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Research Article

Device to Device Disaster Management: Squirrel Search Algorithm Approach

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Abstract: Cellular networks can overcome their bandwidth bottleneck problem through the use of device-to-device communication paradigm. In instances of traffic congestion and natural calamities, these technologies aid in preserving the essential connection between user devices. It overcomes the need for nearby user equipment (UEs) to send their radio signals through the BS or the core network to facilitate immediate information sharing. This work addresses relay-assisted device-to-device (D2D) communication in disaster scenarios. An adaptive architecture for D2D communications is developed that can be used in emergency conditions. In particular, fuzzy based a new nature-inspired squirrel search algorithm (SSA) is proposed for CH selection. By using this method, a UERCH is selected and the information is passed through this relay CH. To enable communication between victims of natural catastrophes and emergency personnel, the architecture uses an SDN controller to help it establish a multi-hop routing path. Additionally, we offer a public safety scenario in which a portion of the network goes down as a result of exceptional occurrences like natural disaster, showcasing the robustness and potential of our proposed method. On comparing with the existing approach, the simulation results show that the suggested method achieves low energy usage with enhanced device battery life.

***Keywords*:** device to device communication, Internet of Things, disaster area, functional area, cluster head selection

1. Introduction

A reliable catastrophe and warning system is essential during a disaster, requiring key features such as high precision, quick access to information, and secure transmission of events to the emergency response centre [1]. In extraordinary situations or natural disasters, infrastructure-based communication may be unavailable. Therefore, alternative communication methods are crucial for informing rescue workers about the disaster [2]. Connectivity becomes a significant challenge in post-disaster scenarios, making it a critical area of research in recent years. Assessing the damage and re-establishing communication networks is a major concern post-disaster. Additionally, rescuers face difficulties in contacting victims buried beneath debris. People carrying D2D-capable devices, who share various social attributes, are often in close proximity. As a result, D2D communication has been prioritized for public safety in LTE 3GPP versions 12 and 13, demonstrating its potential to meet societal obligations [3].

In remote and inaccessible areas, natural disasters are monitored by Wireless Sensor Networks (WSNs), which are integral to the Internet of Things (IoT). Autonomous, low-energy sensor nodes using WSNs record and measure

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environmental conditions [4]. Connectivity among sensing devices is established to monitor specific phenomena [5]. However, a fully connected sensor network may not be possible if there is a communication breakdown or if the sensors are placed far from the sink [6]. To enhance disaster management systems in next-generation communication, the integration of advanced artificial intelligence technologies and heterogeneous resources is vital [7].

The IoT has demonstrated its inherent ability to offer substantial, scalable, and energy-efficient solutions to various disaster management challenges [8]. Several paradigms have been considered for re-establishing connectivity. In infrastructure-less post-disaster scenarios, IoT can be combined with Unmanned Aerial Vehicles (UAVs) and D2D communication, providing a more effective solution than conventional methods like satellite imagery and remote camera-based sensing, which may not be efficient in these situations [9]. Given these challenges, understanding how to re-establish seamless communication without infrastructure becomes crucial [10]. D2D communication is increasingly prevalent due to its potential for enhanced network coverage, efficient spectrum use, high data rate transmissions for collocated users, and greater energy efficiency [11]. D2D communication can be utilized for both business and public safety purposes. During natural disasters, D2D communication facilitates proximity-based communication between nodes when cellular network services are partially or completely unavailable [12]. In the context of public safety, D2D offers strong solutions for direct communication. Additionally, D2D communication provides benefits such as better resource allocation and increased data rates [13].

A significant challenge in Disaster Management Scenarios (DMS) arises in multicast routing, where a source node must connect with multiple destination nodes, or vice versa. Therefore, to meet Quality of Service (QoS) requirements in dynamic network scenarios, an efficient routing algorithm is essential for maximizing the lifetime of such dense and complex networks [14].

The remainder of the paper is organized as follows: Section 2 reviews recent related works on disaster management and device-to-device communication; Section 3 describes the proposed approach, including routing, Cluster Head (CH) selection, and device-to-device management; Section 4 presents the simulation results of the proposed approach; Section 5 highlights the limitation of the proposed method; and Section 6 concludes the paper.

2. Related work

The authors in [15] proposed a system of interactive trust management based on evidence for disaster management using wireless sensor networks studies. The capacity to transmit signals to initiate prompt rescue operations has enabled the sensor network to become more capable. The goal of the Evidence-Based Interactive Trust Management System is to stop abnormal node behaviour. At the application level, this technology is needed for communications between autonomous and adaptive nodes. This method works effectively by integrating and discounting evidence-based trust reports. Packet routing only takes place between reliable nodes. If there are non-trusted nodes, the results indicate that there is no packet forwarding.

A hierarchal D2D communication architecture was proposed in [16], wherein energy consumption is minimised by using a centralised software-defined network (SDN) controller that communicate with the cloud, thereby lowering the number of long-term evolution (LTE) communication links needed. By utilising the concept of the local and central controller, the architecture can operate in scenarios involving hotspot traffic and infrastructure failure. The SDN controller helps establish a multi-hop routing path to facilitate communication between catastrophe victims and first responders. Furthermore, the work illustrates the potential and resilience of the architecture by presenting a public safety scenario where an area of the network goes offline due to extraordinary events like a natural disaster.

The authors in [17] proposed formal paradigm for managing and mitigating earthquakes disasters. Because wireless sensor and actor networks (WSANs) have a multitude of applications in mission-critical systems, safety, and security, they have emerged as an important research topic. Initially, a subnet-based model is represented using graph theory and subsequently formalised. The formal specification is described and its validity is demonstrated using the Vienna Development Method-Specification Language (VDM-SL). Using the VDM-SL Toolbox tools, the resulting specification is then validated and verified by examining the pre/post conditions and invariants over the formal system.

In [18], the authors suggested SpEED-IoT: Spectrum aware Energy-Efficient multi-hop multi-channel routing method for D2D communication in IoT mesh networks. Understanding a radio environment map (REM), which is collected by specialised spectrum sensors that document the spatiotemporal usage of the spectrum, is crucial to this work. In order to leverage the knowledge of REMs, the study proposes a multi-hop routing approach that determines the optimum path, the best channels that are accessible at each hop along the route, and the optimal transmission power for each hop. Through the use of a simulation-driven GENI-based IoT testbed, this work evaluates the efficacy of SpEED-IoT in terms of (a) providing reachability and connectivity across IoT devices in a range of spectrum usage scenarios, (b) improving the IoT network's overall data rate as well as the assigned routes, (c) efficacy in protecting licenced incumbents, and (d) degree of fairness when allocating routes to various devices.

An energy-efficient and scalable D2D architecture design for public safety network was proposed in [19]. In this study, an adaptive architecture for D2D communications to be employed in emergency scenarios was designed taking into account relay-assisted D2D communications. In order for disaster networks, and D2D communications in particular, to meet public safety network standards, this article examines some of the most significant prerequisites, technological difficulties, and solution strategies. This paper also introduces a clustering procedure-based approach to system design that combines D2D and cellular operating modes based on infrastructure node availability. The results show that a clustering technique based on a low complexity threshold may balance the energy consumption, formation speed, and coverage.

The work in [20] proposed fast network organization using a model of a middle-scale post-disaster scenario. Content-Centric Networking (CCN) is used to place access points and route data to rapidly connect users, which simulates real-world maps and performs a comparative analysis with current Ad Hoc techniques. In [21] the authors highlight some inexpensive and flexibility developments in disaster management with the help of UAV-assisted network architecture and design considerations, along with their ability to be quickly deployed for disaster management through dynamic communications and sensing.

The work in [22] proposed a multi-hop D2D connection supported by UAVs for hybrid power-time switching (PTS), enabling D2D users in one cluster to communicate with D2D users in another cluster using UAVs. The authors additionally proposed that D2D users utilise a hybrid PTS-based method to collect energy from each of their personal ad hoc energy stations and communicate that information to another D2D user in the vicinity.

The authors in [23] discuss the use of LTE Device-to-Device ProSe (D2D ProSe) technology in conjunction with Internet of Things devices. The authors offer a way to create an effective emergency communications network that can be utilised in times of crisis. This method enables quick and easy service discovery and query heterogeneous IoT devices like smartwatches, wireless cameras, health sensors, and other pertinent devices or sensors, establishing a distributed D2D broadcast backbone with LTE ProSe to enable high coverage and energy efficiency for efficient and dependable message distribution. That will enable rescuers to access data generated by various sources during the rescue operation.

In [24], the authors presented a hybrid intelligence architecture to find and reconnect nodes within the disaster region to the functioning area. They take into account a scenario in which devices located in the disaster region are able to continuously monitor the radio environment. In an emergency, this enables the devices to recognise one another, make a crucial link by switching to the device-to-device (D2D) communication mode. The authors used the oscillating spider monkey optimisation (OSMO) approach to group devices together in the disaster region in order to improve network efficiency. Where the cluster heads act as nodes transferring information from the disaster area to the functional area nodes. By combining a priority-based path encoding method with oscillating particle swarm optimisation (OPSO), path discovery is accomplished.

The limitations of the existing literatures are highlighted in Table 1.

Table 1. Limitation of related work

Reference No.	Limitation
[15]	The impact of trust management on node energy consumption has not been taken into account in their studies to ensure that the system remains operational. Moreover, the system's adaptability to different types of disasters and varying network conditions needs further exploration.
[16]	One specific limitation of the work described in the paper is its reliance on hierarchical SDN controllers for managing D2D communications in public safety scenarios. While this hierarchical architecture improves scalability and resource utilization, it introduces potential vulnerabilities in cases of controller failure or communication breakdowns between local and central controllers. If the central controller becomes unreachable due to infrastructure damage or network overload, the effectiveness of the entire system could be compromised, particularly in critical public safety situations where timely and reliable communication is essential.
[17]	One of the main limitations of this work lies in its focus on indoor environments, limiting its applicability to outdoor disaster scenarios. The evacuation models and systems described are mostly designed for controlled, enclosed spaces. The paper focuses on a specific disaster type, the chemical plant explosion. Further study is needed to explore CLOTHO's adaptability to different disaster types in general.
[18]	The main limitation of this work lies in its reliance on dedicated spectrum sensors to build and maintain accurate radio environment maps (REMs) for spectrum availability. While these REMs are crucial for the proposed routing scheme to function effectively, their deployment and maintenance can be resource-intensive, especially in dynamic and large-scale IoT networks.
[19]	The limitation of the proposed architecture relies heavily on the availability of relay nodes with sufficient energy, which may not always be feasible in disaster scenarios where power sources are compromised.
[20]	The limitations of this work include the reliance on a specific post-disaster scenario, which may not generalize to all disaster situations. The proposed approach assumes the availability of certain network infrastructure, like routers, servers and Content-Centric Networking (CCN) framework which might not be present or operational after a disaster.
[21]	Limited flight time: Energy-efficient designs are crucial for UAVs to enhance their operational time and coverage in disaster response. Further studies to incorporates energy-efficient solution to extend the operational range and duration of UAVs are needed to make them more effective in disaster response.
[22]	The study emphasis on the energy-efficiency, path planning and co-ordination of the UAVs, lacking the consideration of ground network devices. Further studies are needed considering the energy consumption, co-ordination and performance including the device in the disaster area.
[23]	The study considers integration with existing infrastructures and dependency on stable energy sources, which may not be the case after a disaster.
[24]	The study focus on improving energy efficiency and network stability, it does not extensively address the impact of dynamic disaster environments. Moreover, hybrid intelligence approaches may have limitations in real-time adaptability and integration with existing communication systems.

3. Proposed methodology

3.1 *Problem statement*

Victims of earthquakes, tornadoes, landslides, and other natural disasters are frequently buried and trapped beneath the debris of houses, buildings, bridges, and other structures. Without available communication infrastructure support and outage of power supply, communication among disaster victims and first responders becomes a challenge during disaster. There are two main barriers to communication in the event of a disaster: first, damaged or destroyed terrestrial networks may cause a blackout; second, an abrupt spike in demand for communication may cause the current communication system to quickly oversubscribe, making communication challenging or even impossible.

3.2 *System model*

The base station of the network has been destroyed due to a disaster. In this situation, the data packets are transmitted to the sink node via an ad hoc relay stations. This information is forwarded to the base station through the sink node. The following Figure 1 shows the emergency operation centre. The three rescue procedures that network architecture uses in the event of a disaster are as follows.

3.2.1 *User device network field*

Considering four adjacent cells forming a neighbouring hood network during a disaster. Four ad hoc relay stations are in each cluster of particular network architecture. The cluster head is placed in the middle and Action Relay Stations (ARS) are placed at surrounding nodes within each cluster. All communication between nodes in the network field is handled by the CH. Here, each cluster faces the Sink node directly in the direction of the base station in order to preserve the communication path between the head nodes. The base station uses a WiMAX or GSM-based communication system to send information about the disaster to the emergency response centres via a cluster-based network architecture.

3.2.2 *Emergency response databasecenter*

Emergency response database centres are deployed for receiving the crucial disaster information pertaining to a disaster. Emergency response information will be provided to the rescue teams in a limited amount of time when they are needed for mission-critical applications. Additionally, the data centre uses the satellite broadcast antenna to transmit the data to the satellite station.

3.2.3 *Satellite communication infrastructure*

Through this communication system, information concerning disasters is relayed to hospitals and mobile ambulances. Medical services like first aid can be accessed instantly through the telemedicine-based infrastructure [25]. Particular topographies of mobile communications with D2D proximity are useful in emergency and disaster scenarios. Wireless links between users within BS's coverage area can be established with convenience as long as BS is operational in the functional area or in an ad hoc mode and able to deliver dependable communications (relay system).

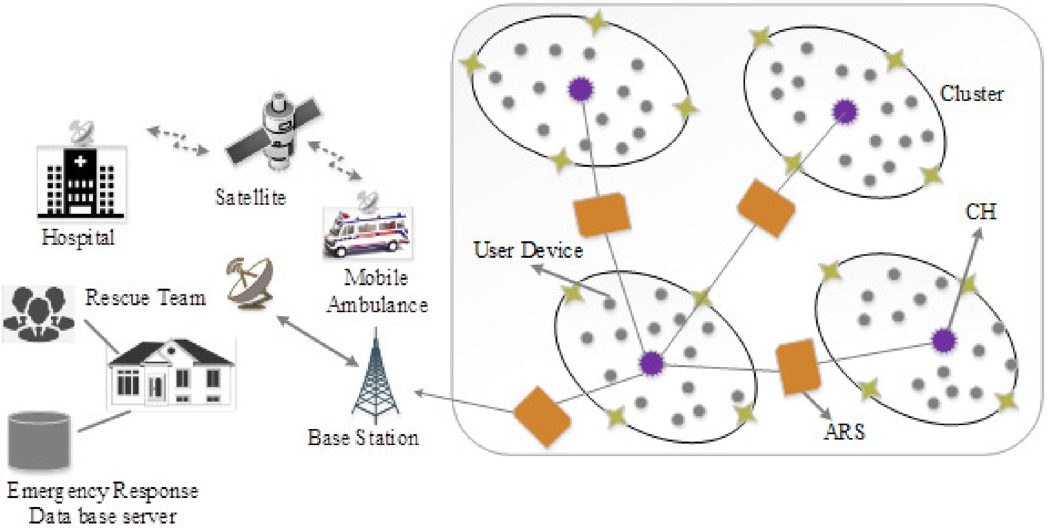


Figure 1. System model

3.3 *Disaster management architecture*

As illustrated in Figure 2, We investigate a scenario pertaining to public safety in which the source, or BS, has a fixed energy supply and wants to send data to a place outside of its coverage region. The source employs a relay to help with information transmission via D2D communication proximity services because the destination is in a disaster area and direct contact is not feasible due to the barrier between the source and destination, also known as the direct connection distance. However, the relay needs to gather energy before transmitting the data due to its low energy or self-centred nature. This paper, takes into consideration the following presumptions:

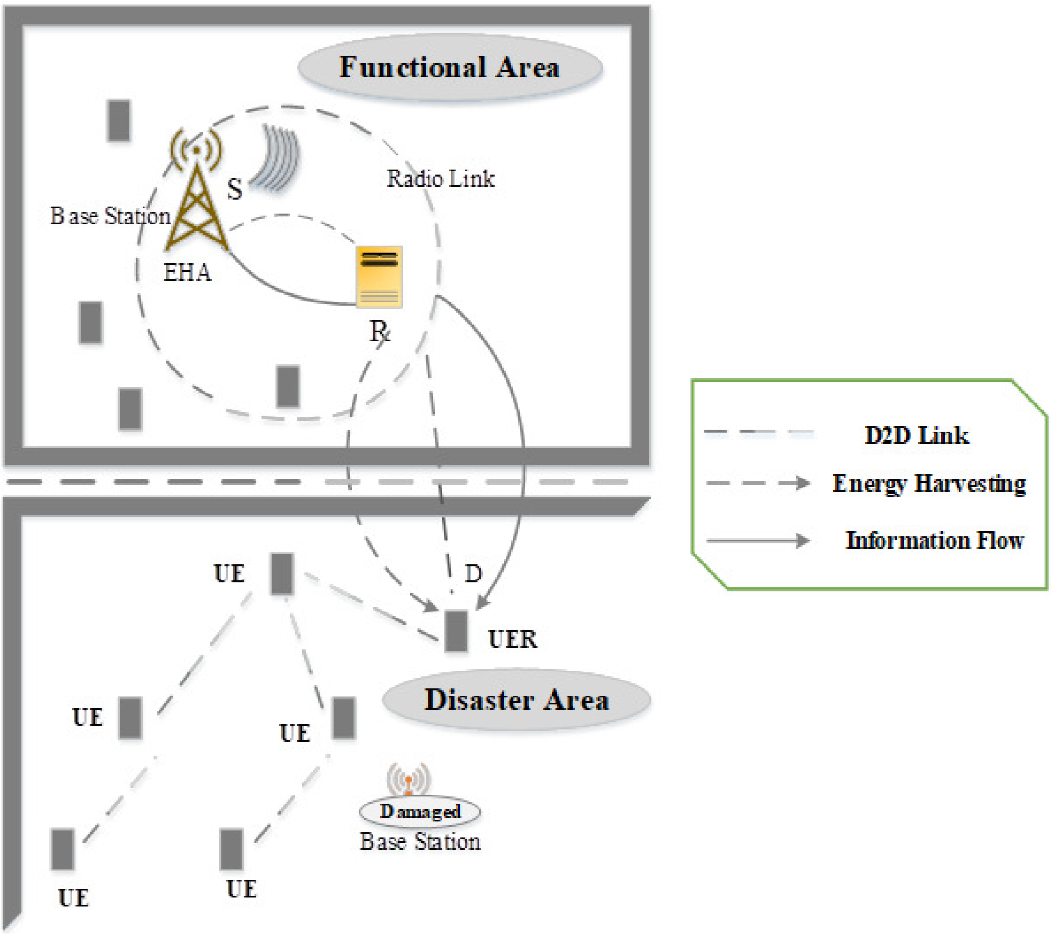


Figure 2. Public safety scenario

First assumption: We investigate a wireless D2D communication system, depicted in Figure 2, where data is sent from source S to destination node D through an intermediate relay node R. In a subsequent hop within the disaster area, the destination node D may function as a User Equipment Relay (UER) node. Moreover, during the clustering formation phase, UER serves as a cluster head (UERCH).

Second assumption: There may be an intermediary relay node R, with energy constraints. In order to send the information from the source to the destination, it first gathers energy from node S and uses it as a source of transmission power.

Third assumption: If the relay node has enough energy or can harvest energy from the source, it is chosen to transmit the energy and messages to the intended destination.

Fourth assumption: In our study, we assumed secure communication between cluster nodes, cluster heads, and the base station to ensure the integrity and reliability of the proposed disaster management framework. This assumption is supported by recent advancements in secure data transmission protocols for IoT devices [26] and robust authentication methods tailored for post-disaster emergency communications [27]. These references substantiate our approach by illustrating effective security measures relevant to similar contexts.

3.3.1 *Time switching based protocol*

The source node transfers a block of data to the destination node at a given block time (α_1, α_2, and α_3), represented by T at the relay, where $\alpha_1 + \alpha_2 + \alpha_3 = 1$. During the first time slot, which lasts for α_1T, energy from the source is transmitted to the relay. The source sends a signal to the relay in time slot α_2T, and the relay sends a signal to the destination during time slot α_3T. There is no direct connection between the source and destination nodes. The source to relay and relay to destination links are the two wireless links that make up the relay network. The total bandwidth in this network is split up into N orthogonal sub-carriers. Here, information and energy transfer must come first, and the optimal relay node must be determined. Every channel in the field is familiar to the BS. It can therefore decide which node in the vicinity will serve as a relay. A relay needs a high received power from a neighbouring base station (BS) in order to harvest energy. The term "energy harvesting area" (EHA) refers to the region surrounding the BS.

3.3.2 *Network configuration*

A cellular network is considered in this configuration which is made up of relays that can gather energy from other adjacent BS and base stations (BS) that are able to transfer energy wirelessly. A BS's, a relay's, and a UE's transmission powers are represented as ρ_{bs}, ρ_r and ρ_{ue} respectively. A relay can transmit data from the BS to a different hop in the disaster area node via D if it accumulates sufficient energy. Through the usage of a relay and the destination UE, D2D communication enables communication between two user devices via the node, which acts as a UER. Typically, UEs cannot communicate with a BS regarding their own data, which each UER most likely receives for itself with probability p_{rc}. Each UE connects to a base station (BS) via one of the N sub-channels that make up the cellular spectrum. Load ρ_{bs}, during any random time slot as BS using the same spectrum, is expressed as

$$\rho_{bs} = \frac{p_{rc}\lambda_r}{\lambda_{bs}N} \tag{1}$$

where λ_r is the relay spatial density, λ_{bs} is the BS spatial density.

3.3.3 *Relay-based power transfer and clustering*

The objective we had in the previous section was to use a network relay to convey the signal to non-functional area from the functional area. According to the needs of the system, the relay can be actively involved in energy gathering and then transmit information and energy to the disaster region. This section presents clustering approaches in D2D relay mode to let several affected users communicate within the disaster area. From a technical standpoint, taking advantage of proximity's properties could offer several advantages in emergency scenarios such as:

- D2D communication benefit from reduced end-to-end latency and high data rates.
- Direct communication reduces energy consumption and maximises channel utilisation when compared to standard cellular communication.
- To relieve congestion and unload cellular traffic, we can use traffic from an infrastructure path to a direct path.

We suggested expanding the D2D underlay idea to enable infrastructure/infrastructure-less operation, as network aided D2D communications need to use the availability of cellular infrastructure. In our scenario, when one or more base stations (BS) become non-functional after a disaster, parts of the radio access network (RAN) activities can be taken over by a high-end capable UE. These functions include serving as a cluster head (CH), UER, and source of synchronisation signals. For which two types of UEs are distinguished by network coverage,

Category-1, UEs have the ability to become UER/CH, in charge of managing the D2D links and the use of resources by a collection of D2D devices that are connected (UEs).

Category-2, UEs devices that are outside of the network coverage area and under the supervision of suitable *Category-1* UEs, and can only function as cluster members (CM) after a disaster.

3.4 *Fuzzy based squirrel search algorithm (SSA) for cluster head selection*

Fuzzy logic has proven beneficial for researchers trying to choose the most effective cluster heads in wireless sensor networks. Among its responsibilities are the distribution of synchronisation signals throughout the cluster, radio resource control, serving as a gateway between the cluster and adjacent clusters, and UE control within the cluster. For the fuzzy logic-based CH selection, three inputs are considered which includes mobility, capacity and network coverage for communication in the network.

Selecting the user device that will function as UERCH is crucial to our approach as we create a communication link through network relay. The following factors are taken into consideration to select the UERCH:

3.4.1 *Mobility*

Fast mobile users have the potential to quickly leave the cluster in which they are currently located, changing the cluster network's stability and necessitating a computationally and temporally demanding UERCH reselection. As a result, devices that move slowly or remain still are more suited to be UERCHs.

3.4.2 *Capacity*

Certain functions, such as dual mode function—the ability to operate in both low and high power modes—must have been included in UERCH.

3.4.3 *Network coverage*

Other devices may be able to connect to the network via it if the device is successful in achieving network coverage. Additionally, the network can help by facilitating D2D communication, which will increase system efficiency.

A fuzzifier, fuzzy rules, fuzzy inference engine, and a defuzzifier make up the fuzzy logic control model. The three input functions mobility, capacity and network coverage to BS were applied to convert the inputs of the system into fuzzy sets. The mobility is represented by a static, slow, and fast membership function. The capacity is represented by the functions low, medium, and high. The network coverage is represented by the functions close, attainable and far. The linguistic variables for the fuzzy set of output variable are divided into six levels as follow: very low, low, rather medium, medium, high and very high. The membership functions of the input variables are included in Table 2. As shown in Table 3, a total of 27 rules are formed from the combination of various linguistic characteristics.

3.4.3.1 *Example of the fuzzy rules are given as below*

R-1: If mobility is fast, capacity is low and network coverage is close, then the resultant rank is rather medium.
R-2: If mobility is fast, capacity is low and network coverage is attainable, then the resultant rank is low.
R-3: If mobility is static, capacity is low and network coverage is far, then the resultant rank is low.
R-4: If mobility is slow, capacity is high and network coverage is attainable, then the resultant rank is medium.
R-5: If mobility is slow, capacity is high and network coverage is close, then the resultant rank is high.
R-6: If mobility is static, capacity is high and network coverage is attainable, then the resultant rank is high.

It is a challenge to decide how many cluster heads to have and where to put them. Because of the issue's dynamic nature—which arises from the numerous changes in cluster heads during each round of the network's activity—makes it difficult to model the problem using traditional mathematical techniques. Heuristic techniques have gained popularity in other studies' common clustering algorithms. This paper presents a new Squirrel Search Algorithm (SSA) that is inspired by nature which aims to minimize energy consumption while determining the optimal locations for cluster heads.

Placement of user devices at random is how SSA starts, just like other population-based algorithms. The position of the user device is represented as a vector in a d-dimensional search space.

Table 2. Input variables

Input Variable	**Membership Functions**		
Mobility	Static	Slow	Fast
Capacity	Low	Medium	High
Network Coverage	Close	Attainable	Far

Table 3. Fuzzy rules

Rules	***Mobility***	***Capacity***	***Network Coverage***	***Rank***
1	Static	Low	Close	High
2	Static	Low	Attainable	Rather Medium
3	Static	Low	Far	Low
4	Static	Medium	Close	Medium
5	Static	Medium	Attainable	Rather Medium
6	Static	Medium	Far	Low
7	Static	High	Close	Very High
8	Static	High	Attainable	High
9	Static	High	Far	Rather Medium
10	Slow	Low	Close	Rather Medium
11	Slow	Low	Attainable	Low
12	Slow	Low	Far	Low
13	Slow	Medium	Close	Rather Medium
14	Slow	Medium	Attainable	Rather Medium
15	Slow	Medium	Far	Low
16	Slow	High	Close	High
17	Slow	High	Attainable	Medium
18	Slow	High	Far	Rather Medium
19	Fast	Low	Close	Rather Medium
20	Fast	Low	Attainable	Low
21	Fast	Low	Far	Very Low
22	Fast	Medium	Close	Rather Medium
23	Fast	Medium	Attainable	Medium
24	Fast	Medium	Far	Low
25	Fast	High	Close	High
26	Fast	High	Attainable	Rather Medium
27	Fast	High	Far	Low

3.4.4 *Random initialization*

A cluster has *n* user devices (UD), and a vector can be used to specify the location of the i^{th} device. The following matrix can be used to represent the locations of all user devices:

$$UD = \begin{bmatrix} UD_{1,1} & UD_{1,2} & \cdots & UD_{1,d} \\ UD_{2,1} & UD_{2,2} & \cdots & UD_{2,d} \\ \vdots & \vdots & \vdots & \vdots \\ UD_{n,1} & UD_{n,2} & \cdots & UD_{n,d} \end{bmatrix} \tag{2}$$

where UD_{ij} represents the j^{th} dimension of the i^{th} user device. Every user device in the cluster has its initial location assigned following a uniform distribution.

$$UD_i = UD_L + U\,(0,\,1)\;(UD_U - UD_L) \tag{3}$$

where UD_L and UD_U are the i^{th} flying squirrel's lower and upper bounds in the j^{th} dimension, respectively, and U(0, 1) represents a random number with a uniform distribution in the range U[0,1].

3.4.5 *Fitness evaluation*

Each user device's location fitness is determined by feeding the choice variable's (solution vector's) values into a user-defined fitness function. The resulting values are then stored in the array below:

$$Fitness = \begin{bmatrix} Fit\left(\left[UD_{1,1}, UD_{1,2}, \cdots UD_{1,d}\right]\right) \\ Fit\left(\left[UD_{2,1}, UD_{2,2}, \cdots UD_{2,d}\right]\right) \\ \vdots \\ \vdots \\ Fit\left(\left[UD_{n,1}, UD_{n,2}, \cdots UD_{n,d}\right]\right) \end{bmatrix} \tag{4}$$

Each user device's fitness value indicates the quality of food source that it has searched for i.e., static mobility, high capacity, and close network coverage and hence their probability of survival. The fitness function represented as $\pounds(\mathrm{t})$ for the user device is specified in the following equation:

$$\pounds(\mathrm{t}) = \vartheta_1\pounds_1 + \vartheta_2\pounds_2 + \vartheta_3\pounds_3;\ subject\ to \tag{5}$$

$$\left.\begin{aligned} \boldsymbol{Objective\ function}: \ static\ or\ slow\ \text{mobility}\ (\pounds_1) \\ min\ \text{capacity}\ (\pounds_2) \\ close\ \text{network coverage}\ (\pounds_3) \end{aligned}\right\} \tag{6}$$

- **Sorting and Declaration**

Following the storage of the fitness values for each user device location, the array is sorted in ascending order. The CH is identified as the user device with the lowest fitness value. The remaining devices are regarded as member nodes.

- **Electing Cluster Head**

The cluster heads election is carried out according to the three points which are considered to select the UERCH. The fitness value of the user device reaching the maximum i.e., static mobility, high capacity and nearer network coverage, that user node is elected as CH or else act as a member node. Because the packet routing will be forwarded through the UERCH.

- **Stopping Criterion**

A narrow threshold value is established in between the subsequent outcomes. The maximum execution time is occasionally applied as a condition for stopping. The maximum number of iteration is taken into consideration as a stopping condition in the current investigation.

3.5 *Routing for D2D communication in IoT network*

To achieve a greater range, our approach uses in-band D2D communication between the CH and other CHs, with the CH serving as a relay UE. A situation when a natural disaster causes one of the base stations to collapse as shown in Figure 3, to connect to the closest UEs inside the service region, the mobile devices form a relay network (User Equipment to Network Relay). By serving as relays, the devices transfer data from out-of-coverage devices to the network's functional area. We examine two scenarios: The network may be congested for two reasons: (i) several UEs requesting resources may cause congestion; (ii) a disaster may cause multiple devices attempting to connect to the operational eNB (base station) to cause congestion. All out-of-coverage UEs attempt to use the relay network to contact the closest base station in the event of a disaster.

It causes an increase in traffic from the network's unreachable region and, as a result of the limited resources at the BS, causes congestion in other areas of the network. Our architecture offers a practical remedy for this kind of circumstance. Using a weighted double-heuristic search technique, since it has global knowledge about every device within its range, the central SDN controller may create a route between UEs inside the coverage region. The associated cellular network can be reached by the UEs in the out-of-coverage area by creating a multi-hop route. Our design accomplishes this without overburdening the cellular network with the seamless integration of public safety applications.

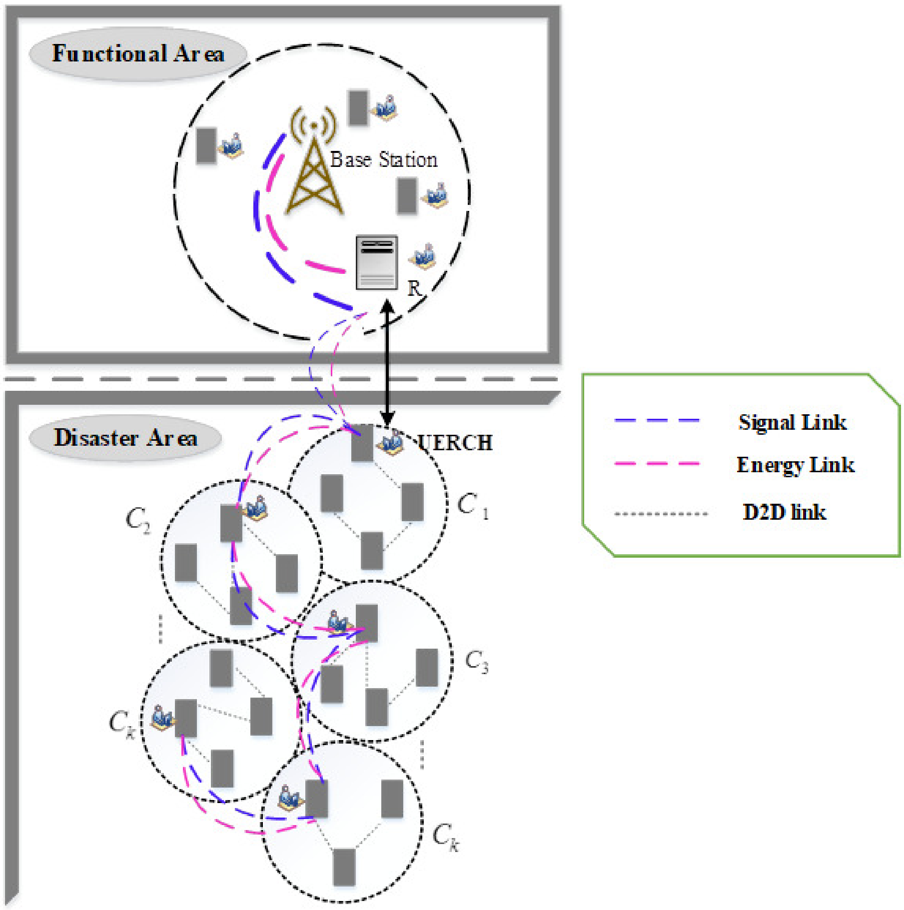
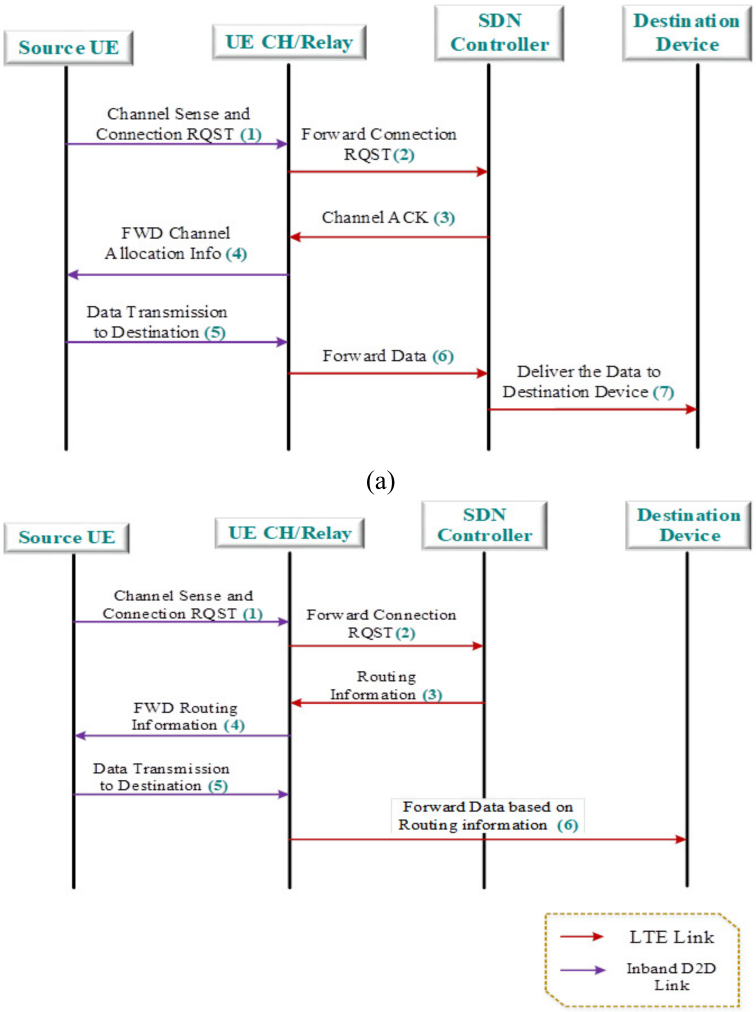


Figure 3. Combined system model framework with D2D, clustering, and CH for disaster recovery communication

3.6 *Route computation*

Figure 4 shows the signalling that may be used to send data from the source to the destination. The destination eNB will distribute cellular radio resources for transmission when it has enough radio resources to meet incoming resource demands, as shown by the signalling number [(1)–(7)]. This is the situation that Figure 4a shows. Conversely, the signalling that occurs when the cellular network radio resource is fully exploited is depicted in Figure 4b. Here, the central SDN controller sends the routing data to the Relay UE (i.e., as indicated by the signalling number (4)), which uses the in-band D2D communication channels between CHs to compute a route from the source (i.e., Relay UE) to the destination device.



(a)

(b)

Figure 4. Signalling between cloud heads for multi-hop routing. (**a**) There are sufficient resources in eNB. (**b**) The eNB calculates route data having fully loaded

The channel quality indicator (CQI), which affects the physical data rate of the channel, computing power, and device battery life could all be used to determine the link cost function. Each of these characteristics has a direct relation to the likelihood that the link will be chosen as the shortest path.

$$P_n \,\alpha\, f\left(P_{comp}, L_{battery}, CQI\right) \tag{7}$$

where P_n is the probability of choosing a link as the shortest path to the next hop and P_{comp} is the device's processing capability. The received signal strength indicator (RSSI) function, or CQI, is directly correlated with the channel's SNR, providing a clear understanding of the link's channel capacity. Further P_{comp} and $L_{battery}$ are provided as:

$$P_{comp} = vk^2 \tag{8}$$

where k is the number of instructions that are performed per second and v is the voltage input to the device's processor.

$$L_{battery} = \frac{Capacity\ of\ battery\ (mAh)}{Load\ Current\ \ (mA)} \tag{9}$$

The device battery life ($L_{battery}$), followed by the device's computational power (P_{comp}) and channel link quality, is expected to have the highest priority when choosing the cost function. To make end-to-end route computation easier, each link that a UE uses to connect to the subsequent hop is given a link cost determined by these priorities.

4. Performance evaluation

We take into consideration a uniformly distributed UE in an LTE covered area. Within its coverage region, the BS is broadcasting at maximum power, using a 10 MHz bandwidth divided into 50 RBs, each with 12 sub-carriers. Table 4 displays the Number of device, capacity and other relevant parameters used for the simulation.

Table 4. Simulation parameters

Sl. No	Parameter Name	Rate
1	No. of Devices	100–500
2	Maximum Battery Capacity	6.5 J
3	Simulation Duration	20 h
4	Disaster Zone Radius	100 m–500 m
5	Transmitting Power	10 MHz
6	Bandwidth	10 MHz
7	Content Size	1 Mbits

In this work, the experimental simulations are done using MATLAB platform to evaluate the effect of UE device differences, UE energy usage, UE count, and number of clusters in the field. The scenario examined in Figure 5 is predicated on one base station (BS) operating at full power in the functional region and non-operational BS(s) in the disaster area. In an emergency, users can benefit from D2D UE proximity services while they are in the non-functional area. D2D relay also improves the edge-user(s)'s data throughput, which can be utilised to connect outage UEs with cellular coverage to the BS and extend the coverage area. A cluster of UEs is made up of several nodes, each of which serves as a UERCH. The remaining nodes in the cluster are referred to as cluster members.

4.1 *Performance metrics*

This paper analyses performance metrics such as energy consumption, mean excess path loss, average battery lifespan, and probability of battery lifetime. The parameters' mathematical expression is given as follows:

- ***Total Energy Utilization:*** It is the total energy used by the devices in the area under consideration, including the UECH.

$$EC_T = \sum_{n=1}^{l} \left[UECH_E\,(n) + \sum_{m=1}^{kn} S_E\,(mn) \right] \tag{10}$$

- ***Probability of Battery Lifetime:*** This refers to the likelihood of the battery's utilisation to its overall lifespan.

$$P(battery\ Lifetime) = \frac{Usage\ of\ the\ battery}{Total\ lifetime\ of\ the\ battery} \tag{11}$$

- ***Average Battery Lifetime:*** It is the ratio of the total number of devices to the sum of each device's battery level.

$$Avg\ battery\ lifetime = \frac{\sum Battery\ level\ of\ each\ device}{Number\ of\ devices} \tag{12}$$

4.2 *Performance analysis*

The obtained experimental results are analysed in this section and the following tables give the evaluated values of metrics and it is contrasted with the current methods, which include D2D-SOS (Survival on Sharing), D2D fuzzy-SSA cluster, non-cluster, and D2D cluster. The values of energy consumption for various devices are shown in Table 5. D2D cluster and non-cluster are contrasted with our proposed approach. Our suggested approach uses the least amount of energy in comparison, extending the life of the device. The battery lifespan probability is shown in Table 6 after that, and it is compared with the current techniques. The average battery life in relation to the disaster radius is therefore shown in Table 7. Furthermore, Table 8 gives mean excess path loss (dB) for D2D and D2D Fuzzy-SSA.

Table 5. Energy consumption comparison

No. of Devices	Non Cluster (J)	D2D with Cluster (J)	D2D Fuzzy-SSA Cluster (J) [Proposed]
10	$10^{2.85}$	$10^{1.6}$	10^{1}
20	$10^{3.4}$	$10^{1.8}$	$10^{1.3}$
30	$10^{3.7}$	$10^{1.9}$	$10^{1.35}$
40	10^{4}	10^{2}	$10^{1.6}$
50	$10^{4.2}$	$10^{2.1}$	$10^{1.8}$
60	$10^{4.6}$	$10^{2.2}$	$10^{1.85}$
70	$10^{4.7}$	$10^{2.35}$	$10^{1.9}$
80	$10^{4.8}$	$10^{2.4}$	$10^{1.95}$
90	$10^{4.85}$	$10^{2.45}$	10^{2}
100	$10^{4.9}$	$10^{2.55}$	$10^{2.01}$

Table 6. Probability of battery lifetime

Time in Hour	Cellular Network	D2D with SoS	D2D Fuzzy-SSA [Proposed]
1	3	1	0
2	4	2	0
3	6	3	3
4	8	6	4
5	10	8	5
6	12	10	7
7	13	12	9
8	14	13	11
9	13	14	13
10	12	13	14
11	10	11	13
12	5	8	11
13	3	7	9
14	2	4	7
15	2	2	5
16	1	1	3
17	1	0	2
18	1	-	0
19	1	-	0
20	1	-	0

Table 7. Average battery lifetime

Disaster Radius (m)	Cellular Network	D2D with SoS	D2D Fuzzy-SSA [Proposed]
100	8.95	9.05	11.23
200	9.53	9.95	11
300	9	9.25	10.25
400	8	8.25	9.25
500	7.75	7.79	8.79

Table 8. Mean excess path loss (dB) for D2D and D2D fuzzy-SSA

Mean Excess Path Loss (dB)	D2D	D2D Fuzzy-SSA [Proposed]
5	0.1	0.05
10	0.45	0.25
15	0.8	0.5
20	1.25	1
25	1.7	1.5
30	2.2	2

In addition to this, the analysis of the experimental data is displayed in the following figures. The average battery lifespan, mean excess path loss, batter lifetime probability, and energy consumption performance study are show as below:

The energy consumption for the number of devices is displayed in Figure 5. contrasting the amount of energy used for our proposed method i.e., D2D fuzzy-SSA clustering with other existing techniques, such as non-clustering, and clustering. Our suggested method uses the least amount of energy when compared to other methods. In comparison, our proposed approach uses 10 times as many devices yet consumes 10^1 J of energy. Current methods, D2D clustering and non-clustering, use 10 number of devices to utilise $10^{1.6}$ J and $10^{2.85}$ J of energy, respectively. Energy usage rises in proportion to the number of device. However, when compared to other existing methods, our suggested strategy uses the least amount of energy.

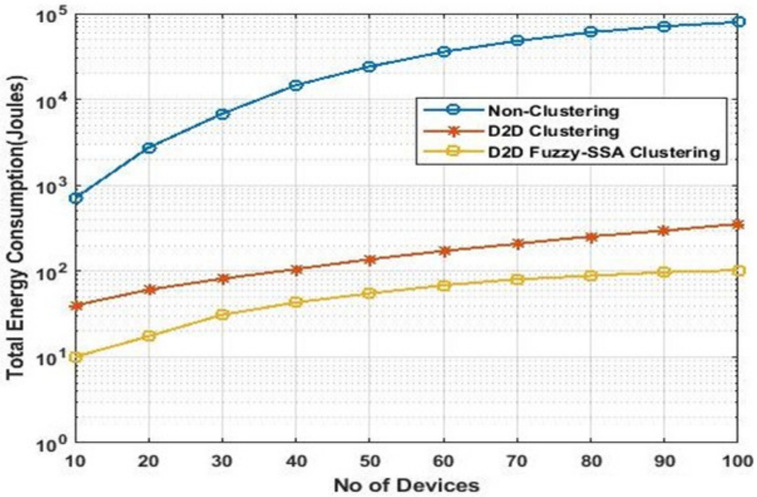


Figure 5. Performance of total energy consumption

Figure 6 displays the probability analysis for the device's battery life and performance. Here, the suggested strategy is contrasted with the current approaches—cellular and D2D-SoS. When compared to the current approaches, our suggested method's battery life performs better. It depicts the situation when a variety of devices' batteries are constantly being used. However, using the D2D-Fuzzy SSA technology, almost half of the devices never experience a power drain. The suggested approach distributes the energy throughout the network, increasing the devices' usage time. Compared to current solutions, our suggested approach has a battery lifespan of 90% longer.

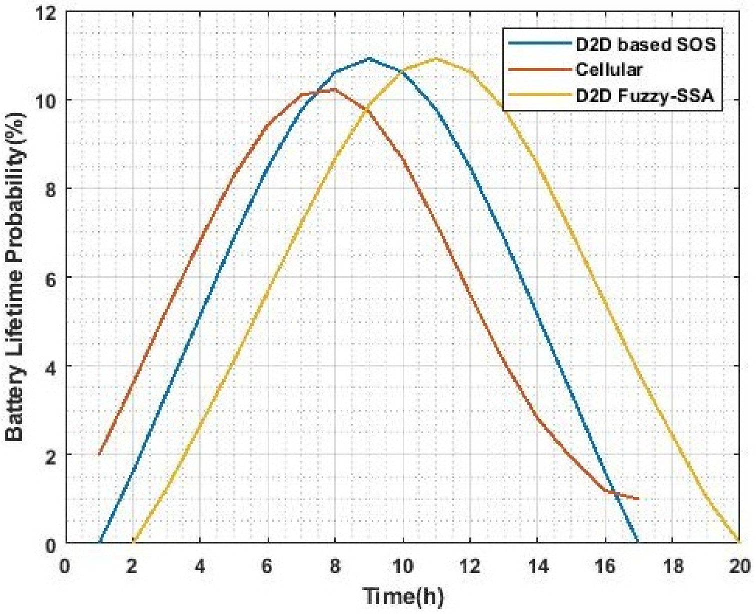


Figure 6. Probability of battery lifetime analysis

The average battery lifespan analysis is presented in Figure 7 along with a comparison between the D2D SOS and cellular techniques. Compared to the current methods, the suggested D2D Fuzzy-SSA has a longer average battery life. Analysis is done on average battery life in relation to the area affected by a disaster. The average battery life decreases as the disaster radius increases. Therefore, the likelihood of developing D2D collaboration decreases as the disaster area grows and the distance between devices grows. It is noteworthy, nonetheless, that even in wider disaster zones, our suggested approach performs better than the existing method.

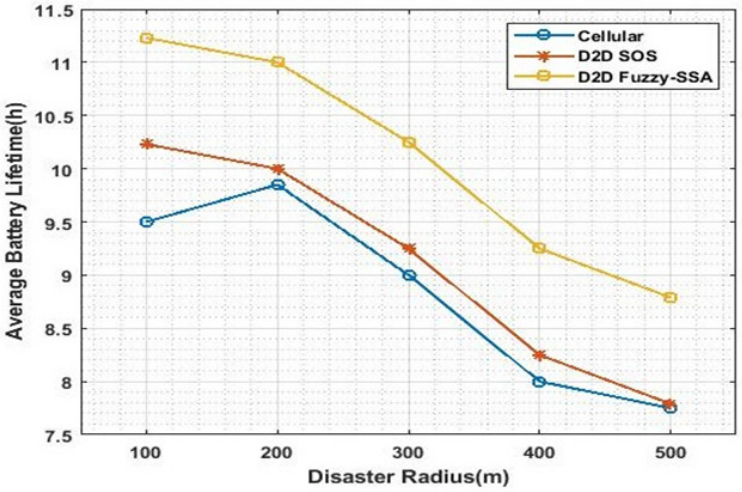


Figure 7. Average battery lifetime analysis

The findings of the analysis of the UE's energy consumption are shown in Figure 8. Computation takes into account the corresponding re-transmission values for each mean excess path loss level. In an emergency, the proposed approach uses approximately ninety times less energy on the UE than the D2D direct transmission for 5 dB excess path loss. The corresponding energy usage for the 10 dB increased route loss in the proposed system is approximately eight times lower. The D2D method is contrasted with our suggested approach where the mean excess path loss is less than that of the current method.

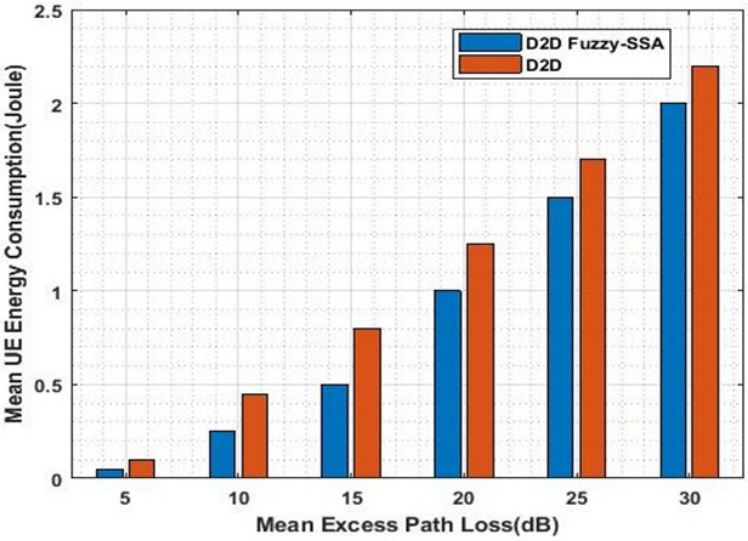


Figure 8. UE energy consumption analysis

Figure 9 shows the comparison of data throughput with respect to the number of devices. In terms of data throughput, our proposed method performs better as compared to non-clustering and marginally underperform for larger number of device with that of D2D with clustering. This is because the proposed method prioritizes energy efficiency over throughput, which is clearly shown by the result in Figure 10. As the simulation time increases, employing D2D with clustering, the devices battery life gets exhausted and data throughput decrease over time. On the other hand, using Fuzzy-SSA, the overall network life is extended with significant data throughput.

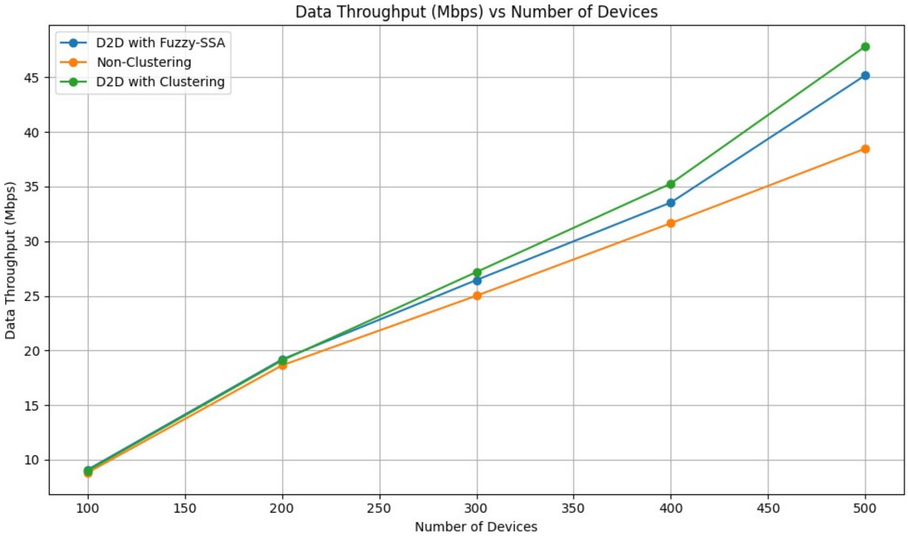


Figure 9. Data throughput vs number of devices

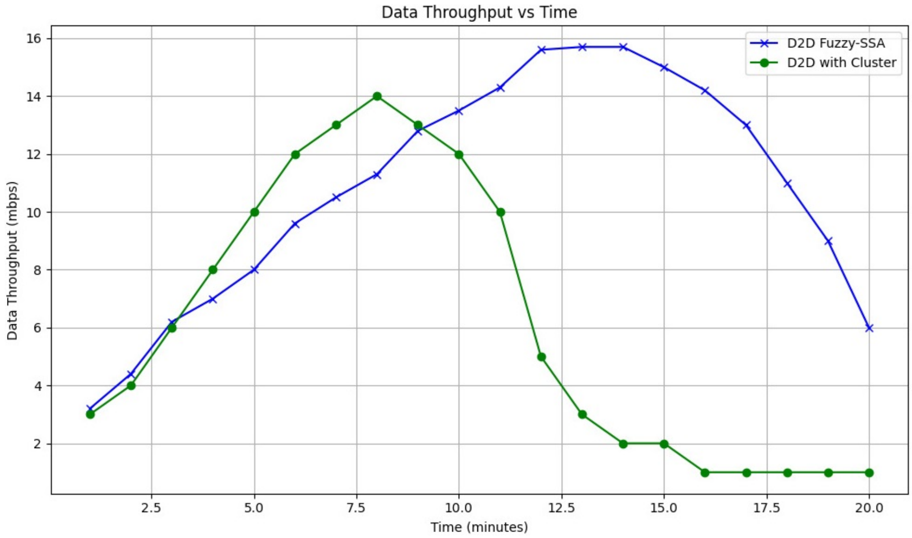


Figure 10. Data throughput vs simulation time

5. Limitation of the proposed method

While our proposed disaster recovery communication framework shows promising results, several limitations may be taken into consideration. Firstly, the effectiveness of our proposed method heavily relies on the density and distribution of User Equipment Relay (UER) nodes, which may vary significantly in different disaster scenarios and geographical locations. Limited battery life and resource constraints of UER nodes could also impact sustained communication reliability over extended periods. Secondly, the Squirrel Search Algorithm (SSA) for Cluster Head (CH) selection, while effective in simulations, requires further validation in practical deployments to assess its scalability and adaptability to real-time dynamic network conditions. Thirdly, this paper does not take into consideration the diverse specifications of devices in the network. In disaster management scenarios, devices can vary significantly in terms of processing power, battery life, communication capabilities, and device types. Addressing these limitations will be critical in enhancing the robustness and scalability of our framework for broader deployment and adoption in real-world disaster recovery operations.

6. Conclusions and future work

This study introduces a robust disaster recovery communication framework utilizing Device-to-Device (D2D) communication, clustering, and a fuzzy logic-based cluster head selection mechanism. Our framework addresses the critical challenge of maintaining reliable communication during disasters when traditional infrastructures are compromised due to disaster. Key contributions include a resilient architecture featuring User Equipment Relay (UER) nodes for extending coverage beyond base stations (BS), optimized D2D communication through clustering by employing Squirrel Search Algorithm (SSA) for efficient Cluster Head (CH) selection based on mobility, capacity and network coverage. Simulation results demonstrate superior performance in energy efficiency, battery lifespan probability, and path loss reduction compared to conventional methods, confirming its suitability for disaster scenarios and emergency response operations. Future research may focus on validating our framework through real-world deployments and large-scale simulations under diverse disaster conditions. Integration with emerging technologies such as 5G networks and edge computing may be explored to boost data throughput and latency management in disaster environments. These efforts collectively aim to advance disaster preparedness and response capabilities, ensuring more resilient communication infrastructures for critical situations.

Conflict of interest

The authors declare no conflict of interest.

References

[1] V. Dhiman, V. Kaur, and A. Singh, "Performance Investigation of Energy Aware Routing Protocol for Heterogeneous WSNs," in *Emerging Research in Computing, Information, Communication and Applications*, N. Shetty, N. Prasad, and N. Nalini, Eds. New Delhi, India: Springer, 2015, pp. 239–251. https://doi.org/10.1007/978-81-322-2550-8_23.

[2] M. Erd, F. Schaeffer, M. Kostic, and L. M. Reindl, "Event monitoring in emergency scenarios using energy efficient wireless sensor nodes for the disaster information management," *Int. J. Disaster Risk Reduct.*, vol. 16, pp. 33–42, 2016. https://doi.org/10.1016/j.ijdrr.2016.01.001.

[3] N. Saxena, M. Agiwal, H. Ahmad, and A. Roy, "D2D-Based Survival on Sharing: For Enhanced Disaster Time Connectivity," *IEEE Technol. Soc. Mag.*, vol. 37, no. 3, pp. 64–73, 2018. https://doi.org/10.1109/MTS.2018.2857640.

[4] A. Adeel, et al., "A survey on the role of wireless sensor networks and IoT in disaster management," in *Geological Disaster Monitoring Based on Sensor Networks*, New Delhi, India: Springer, 2019, pp. 57–66. https://doi.org/10.1007/978-981-13-0992-2_5.

[5] A. Ahmed, K. A. Bakar, M. I. Channa, A. W. Khan, and K. Haseeb, "Energy-aware and secure routing with trust for disaster response wireless sensor network," *Peer-to-Peer Netw. Appl.*, vol. 10, no. 1, pp. 216–237, 2017. https://doi.org/10.1007/s12083-015-0421-4.

[6] M. A. Araghizadeh, P. Teymoori, N. Yazdani, and S. Safari, "An efficient medium access control protocol for WSN-UAV," *Ad Hoc Netw.*, vol. 52, pp. 146–159, 2016. https://doi.org/10.1016/j.adhoc.2016.09.007.

[7] F. Al-Turjman, "Cognitive routing protocol for disaster-inspired internet of things," *Future Gener. Comput. Syst.*, vol. 92, pp. 1103–1115, 2019. https://doi.org/10.1016/j.future.2017.03.014.

[8] G. Han, X. Yang, L. Liu, W. Zhang, and M. Guizani, "A Disaster Management-Oriented Path Planning for Mobile Anchor Node-Based Localization in Wireless Sensor Networks," *IEEE Trans. Emerg. Topics Comput.*, vol. 8, no. 1, pp. 115–125, 2020. https://doi.org/10.1109/TETC.2017.2687319.

[9] O. M. Bushnaq, A. Chaaban, and T. Y. Al-Naffouri, "The Role of UAV-IoT Networks in Future Wildfire Detection," *IEEE Internet Things J.*, vol. 8, no. 23, pp. 16984–16999, 2021. https://doi.org/10.1109/JIOT.2021.3077593.

[10] S. R. Jain and N. V. Thakur, "Overview of cluster based routing protocols in static and mobile wireless sensor networks," in *Information Systems Design and Intelligent Applications: Proceedings of Second International Conference INDIA 2015, Volume 1*, New Delhi, India: Springer, 2015, vol. 339, pp. 619–626. https://doi.org/10.1007/978-81-322-2250-7_62.

[11] I. O. Nunes, P. O. S. V. de Melo, and A. A. F. Loureiro, "Leveraging D2D multihop communication through social group meeting awareness," *IEEE Wireless Commun.*, vol. 23, no. 4, pp. 12–19, 2016. https://doi.org/10.1109/MWC.2016.7553021.

[12] F. Shaikh and R. Wismüller, "Routing in multi-hop cellular device-to-device (D2D) networks: A survey," *IEEE Commun. Surv. Tutor.*, vol. 20, no. 4, pp. 2622–2657, 2018. https://doi.org/10.1109/COMST.2018.2848108.

[13] D. Panaitopol, C. Mouton, B. Lecroart, Y. Lair, and P. Delahaye, "Recent advances in 3GPP Rel-12 standardization related to D2D and public safety communications," *Netw. Internet Archit.*, 2015. https://doi.org/10.48550/arXiv.1505.07140.

[14] R. Chaudhry, S. Tapaswi, and N. Kumar, "A Green Multicast Routing Algorithm for Smart Sensor Networks in Disaster Management," *IEEE Trans. Green Commun. Netw.*, vol. 3, no. 1, pp. 215–226, 2019. https://doi.org/10.1109/TGCN.2019.2891752.

[15] P. U. Priyadarsini and P. Sriramya, "Disaster management using evidence-based interactive trust management system for wireless sensor networks by Internet of Things," *Comput. Electr. Eng.*, vol. 75, pp. 164–174, 2019. https://doi.org/10.1016/j.compeleceng.2019.02.020.

[16] M. Usman, A. A. Gebremariam, U. Raza, and F. Granelli, "A software-defined device-to-device communication architecture for public safety applications in 5G networks," *IEEE Access*, vol. 3, pp. 1649–1654, 2015. https://doi.org/10.1109/ACCESS.2015.2479855.

[17] X. Xu, L. Zhang, S. Sotiriadis, E. Asimakopoulou, M. Li, and N. Bessis, “CLOTHO: A Large-Scale Internet of Things-Based Crowd Evacuation Planning System for Disaster Management,” *IEEE Internet Things J.*, vol. 5, no. 5, pp. 3559–3568, 2018. https://doi.org/10.1109/JIOT.2018.2818885.

[18] S. Debroy, P. Samanta, A. Bashir, and M. Chatterjee, “SpEED-IoT: Spectrum aware energy efficient routing for device-to-device IoT communication,” *Future Gener. Comput. Syst.*, vol. 93, pp. 833–848, 2019. https://doi.org/10.1016/j.future.2018.01.002.

[19] K. Ali, H. X. Nguyen, P. Shah, and Q. -T. Vien, “Energy efficient and scalable D2D architecture design for public safety network,” in *Proc. 2016 Int. Conf. Adv. Commun. Syst. Inf. Security (ACOSIS)*, Marrakesh, Morocco, Oct. 17–19, 2016, pp. 1–6. https://doi.org/10.1109/ACOSIS.2016.7843929.

[20] J. Xu, K. Ota, and M. Dong, “Fast networking for disaster recovery,” *IEEE Trans. Emerg. Topics Comput.*, vol. 8, no. 3, pp. 845–854, 2020. https://doi.org/10.1109/TETC.2017.2775798.

[21] O. M. Bushnaq, D. Mishra, E. Natalizio, and I. F. Akyildiz, “Unmanned aerial vehicles (UAVs) for disaster management,” in *Nanotechnology-Based Smart Remote Sensing Networks for Disaster Prevention*, Amsterdam, The Netherlands: Elsevier, 2022, pp. 159–183. https://doi.org/10.1016/B978-0-323-91166-5.00013-6.

[22] S. Ghosh, A. Bhowmick, S. D. Roy, and S. Kundu, “UAVs-assisted Multi-Hop D2D Communication using Hybrid PTS for disaster management,” in *Proc. 2023 5th Int. Conf. Recent Adv. Inf. Technol. (RAIT)*, Dhanbad, India, Mar. 3–5, 2023, pp. 1–6. https://doi.org/10.1109/RAIT57693.2023.10127102.

[23] S. Abdellatif, O. Tibermacine, W. Bechkit, and A. Bachir, “Heterogeneous IoT/LTE ProSe virtual infrastructure for disaster situations,” *J. Netw. Comput. Appl.*, vol. 213, p. 103602, 2023. https://doi.org/10.1016/j.jnca.2023.103602.

[24] Y. M. Balakrishna and V. Shivashetty, “Device-to-device based path selection for post disaster communication using hybrid intelligence,” *Int. J. Electr. Comput. Eng. (IJECE)*, vol. 14, no. 1, pp. 796–810, 2024. http://doi.org/10.11591/ijece.v14i1.

[25] N. Ahmad, N. Riaz, and M. Hussain, “Ad hoc wireless sensor network architecture for disaster survivor detection,” *Int. J. Adv. Sci. Technol.*, vol. 34, no. 9, pp. 9–16, 2011. https://api.semanticscholar.org/CorpusID:17248744.

[26] I. Al-Hejri, F. Azzedin, S. Almuhammadi, and M. Eltoweissy, “Lightweight Secure and Scalable Scheme for Data Transmission in the Internet of Things,” *Arab. J. Sci. Eng.*, vol. 49, 2024. https://doi.org/10.1007/s13369-024-08884-z.

[27] D. Wang, Y. Cao, K. Y. Lam, Y. Hu, and O. Kaiwartya, “Authentication and Key Agreement Based on Three Factors and PUF for UAVs-assisted Post-Disaster Emergency Communication,” *IEEE Internet Things J.*, vol. 11, no. 11, pp. 20457–20472, 2024. http://doi.org/10.1109/JIOT.2024.3371101.