Available: http://arxiv.org/abs/2010.09317

[5] A. Saif, K. Dimyati, K. A. Noordin, N. S. M. Shah, Q. Abdullah, and F. Mukhlif, "Unmanned aerial vehicles for post-disaster communication networks," in *Proc. IEEE 10th Int. Conf. Syst. Eng. Technol. (ICSET)*, Nov. 2020, pp. 273–277.

[6] E. Christy, R. P. Astuti, B. Syihabuddin, B. Narottama, O. Rhesa, and F. Rachmawati, "Optimum UAV flying path for device-to-device communications in disaster area," in *Proc. Int. Conf. Signals Syst. (ICSigSys)*, May 2017, pp. 318–322.

[7] M. S. Bahbahani and E. Alsusa, "A cooperative clustering protocol with duty cycling for energy harvesting enabled wireless sensor networks," *IEEE Trans. Wireless Commun.*, vol. 17, no. 1, pp. 101–111, Jan. 2018.

[8] T. Prior and F. Roth, "Preparing for disasters in global cities: An international comparison," Center Secur. Studies, ETH Zürich, Zürich, Switzerland, Tech. Rep., 2013.

[9] M. A. Kishk, A. Bader, and M.-S. Alouini, "On the 3-D placement of airborne base stations using tethered UAVs," *IEEE Trans. Commun.*, vol. 68, no. 8, pp. 5202–5215, Aug. 2020.

[10] S. Alsamhi, F. Almalki, O. Ma, M. Ansari, and M. Angelides, "Performance optimization of tethered balloon technology for public safety and emergency communications," *Telecommun. Syst.*, vol. 75, pp. 235–244, May 2019.

[11] K. Ali, H. X. Nguyen, Q.-T. Vien, P. Shah, and Z. Chu, "Disaster management using D2D communication with power transfer and clustering techniques," *IEEE Access*, vol. 6, pp. 14643–14654, 2018.

[12] J. Zhang, Y. Zeng, and R. Zhang, "Multi-antenna UAV data harvesting: Joint trajectory and communication optimization," *J. Commun. Inf. Netw.*, vol. 5, no. 1, pp. 86–99, Apr. 2020.

[13] F. Mukhlif, K. A. B. Nooridin, Y. A. AL-Gumaei, and A. S. AL-Rassas, "Energy harvesting for efficient 5G networks," in *Proc. Int. Conf. Smart Comput. Electron. Enterprise (ICSCEE)*, Jul. 2018, pp. 1–5.

[14] Z. Zhou, C. Gao, C. Xu, T. Chen, D. Zhang, and S. Mumtaz, "Energy-efficient stable matching for resource allocation in energy harvesting-based device-to-device communications," *IEEE Access*, vol. 5, pp. 15184–15196, 2017.

[15] S. T. Shah, K. W. Choi, S. F. Hasan, and M. Y. Chung, "Throughput analysis of two-way relay networks with wireless energy harvesting capabilities," *Ad Hoc Netw.*, vol. 53, pp. 123–131, Dec. 2016.

[16] F. Mukhlif, K. A. B. Nooridin, Y. A. AL-Gumaei, and A. S. AL-Rassas, "Energy harvesting for efficient 5G networks," in *Proc. Int. Conf. Smart Comput. Electron. Enterprise (ICSCEE)*, Jul. 2018, pp. 1–5.

[17] T. Koskela, S. Hakola, T. Chen, and J. Lehtomaki, "Clustering concept using device-to-device communication in cellular system," in *Proc. IEEE Wireless Commun. Netw. Conf.*, Apr. 2010, pp. 1–6.

[18] A. A. Khan, M. Abolhasan, and W. Ni, "An evolutionary game theoretic approach for stable and optimized clustering in VANETs," *IEEE Trans. Veh. Technol.*, vol. 67, no. 5, pp. 4501–4513, May 2018.

[19] M. F. Khan, F. Aadil, M. Maqsood, S. H. R. Bukhari, M. Hussain, and Y. Nam, "Moth flame clustering algorithm for Internet of vehicle (MFCA-IoV)," *IEEE Access*, vol. 7, pp. 11613–11629, 2019.

[20] W. Qi, Q. Song, X. Wang, L. Guo, and Z. Ning, "SDN-enabled social-aware clustering in 5G-VANET systems," *IEEE Access*, vol. 6, pp. 28213–28224, 2018.

[21] D. Zhang, H. Ge, T. Zhang, Y.-Y. Cui, X. Liu, and G. Mao, "New multi-hop clustering algorithm for vehicular ad hoc networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 20, no. 4, pp. 1517–1530, Apr. 2019.

[22] X. Liu, Y. Liu, Y. Chen, and L. Hanzo, "Trajectory design and power control for multi-UAV assisted wireless networks: A machine learning approach," *IEEE Trans. Veh. Technol.*, vol. 68, no. 8, pp. 7957–7969, Aug. 2019.

[23] K. G. Panda, S. Das, D. Sen, and W. Arif, "Design and deployment of UAV-aided post-disaster emergency network," *IEEE Access*, vol. 7, pp. 102985–102999, 2019.

[24] F. Syed, S. K. Gupta, S. H. Alsamhi, M. Rashid, and X. Liu, "A survey on recent optimal techniques for securing unmanned aerial vehicles applications," *Trans. Emerg. Telecommun. Technol.*, Oct. 2020, Art. no. e4133.

[25] Z. Liu, Y. Zhao, P. Fang, J. Gao, and Z. Chen, "UAV-assisted time division power allocation strategy based on RF energy harvesting," in *Proc. IEEE 91st Veh. Technol. Conf. (VTC-Spring)*, May 2020, pp. 1–5.

[26] S. K. Haider, M. A. Jamshed, A. Jiang, H. Pervaiz, and Q. Ni, "UAV-assisted cluster-head selection mechanism for wireless sensor network applications," in *Proc. UK/ China Emerg. Technol. (UCET)*, Aug. 2019, pp. 1–2.

[27] S. K. Haider, M. A. Jamshed, A. Jiang, and H. Pervaiz, "An energy efficient cluster-heads re-usability mechanism for wireless sensor networks," in *Proc. IEEE Int. Conf. Commun. Workshops (ICC Workshops)*, May 2019, pp. 1–6.

[28] H. Yang, Y. Ye, X. Chu, and M. Dong, "Resource and power allocation in SWIPT-enabled device-to-device communications based on a nonlinear energy harvesting model," *IEEE Internet Things J.*, vol. 7, no. 11, pp. 10813–10825, Nov. 2020.

[29] R. Li, P. Hong, K. Xue, M. Zhang, and T. Yang, "Energy-efficient resource allocation for high-rate underlay D2D communications with statistical CSI: A one-to-many strategy," *IEEE Trans. Veh. Technol.*, vol. 69, no. 4, pp. 4006–4018, Apr. 2020.

[30] M.-N. Nguyen, L. D. Nguyen, T. Q. Duong, and H. D. Tuan, "Real-time optimal resource allocation for embedded UAV communication systems," *IEEE Wireless Commun. Lett.*, vol. 8, no. 1, pp. 225–228, Feb. 2019.

[31] C. Xing and F. Li, "Unlicensed spectrum-sharing mechanism based on Wi-Fi security requirements implemented using device to device communication technology," *IEEE Access*, vol. 8, pp. 135025–135036, 2020.

[32] M. M. Selim, M. Rihan, Y. Yang, L. Huang, Z. Quan, and J. Ma, "On the outage probability and power control of D2D underlaying NOMA UAV-assisted networks," *IEEE Access*, vol. 7, pp. 16525–16536, 2019.

[33] S. A. Rashid, L. Audah, M. M. Hamdi, and S. Alani, "Prediction based efficient multi-hop clustering approach with adaptive relay node selection for VANET," *J. Commun.*, vol. 15, no. 4, pp. 332–344, 2020.

[34] X. Lu, P. Wang, D. Niyato, D. I. Kim, and Z. Han, "Wireless networks with RF energy harvesting: A contemporary survey," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 2, pp. 757–789, 2nd Quart., 2015.

[35] G. Huang, Q. Zhang, and J. Qin, "Joint time switching and power allocation for multicarrier decode-and-forward relay networks with SWIPT," *IEEE Signal Process. Lett.*, vol. 22, no. 12, pp. 2284–2288, Dec. 2015.

[36] A. A. Nasir, X. Zhou, S. Durrani, and R. A. Kennedy, "Relaying protocols for wireless energy harvesting and information processing," *IEEE Trans. Wireless Commun.*, vol. 12, no. 7, pp. 3622–3636, Jul. 2013.

[37] Z. Ding, I. Krikidis, B. Sharif, and H. V. Poor, "Wireless information and power transfer in cooperative networks with spatially random relays," *IEEE Trans. Wireless Commun.*, vol. 13, no. 8, pp. 4440–4453, Aug. 2014.

[38] E. Yaacoub and O. Kubbar, "Energy-efficient device-to-device communications in LTE public safety networks," in *Proc. IEEE Globecom Workshops*, Dec. 2012, pp. 391–395.

[39] B. Peng, T. Peng, Z. Liu, Y. Yang, and C. Hu, "Cluster-based multicast transmission for device-to-device (D2D) communication," in *Proc. IEEE 78th Veh. Technol. Conf. (VTC Fall)*, Sep. 2013, pp. 1–5.

[40] W. Shi, J. Li, N. Cheng, F. Lyu, S. Zhang, H. Zhou, and X. Shen, "Multi-drone 3-D trajectory planning and scheduling in drone-assisted radio access networks," *IEEE Trans. Veh. Technol.*, vol. 68, no. 8, pp. 8145–8158, Aug. 2019.

[41] W. Mei, Q. Wu, and R. Zhang, "Cellular-connected UAV: Uplink association, power control and interference coordination," *IEEE Trans. Wireless Commun.*, vol. 18, no. 11, pp. 5380–5393, Nov. 2019.

[42] D. P. Dobkin and S. P. Reiss, "The complexity of linear programming," *Theor. Comput. Sci.*, vol. 11, no. 1, pp. 1–18, May 1980.

ABDU SAIF (Member, IEEE) received the B.E. degree in electronics communication from IBB University, Yemen, in 2005, and the M.Sc. degree in project management from the University of Malaya, Malaysia, in 2017. He is currently pursuing the Ph.D. degree in electrical engineering (major in wireless communication) with the Faculty of Engineering, University of Malaya, Kuala Lumpur, Malaysia. He has more than nine years of industrial experience in telecommunications companies. His research interests include wireless networks, 3D coverage by UAV, the Internet of Things, emergency management systems, and public safety communication for 5G.

KAHARUDIN DIMYATI (Member, IEEE) received the B.E. degree in electrical from the University of Malaya, Kuala Lumpur, Malaysia, in 1992, and the Ph.D. degree in communication systems from the University of Wales Swansea, U.K., in 1993 and 1996, respectively. He is currently a Professor with the Department of Electrical Engineering, University of Malaya. His research interests include wireless communication, optical communication, and coding theory. He had supervised to completion to date 20 Ph.D. students and 33 master by research students. He had published more 100 articles in reputed journals. He is a member of IET (U.K.), IEICE (Japan), and IEM (Malaysia).

KAMARUL ARIFFIN NOORDIN (Senior Member, IEEE) received the B.Eng. (Hons.) and M.Eng degrees from the University of Malaya, Kuala Lumpur, Malaysia, in 1998 and 2001, respectively, and the Ph.D. degree in communication systems from Lancaster University, U.K., in 2009. He is an Associate Professor with the Department of Electrical Engineering, University of Malaya. His research interests mainly include resource allocation in wireless networks, cognitive radio networks, device-to-device communications, network modeling, and performance analysis.

DEEPAK G C (Member, IEEE) received the B.E. degree in electronics engineering from Pokhara University, Nepal, the M.Sc. degree in computer engineering from Chonbuk National University, South Korea, and the Ph.D. degree from Lancaster University, U.K., in 2017. He is a Lecturer at the School of Computer Science and Mathematics, Kingston University London. He has previously worked as a Research Fellow at Liverpool John Moores University, U.K., under EU H2020 Project Wi-5 and Kingston University London under EPSRC GCRF Project DARE. His research interests include radio access technologies, cognitive radio, 5G, physical layer security, the Internet of Things, cyber security, and public safety communications.

QAZWAN ABDULLAH (Member, IEEE) was born in Taiz, Yemen. He received the bachelor's and master's degrees in electrical and electronic engineering from Universiti Tun Hussein Onn Malaysia (UTHM), in 2013 and 2015, respectively. He is currently pursuing the Ph.D. degree with a focus on control systems, wireless technology, and antenna filter design.

NOR SHAHIDA MOHD SHAH (Member, IEEE) received the B.Eng. degree from the Tokyo Institute of Technology, in 2000, the M.Sc. degree from the University of Malaya, in 2003, and the Ph.D. degree from Osaka University, in 2012. Since 2004, she has been with Universiti Tun Hussein Onn Malaysia. Her research interests include optical fiber devices, optical communication, antenna and propagation, and wireless communication.

MAHATHIR MOHAMAD received the B.Sc. degree from Universiti Putra Malaysia, in 2000, the M.Sc. degree from the National University of Malaysia, in 2003, and the Ph.D. degree from Osaka University, in 2012. He is currently a Senior Lecturer at Universiti Tun Hussein Onn Malaysia. He is majoring in applied mathematics.

• • •