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# Optimized UAV-Based Relay Algorithm for Enhanced Emergency Wireless Coverage in Disaster Areas

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## ABSTRACT

In disaster-affected areas where traditional communication infrastructure is often damaged or unavailable, maintaining reliable wireless connectivity is critical for effective emergency response. This paper presents an optimized Unmanned Aerial Vehicle (UAV)-based relay algorithm designed to enhance emergency wireless coverage through dynamic positioning and energy-efficient routing. The proposed system employs UAV-mounted sensors to assess disaster zones in real time, identify communication blackspots, and guide UAV deployment based on key parameters such as altitude, battery life, and coverage radius. A communication protocol incorporating error correction mechanisms ensures robust data exchange between UAVs and ground users. Two core algorithms are introduced: one for optimal UAV deployment using population and terrain data, and another for maximizing device-to-device (D2D) communication capacity while minimizing interference. Simulation results validate the proposed approach, demonstrating substantial improvements in key performance metrics including path loss reduction, lower packet loss probability, and enhanced D2D capacity. Additionally, the system achieves over 93% communication efficiency while maintaining low energy consumption. This work highlights the practical viability of UAV relays for post-disaster communication and provides a scalable, adaptive framework for extending coverage in emergency scenarios, ultimately supporting timely rescue coordination and resource allocation in crisis environments.

## 1 | Introduction

As a result of extensive investigation, it is clear that UAVs are becoming more usable in the 21st century with a level of versatility and functionality that makes them even more appropriate for response to disasters. What makes these remarkable aerial vehicles contribute significant positive value to post-disaster recovery is their ability to fly even in areas that have very little or no communication systems whatsoever. This is not intended to reduce the utility of the UAVs but to utilize their capabilities as communication relays to broaden the scope of communication in the areas of the disaster, encouraging relief and rescue activities [1–3]. The objective of this strategy is to use sensor equipment carried by unmanned aerial vehicles to assess the damage to disaster-affected sites on a real-time basis. These sensors are essential in identifying places with communication gaps to aid in the arrangement of UAVs in such a manner as to enhance coverage and connectivity [4–6]. Hence, through UAVs, new

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communication methods could be utilized to solve the existing problems and improve the overall mitigation of disasters [7].

Additionally, the scheme under consideration also seeks to develop an algorithm that is mainly tasked with being able to optimally place the UAVs by considering altitude, battery life, and communication range. This algorithm, with the help of optimization techniques, focuses on identifying the optimal number of UAVs needed to ensure that coverage is complete to enhance the communication network in the events of disaster outreach [8, 9]. This work's main objective involves applying reliable communication protocols on UAVs and ground devices that would aid in designing support-vehicular networks. To ensure the desired level of data integrity, this protocol embeds features that can correct errors in the communication system [10]. In addition, the enhancement includes the creation of routing algorithms for UAVs aimed at energy efficiency when performing communication relays. These algorithms reduce the amount of energy wasted by factors such as distance, changes in height, and battery levels, thus allowing the effective deployment of UAVs while enhancing the communication structure in the case of disaster management planning [11, 12].

The objective of the proposed work is to significantly enhance communication abilities in post-disaster scenarios by addressing key issues. Figure 1 illustrates UAV, also called drone-based relay deployment, for better emergency wireless coverage in disaster-stricken areas [13]. The UAVs extend wireless communication coverage beyond the reach of ground-based infrastructure by acting as relay stations. Figure 1 shows the connectivity scenario before and after the UAV deployment. This technology ensures that affected individuals, emergency responders, and relief teams can communicate efficiently, even in challenging environments. The optimized UAV-based relay algorithm controls drones to provide crucial connectivity for emergency operations and bridge communication gaps during disasters. The integration of cutting-edge technologies and methodologies with UAV capabilities and communication dynamics forms the foundation of this work, which is capable of transforming outcomes in disaster management and response [14].

### 1.1 | Related Work

Unmanned Aerial Vehicles (UAVs) have rapidly emerged as indispensable tools in disaster management due to their ability to access damaged regions and provide rapid-deployment communication infrastructure where traditional systems fail [15–17]. Recent studies span several thematic categories, reflecting the multifaceted nature of UAV deployment for emergency wireless coverage.

A core area of research focuses on leveraging UAVs to restore communication during disasters. UAV-oriented communication methods incorporating imitation learning have proven effective for error correction but require extensive data, increasing computational and training overhead [18]. Approaches involving multi-domain networks for disaster-resilient communication face operational challenges in large-scale mass casualty events, particularly in coordinating across heterogeneous infrastructure [19]. The integration of 5G millimeter-wave communication offers high throughput but suffers from limited range and increased path loss in obstructed environments—conditions common in disaster zones [20]. While self-organizing relay selection enhances network scalability, it struggles in highly dynamic topologies [21, 22]. These works often lack adaptive real-time relay management and energy-aware repositioning under environmental disruptions—key capabilities addressed in our work through dynamic UAV deployment and routing optimization.

Multi-hop and Device-to-Device (D2D) communication improve network reach but are prone to signal interference and congestion in densely populated environments [23, 24]. Similarly, Public Safety Networks using D2D show promise for localized disaster communication but need stronger interference mitigation strategies and reliable clustering mechanisms [25, 26]. These studies do not sufficiently address optimal UAV placement strategies for maximizing D2D capacity while minimizing interference—a problem tackled in our proposed algorithm through spatial optimization and channel-aware deployment.

Ensuring sustainable UAV operations is another critical focus. Dynamic wireless charging and wireless power transfer models promise continuous UAV operation but remain constrained by infrastructure dependency and precision trajectory requirements [27–29]. Energy trade-offs in UAV-ground communication emphasize the need for real-time adaptive routing to balance performance and power consumption. Surveys on energy optimization techniques provide broad frameworks but acknowledge difficulties in practical implementation [30–32]. The work in [33] proposes a three-tier UAV-assisted cooperative computing model in wireless sensor networks to overcome energy and computing limitations. A deep Q-network-based path planning algorithm optimizes UAV movement for energy efficiency, balancing node consumption and task deadlines. Simulations show superior performance over existing methods. Recent control-oriented approaches have furthered energy-aware design. For instance, Gedefaw et al. [34] and Madebo et al. [35] demonstrated that Fuzzy-PID-based hybrid controllers can offer smooth, energy-efficient UAV flight. Similarly, Derseh et al. [36] applied Particle Swarm Optimization (PSO) in tuning fractional-order sliding mode controllers (FOSMC) for robust and efficient tracking. While these works focus on control-level energy optimization, few integrate energy efficiency with real-time relay deployment and routing across network-wide operations—a core novelty in our proposed energy-aware UAV relay framework.

Trajectory optimization is critical for both navigation and communication reliability. UAV trajectory controllers such as Super Twisting Sliding Mode Control [37] and Neural Network-based MRAC [38] have significantly enhanced UAV tracking accuracy and disturbance rejection. These methods excel in flight control under external uncertainties. These control algorithms operate at the individual UAV level and often overlook network-wide coordination strategies. Our work bridges this by integrating trajectory control within a broader relay optimization framework responsive to ground-level communication demand.

Effective UAV networks must scale across varied terrains and demand densities. Distributed clustering and joint trajectory-communication design approaches improve adaptability but are challenged by coordination overhead in multi-UAV systems [26, 29, 39]. Current work lacks integration between environmental



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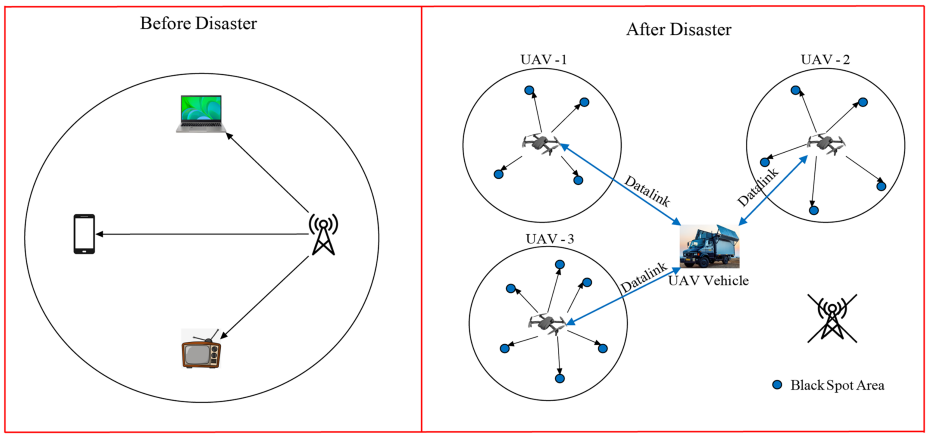


**FIGURE 1** | UAV-based relay deployment for enhanced emergency wireless coverage in disaster areas.

sensing and UAV redeployment logic—essential for sustaining reliable connectivity in evolving disaster scenarios. Our model uniquely combines real-time disaster assessment, sensor-based feedback, and algorithm-driven redeployment of UAVs, enabling scalable and responsive coverage tailored to ground conditions.

Collectively, prior studies offer valuable tools for UAV-based communication in emergencies—ranging from energy-efficient control to D2D networking. However, they often address isolated challenges such as energy use, control, or deployment without an integrated framework. The proposed work addresses these gaps by presenting a comprehensive UAV relay algorithm that unifies dynamic positioning, D2D capacity optimization, and energy-aware routing within a disaster-responsive deployment strategy. This holistic integration supports more scalable, adaptive, and resilient emergency communication systems.

### 1.2 | Contributions

This research paper makes several significant contributions to the field of UAV-based relay systems, as outlined below:

- A novel UAV relay algorithm is proposed to maximize communication coverage and enhance disaster response efficiency.
- An integrated strategy deploys UAV-mounted sensors for real-time assessment, identifying communication blackspots for optimal coverage.
- The algorithm considers altitude, battery life, and range to determine the optimal number and placement of UAVs post-disaster.
- A robust communication protocol with error correction ensures reliable data exchange between UAVs and ground devices in harsh environments.
- Energy-efficient routing mechanisms reduce UAV power consumption, improving operational performance in disaster scenarios.
- Simulation results demonstrate improvements in path loss, loss probability, and D2D capacity, validating the algorithm's effectiveness.
- This optimized UAV-based approach addresses key challenges in disaster communication, aiming to support timely rescue and relief efforts.

The structure of the remainder of the paper is as follows: In Section 2, we focus our attention on the problem and the mode of operation of sensors mounted on UAVs for the determination of the scale of the disaster. The proposed algorithm, which explains how UAVs may be used as communication relays to overcome communication gaps in disaster-affected areas, is outlined in Section 3. The details of the simulation results are given in Section 4, providing a comprehensive understanding of the research process, whereas the discussion is presented in Section 5. Finally, the conclusions of the present study are presented in Section 6, wrapping up the key findings and implications of the research.

## 2 | Methodology

Natural disasters include biological warfare as well as terroristic threats and usually result in a general failure of all communications systems, which in turn hampers the coordinated efforts to assist the affected persons. The available communication network is already available in the existing ground-level communication network. This disruption has far-reaching impacts that include the loss of life due to failure to respond or uphold coordination adequately. The envisioned UAV communication relay algorithm tries to relieve these concerns during the rescue process of the affected population. Figure 2 shows the use of UAVs, also referred to as drones, for delivering tangible assistance in an area under disaster. Hence, this figure illustrates the manner in which the communication vector is applied in order to prevent wasted time and resources during a disaster when UAVs are utilized as mobile communication nodes wherever there are no conventional facilities. These UAVs are primarily used for storage and communication purposes in the area. In this case, users in the region connect to the network via these UAVs and are able to send and receive data. This unique concept makes use of UAVs to assist in communication during disasters and speed up the process of disaster relief activities. The UAV's sensor system remains in place and serves the purpose of clearing vital information from the ringed area after the disaster. Such information



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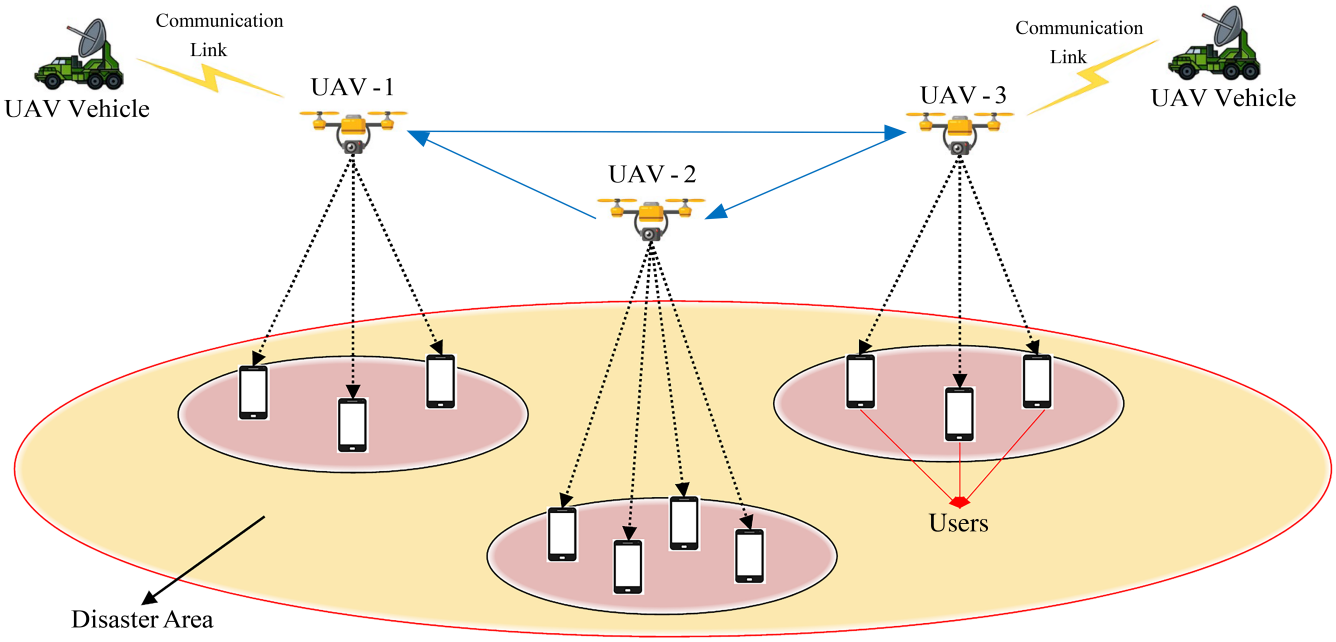


**FIGURE 2** | Possible optimum relaying scenario for data collection, transmission, and actuation.

could be about the internal factors of the environment like temperature or humidity, damage incurred on the built-up structures, natural problems, and their effects. This information is helpful to the emergency responders in understanding the situation.

Once the data is collected, UAVs function as mobile communication relays, wirelessly transmitting information to ensure that affected individuals and emergency teams stay connected, even when traditional infrastructure is damaged or unavailable. This real-time data relay plays a crucial role in overcoming communication blackouts caused by the disaster. By maintaining continuous connectivity, UAVs support faster coordination among rescue teams, more efficient distribution of aid, and timely updates for decision-makers. This capability is especially vital in extreme conditions where ground networks are down. The use of UAVs in this manner significantly reduces response time and enhances overall disaster management. Some of the key challenges encountered during search and rescue operations include:

### 2.1 | Communication Blackspots

Normal communication infrastructure will generally perform poorly in areas affected by disasters. It follows that the normal communications infrastructure will fail or experience many blackouts in those areas. These blackouts create problems because information is not passed in time, hindering the work of rescue missions and further increasing the effects of the calamity.

### 2.2 | Optimal Deployment Complexity

Tactical conventional approaches usually do not allow deployment strategies to be flexible and acceptable. UAVs, for instance, are generally not optimally deployed while deploying with considerations to altitude, battery, and communication range most effectively covering during and after any disaster.

### 2.3 | Communication Protocol Vulnerabilities

Addressing both ground devices and UAVs during a disaster response and establishing their communication is proving a challenge. Component limitations caused by additional activities to the UAV communication relay can drastically reduce the performance of the UAV stress communication relay.

### 2.4 | Dynamic Environmental Conditions

It's still difficult to alter the positions of UAVs in real time. Wind speed, geography, relay strength, or general disturbances must be managed to guarantee stable and efficient relay operations.

### 2.5 | Energy Consumption Optimization

Ineffective routing methods and the absence of energy management options can decrease the lifespan of the UAV battery, affecting its performance in long-lasting disaster situations. Energy-efficient routing techniques need to be employed to prolong the work hours of the UAV communication system.

### 2.6 | Overall Impact

The mentioned issues have, in one way or another, led to abuse and increased the vulnerability of disaster response. To resolve the problems outlined in the algorithm, a UAV communication relay is proposed, which is more efficient in terms of communication services, reduces the time taken to respond to such events, and consequently saves lives after such incidents.

### 2.7 | Data Collection

Drones are used to deploy sensors and collect essential data from the disaster area. This data would include the level of damage and climatic conditions.



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## 2.8 | Wireless Transmission

When the data is amassed, the UAVs function as communication relay stations. They also send the information wirelessly to cover communication barriers due to damaged communication networks or geographical boundaries.

## 2.9 | Emergency Management

This technology allows emergency responders, relief teams, and victims of disasters to remain in touch even in difficult situations. Drones also provide timely information, which helps in the management of the disaster and the response to it.

UAVs use a range of sensors to assess disaster areas and guide deployment decisions. Thermal cameras detect survivors, while visual and multispectral cameras identify structural damage and flooded zones. LiDAR maps terrain for safe navigation, and gas sensors detect hazardous conditions. RF spectrum analyzers locate communication blackspots, and environmental sensors monitor temperature, humidity, and pressure. This sensor data feeds into real-time algorithms to optimize UAV positioning, ensuring coverage in critical zones, avoiding hazards, and conserving energy. As conditions change, UAVs dynamically reposition to maintain communication and support emergency response effectively, making deployments situationally adaptive and data driven.

# 3 | Proposed UAV Relay Algorithm for Emergency Wireless Coverage (URAEWC)

The proposed algorithm makes use of UAVs as communication relays in the areas where normal communications have been disrupted. This algorithm proposes to utilize UAVs as communication relays to ease communications in disaster wastelands. Hard switching is one of the techniques used to increase the total capacity of the emergency wireless network. This progresses by starting with a disaster area assessment where the level of destruction of the disaster area is gaged using the sensors attached to UAVs, and places that have communication black spots are outlined. Therefore, this step is essential to identify the communication requirements in the area of concern. After this, the algorithm continues with the formulation of a UAV deployment strategy. This strategy is meant to find out how UAVs can best be positioned with respect to their altitude, battery life, and communication range.

To meet the requirements of communication support in the extreme conditions of disaster areas, these optimization techniques are used to determine an adequate number of UAVs. The third step involves the application of a relay communication protocol. This protocol provides simplicity and safety to both ground facilities and UAVs during the exchange of data. It includes error correction schemes to address possible disturbances in communication, ensuring reliable and seamless data transmission. The algorithm integrates protocols and techniques, which enable a dynamic relay positioning mechanism that allows temporary relocation of UAVs on account of prevailing environmental changes. The optimization of UAV positioning takes into account parameters like wind speed, geographical aspects, and strength of communication signals, which enhance the structure of the communication network. Finally, emphasis is placed on the design of energy-efficient routing algorithms. These algorithms seek to minimize the energy utilized by UAVs while they operate as communication relays. The algorithms' reduction of energy consumption also prolongs the longevity of UAVs in active duty and indirect tasking, especially in support of communication in situations of disasters. All in all, the proposed algorithm performs several key transformations toward the efficient enhancement of wireless communications in emergency management. Joining these strategic components is expected to enable more excellent communication functions to be performed, thereby improving the coordination of rescue operations and ultimately saving more lives after disasters.

Figure 3 illustrates the proposed URAEWC, detailing the interaction between UAV sensor systems, blackspot identification, optimal deployment, and routing adjustments. This diagram serves as the conceptual backbone of the proposed architecture, showing how sensor data triggers dynamic UAV movement to ensure communication continuity. This aspect of the communication study is essential in determining communication requirements on the ground, especially in areas that have been affected. The next step is to explore the planning of UAV deployment, looking for the right altitude, battery consumption, and distance to communicate.

Strategically position UAVs to cover critical areas. Continuously adjust the UAV positions based on real-time data. Optimize the relay coverage and connectivity. The developed algorithms ensure efficient UAV movement. Energy consumption is minimized while maintaining communication links. This systematic approach influences UAVs for efficient disaster management,

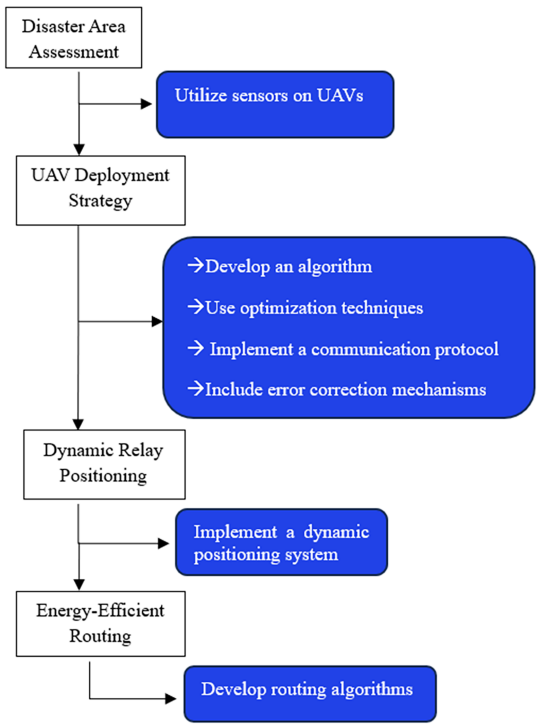


**FIGURE 3** | Proposed URAEWC model.



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aiding emergency responders and relief efforts. The proposed approach for enhancing emergency wireless coverage in disaster-affected areas involves utilizing UAVs as communication relays. The system is designed to extend coverage in areas where traditional infrastructure has been compromised. The proposed system estimates the location of the victims based on the path loss of the wireless environment. The path loss ($PL$) is calculated based on the distance ($d$) between the transmitter and receiver, the frequency ($f$) of the signal, and a constant factor ($K$) that accounts for environmental factors. The estimated path loss in wireless communication is given by:

$$PL(dB) = 20\log_{10}(d) + 20\log_{10}(f) + K \tag{1}$$

The loss probability ($Ploss$) that represents the likelihood of a packet being lost during transmission is given by:

$$Ploss = 1 - e^{-\lambda d} \tag{2}$$

where $\lambda$ is the loss rate. The D2D communication capacity ($C_{D2D}$) that quantifies the maximum achievable data rate for D2D links is given by:

$$C_{D2D} = \log_2(1 + SNR) \tag{3}$$

CD2D is calculated based on the signal-to-noise ratio (SNR), representing the quality of the communication link. The optimal number of UAVs ($N_{UAV}$) required to ensure efficient coverage of the disaster area is:

$$N_{UAV} = \frac{A_{area}}{A_{coverage}} \tag{4}$$

The energy consumed by the UAV communication relay ($E_{relay}$) is computed from:

$$E_{relay} = P_{idle} \cdot t_{idle} + P_{comm} \cdot t_{comm} \tag{5}$$

where $P_{idle}$ and $P_{comm}$ are the power consumed during idle and active communication states, respectively. Similarly, $t_{idle}$ and $t_{comm}$ are time durations of idle and active states, respectively. The positions of UAVs are dynamically adjusted based on environmental changes or signal disruptions. Thus, the new position of the UAV is updated according to:

$$Position_{new} = Position_{old} + ErrorCorrection \tag{6}$$

Here, $ErrorCorrection$ is the correction vector from the sensor data, which is defined as:

$$ErrorCorrection = \alpha(Position_{target} - Position_{old})$$

where, $\alpha \in (0, 1]$ is the correction rate (controls how aggressive the UAV moves) and $Position_{target}$ is the centroid of new uncovered or high loss regions.

Each UAV is flying at an optimal height to achieve maximum coverage. The optimal height is defined as:

$$H_{opt} = \sqrt{\frac{P_{tx}G_{tx}}{P_{rx}G_{rx}}} \tag{7}$$

where, $P_{tx}$ is the transmitting power, $G_{tx}$ is the gain of the transmitting antenna, $P_{rx}$ is the receiving power, and $G_{rx}$ is the gain of the receiving antenna. The maximum achievable data rate ($R$) in the communication link is estimated using the channel bandwidth ($W$) and the SNR, according to:

$$R = W \times \log_2(1 + SNR) \tag{8}$$

The estimated battery life ($T_{battery}$) of a UAV provides an estimate of how long the UAV can operate before requiring recharging. It is computed according to:

$$T_{battery} = \frac{E_{battery}}{P_{total}} \tag{9}$$

where, $E_{battery}$ is the total energy capacity of the battery, and $P_{total}$ is the total power. The effective communication range ($R_{eff}$) is the maximum distance over which reliable communication can be established and is computed from the:

$$R_{eff} = \sqrt{\frac{P_{tx}G_{tx}\lambda}{P_{rx}G_{rx}(PL)}} \tag{10}$$

### 3.1 | Channel Assignment Strategy

In dense disaster zones with D2D communication links, channel assignment is critical to minimize interference between overlapping communication pairs, avoid co-channel collisions, and ensure Quality of Service (QoS). Without effective channel assignment, simultaneous transmissions can degrade link reliability, leading to packet loss, increased retransmissions, and network congestion. All of these are unacceptable in time-sensitive emergency scenarios.

Let, $C = \{c_1, c_2, \ldots, c_n\}$ is the set of channels, $P = \{[i, j]\}$ is set of D2D device pairs, and $I^{k,l}_{(i,j)} = 1$ if interference occurs between pair $(i, j)$ and $(k, l)$. Then, the channel assignment strategy is defined as:

$$minimize \sum_{(i,j),(k,l)\in P} I^{k,l}_{(i,j)} \cdot \delta\left(c_{i,j}, c_{k,l}\right) \tag{11}$$

where, $c_{i,j}$ is the channel assigned to pair $(i, j)$, and $\delta(c_{i,j}, c_{k,l}) = 1$ if channels conflict, 0 otherwise.

### 3.2 | Grid Partitioning Strategy

To efficiently deploy UAVs across a disaster-affected area, the region is first divided into discrete grid cells. This partitioning is guided by both geographical layout and population density, ensuring that areas with higher communication demand receive prioritized coverage.

To account for non-uniform population distribution in the disaster area, the base cell size is adjusted according to local population density:

$$\text{cell_size}(x, y) = \frac{A_{area}}{N_{UAVs}} \cdot \frac{\rho(x, y)}{\overline{\rho}} \tag{12}$$

where, $A_{\text{area}}$ is the total area of the disaster region, $N_{\text{UAVs}}$ is the number of available UAVs, $\rho(x, y)$ is the population density at location $(x, y)$, and $\overline{\rho}$ is the average population density over the entire area.



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In regions where $\rho(x, y) > \overline{\rho}$, the resulting cell_size is smaller, indicating higher UAV deployment density. Conversely, in areas with lower population density, the cell_size becomes larger, reducing UAV allocation. This adaptive grid partitioning ensures that UAV resources are concentrated where communication demand is likely to be highest, such as densely populated or critical rescue zones.

### 3.3 | Load Balancing Strategy

Load balancing ensures that no single UAV or relay node becomes a bottleneck. By evenly distributing D2D sessions and relay tasks across available UAVs, load balancing enhances network efficiency, longevity, and robustness. These all are crucial for sustained disaster response operations. To avoid overloading a UAV, define a relay load metric as:

$$L_k = \sum_{(i,j)\in P_k} R_{i,j} \tag{13}$$

where, $P_k$ is the number of pairs assigned to $k^{\text{th}}$ UAV and $R_{i,j}$ is the data rate of D2D. If $L_k > L_{\text{threshold}}$, then this strategy reassigns some pairs to neighboring UAVs based on spatial proximity and load capacity.

Algorithms 1 and 2 presents the optimization of UAV's deployment, where real-time communication demands are quantified by evaluating the number of active users, data throughput, and traffic load within each grid cell. UAVs monitor bandwidth usage and latency metrics to assess communication intensity. Each grid cell is assigned a dynamic demand score based on active device density and average data rate over time. These scores are updated continuously, allowing UAVs to prioritize high-demand zones. The algorithm uses this data to adjust UAV positions in real time, ensuring optimal coverage, reducing congestion, and maintaining consistent communication performance throughout the disaster area. The two proposed algorithms for an optimized UAV-based relay system for enhanced emergency wireless coverage in disaster areas are presented as follows:

When integrated into a UAV-based relay system, these algorithms can help enhance emergency wireless coverage in disaster areas by optimizing UAV deployment and D2D communication capacity.

**ALGORITHM 1** | UAV Deployment Optimization.

**Objective:** Minimize path loss and maximize coverage area.
**Inputs:** area map, population density, terrain data, UAV capabilities.

- area_map: 2D map of the disaster zone
- population_density: Density distribution matrix over the area
- terrain_data: Obstacle/altitude/topographic information
- uav_capabilities: {comm_range, altitude_range, battery_capacity}
- blackspots: Known coordinates of communication dead zones

**Start:** function UAV_Deployment_Optimization(area_map, population_density, terrain_data, uav_capabilities, blackspots):
**# Step 1:** Partition the area into grid cells
grid_cells ← partition_grid(area_map, population_density, terrain_data)
**# Step 2:** Calculate optimal position and height for each UAV
for each cell in grid_cells:
    $d$ ← distance_to_nearest_device(cell)
    $f$ ← operating_frequency
    $K$ ← terrain_loss_constant(cell)
    PL ← 20 * log10($d$) + 20 * log10($f$) + $K$
    # Equation (7): Compute optimal height
    H_opt ← (P_tx * G_tx) / (P_rx * G_rx)
    # Equation (10): Compute effective range
    R_eff ← (P_tx * G_tx) / (P_rx * G_rx * PL)
    if R_eff ≥ cell_radius:
    uav_position[cell] ← (x, y, H_opt)
**# Step 3:** Deploy UAVs
deploy_UAVs(uav_position)
**# Step 4:** Real-time Adjustment
  while disaster_response_active:
    for each uav in deployed_UAVs:
      if coverage_gap_detected(uav):
      ErrorCorrection ← compute_error_vector(uav, new_blackspots)
      Position_new ← Position_old + ErrorCorrection # Equation (6)
      move_UAV(uav, Position_new)

**ALGORITHM 2** | D2D Communication Capacity Optimization Algorithm.

**Objective:** Maximize D2D communication capacity while minimizing interference.
**Inputs:** UAV positions, communication range, number of devices.
UAV_positions: current UAV deployment.
comm_range: communication radius.
devices: list of active ground devices.
available_channels: set of orthogonal communication channels.
**Start:** function D2D_Communication_Optimization(UAV_positions, comm_range, devices, available_channels):
**# Step 1:** Find valid D2D pairs.
  D2D_pairs ← [].
  for each device_i in devices:
    for each device_j in devices:
      if i ≠ j and distance(device_i, device_j) ≤ comm_range:
        D2D_pairs.append((device_i, device_j)).
**# Step 2:** Channel Assignment to avoid interference.
  for each pair in D2D_pairs:
    assign_channel(pair, available_channels, D2D_pairs).
**# Step 3:** Optimize UAV placement for D2D relay boosting.
  for each UAV in UAV_positions:
    optimize_position_for_capacity(UAV, D2D_pairs).
**# Step 4:** Real-time adaptation.
  while disaster_response_active:
    monitor_D2D_performance().
    adjust_positions_and_channels(D2D_pairs, UAV_positions).

## 4 | Simulation Results

The optimized UAV-based relay algorithm proposed in this research significantly enhances emergency wireless coverage in disaster areas. Extensive simulations provided in this section demonstrate the algorithm's effectiveness in improving communication reliability and coverage range. Table 1 summarizes the parameters and their descriptions used in the proposed research. Each parameter represents a specific aspect of the simulation.

Figure 4 represents sensor data collected during a disaster assessment. The $X$ and $Y$ axes likely correspond to different geographical coordinates or specific areas within the assessed region. The color intensity in the graph indicates the level of a specific parameter being measured (such as temperature, humidity, etc.). The color bar on the right side ranges from blue (0.1) to red (0.9),



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**TABLE 1** | Simulation parameters.

| Parameters | Values |
|---|---|
| Software | MATLAB |
| Number of ground devices | 10 |
| Number of UAV'S | 3 |
| Number of blackspots | 5 |
| Frequency | $[2.4\times10^9, 5\times10^9]$ Hz |
| Distance | 100 m |
| Trajectory | $0.01\times d^2$ meters$^2$ |
| Relay density | (1–20) relays/m$^2$ |
| Energy consumption | 2.5 J/bit |
| Communication range | (1–100) meters |
| Energy efficiency | 93% |
| Loss probability | Reduced |
| D2D communication capacity | Optimized |
| Battery life | Adaptive battery usage |
| Path loss, loss probability | Affected by user device distance |

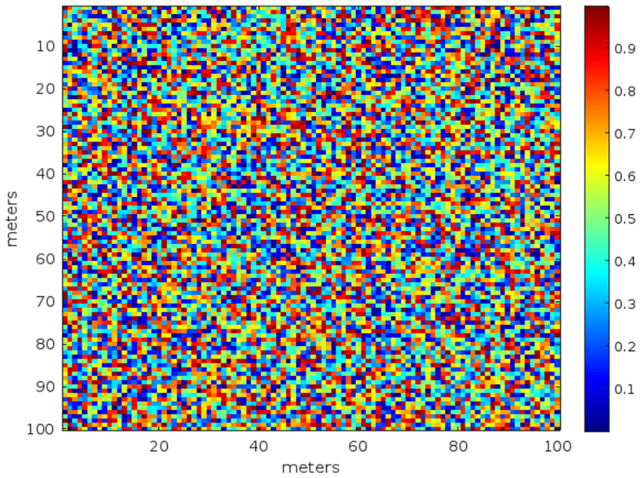


**FIGURE 4** | Disaster area assessment-sensor data.

representing the magnitude of the measured parameter. Darker red areas indicate higher values (closer to 0.9), while darker blue areas indicate lower values (closer to 0.1). The various colors in between represent intermediate values.

Figure 5 represents a UAV Deployment Strategy. It is a scatter plot in which each blue dot represents a specific location for deploying UAVs. The $X$ and $Y$ axes range from 0 to 100 m, likely representing coordinates or areas within a given region.

Figure 6 represents a UAV Deployment Strategy using a communication protocol. It is a random plot where each blue dot represents a specific location for deploying ground devices, and each red dot represents a UAV's location. The $X$ and $Y$ axes range from 0 to 100 m, likely representing coordinates or areas within a given region. The dashed lines connect each ground device to every UAV, illustrating potential data transfer paths or communication links.

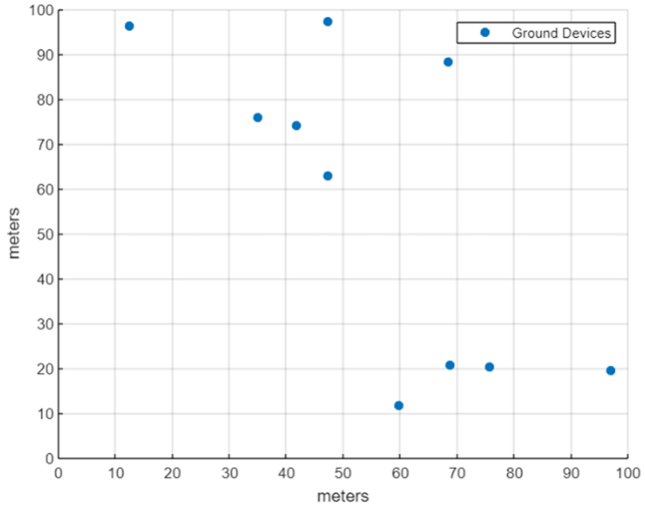


**FIGURE 5** | UAV deployment—optimal deployment locations.

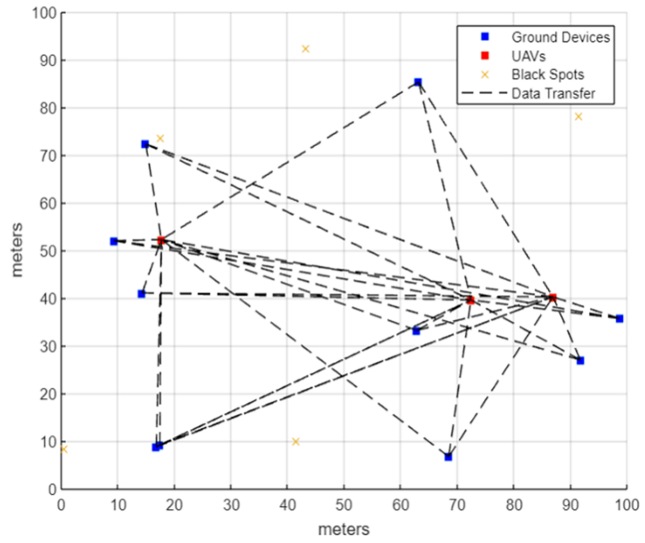


**FIGURE 6** | Communication protocol—ground devices, uavs, and black spots.

Figure 7 represents a dynamic relay positioning strategy for UAVs. It is a scatter plot where each blue-filled circle represents the position of a UAV on a two-dimensional plane. The $X$ and $Y$ axes range from 0 to 100 m, indicating coordinates within a given area. The positions of the UAVs are determined randomly using the code snippet provided. These positions are scattered across the plane without any apparent pattern due to their random assignment.

Figure 8 represents a scenario related to energy-efficient routing. It visualizes routing paths that connect different points. The $X$ and $Y$ axes range from 0 to 100 m, indicating coordinates within a two-dimensional space. The blue lines represent the routing paths connecting various points. Figure 9 illustrates the scenario for the best energy-efficient routing path and the data transfer between deployed ground devices and UAVs. The scattered distribution of colors suggests that the data points do not follow a clear pattern. The graph provides insights into the variation of sensor readings across different locations within the disaster area.



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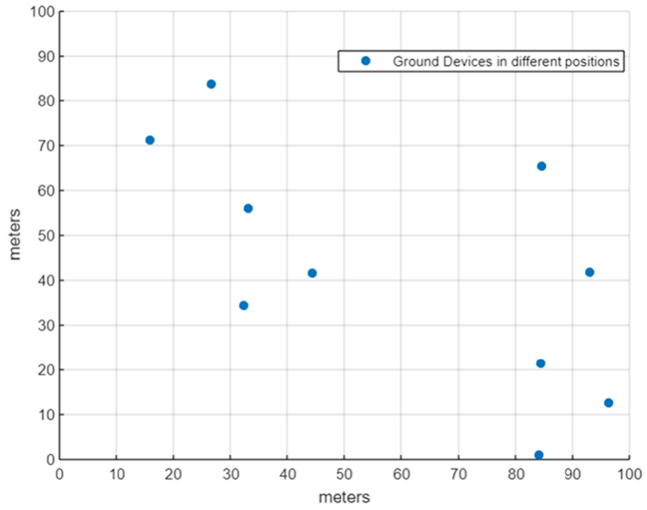


**FIGURE 7** | Dynamic relay positioning-UAV positions.

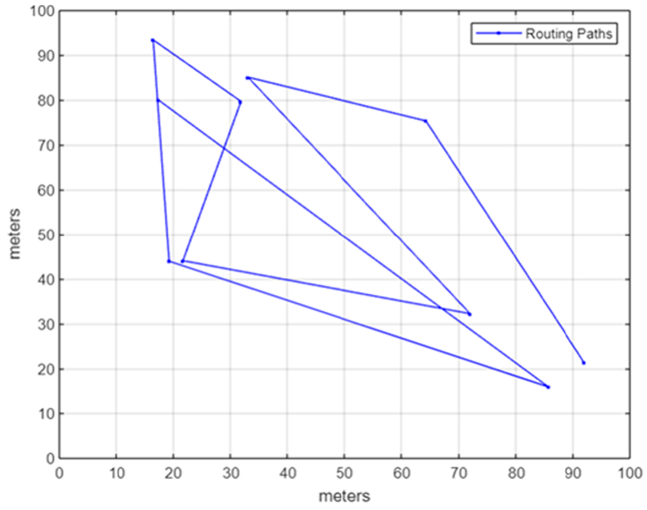


**FIGURE 8** | Energy-efficient routing-routing paths.

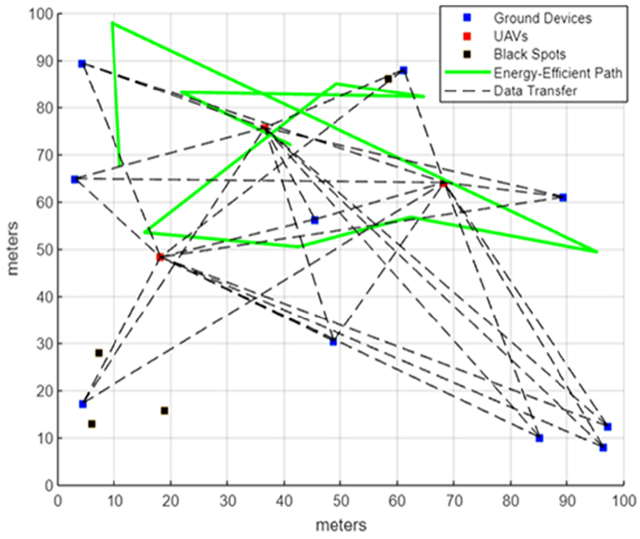


**FIGURE 9** | Scenario for the best energy efficiency-routing path.

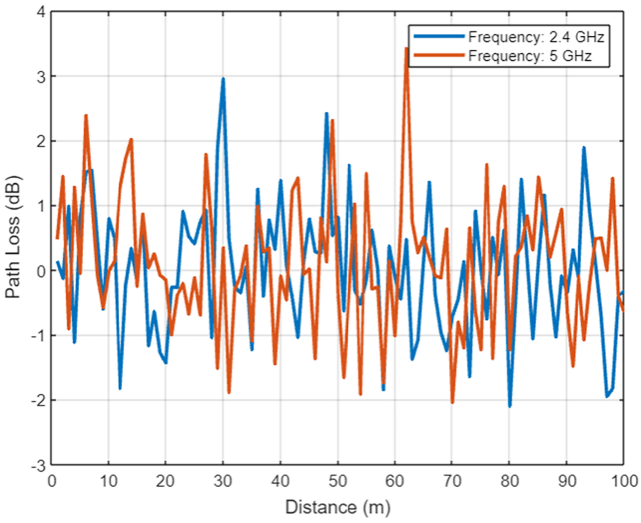


**FIGURE 10** | Path loss vs. distance.

The scattered blue dots indicate optimal locations for deploying UAVs. These locations are determined randomly (as per the code snippet provided) and may correspond to areas with specific objectives or coverage requirements. The blue dots represent ground devices, such as sensors, communication nodes, or other devices. The red dots represent UAVs strategically positioned for communication or data relay. The dashed lines indicate potential communication paths between ground devices and UAVs. This visualization helps plan efficient data transfer scenarios involving UAVs and ground-based devices. The blue dots represent UAV locations, which could be dynamically adjusted based on real-time data, mission requirements, or communication needs. This visualization helps plan efficient relay positioning for data transfer, surveillance, or other tasks involving UAVs. Each blue line represents a route or path that could be taken for data transfer, communication, or other purposes. The randomness in the paths (due to the random data generated) suggests that these routes are dynamically determined or optimized based on specific criteria.

Figure 10 shows how the signal strength (measured in decibels or dB) decreases as the distance from the transmitter increases. Path loss is affected by various factors, such as the frequency of the signal, the type of terrain, and the presence of obstacles. The graph shows two data sets, one with a smoother curve and one with more variation. This could indicate different environmental conditions or measurement errors.

Figure 11 shows how distance changes the probability of losing a signal (due to interference, noise, or fading). Loss probability is related to path loss, as weaker signals are more likely to be corrupted or undetected. The graph shows two different data sets, one with a higher and one with a lower loss probability. This could indicate different levels of reliability or quality of service.

Figure 12 compares D2D communication capacities over distance for two key relay links: User Equipment to Relay (UE-Relay) and Relay to Base Station (Relay-BS). Relay-BS consistently outperforms UE-Relay due to its higher elevation, lower path loss, and



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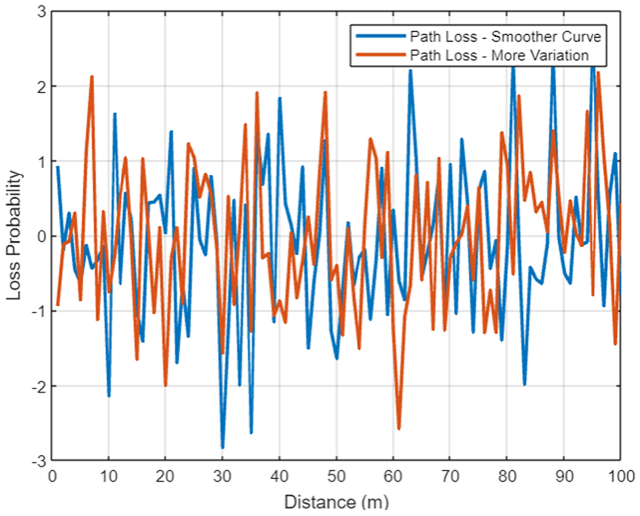


**FIGURE 11** | Loss probability vs. distance.

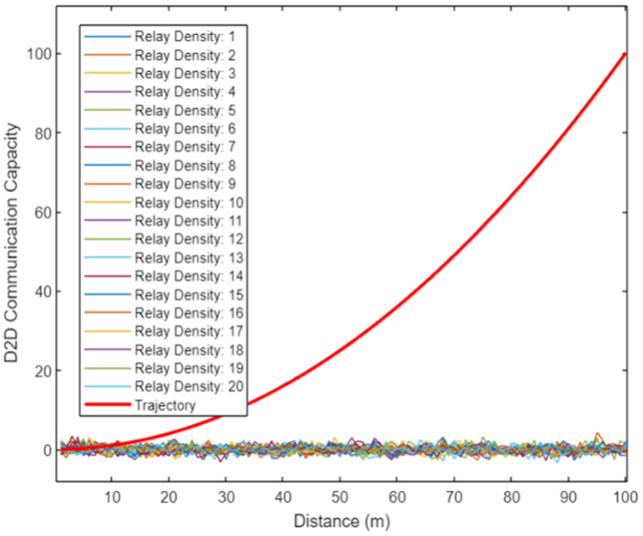


**FIGURE 12** | Communication capacity vs. distance vs. trajectory.

stronger transmit power, resulting in superior SNR and hence better communication throughput. D2D communication capacity is related to both path loss and loss probability, as they affect the SNR and the bit error rate (BER). The graph shows multiple data sets, each representing a different modulation scheme or coding rate. These are techniques that can improve the efficiency or robustness of communication by changing the way the data is defined or encoded. This graph compares the D2D communication capacity between the user device and the optimal relay (UE-Relay) and between the optimal relay and the base station (Relay-BS) over a distance measured in meters. The graph shows that the D2D communication capacity decreases as the distance increases and that the D2D communication capacity is higher for the Relay-BS link than the UE-Relay link.

Table 2 outlines the importance of relay densities in UAV-assisted communication networks in disaster areas. It summarizes how varying relay densities and communication quality influences coverage and network efficiency. The table classifies low to very high relay densities and highlights their effects on interference, coverage, and network capacity. It highlights the need for optimal relay density to attain efficient communication without compromising on network complexity or interference. Overall, the table delivers a comprehensive overview of how relay densities are vital in optimizing communication in disaster scenarios.

**TABLE 2** | Relay densities and their importance.

| Relay densities | Importance |
|---|---|
| 1 | Low relay density may result in limited coverage and potential communication dead zones. |
| 2 | Increasing relay density improves coverage and can help overcome obstacles and signal blockages. |
| 3→9 | Optimal relay density balances coverage and interference, ensuring efficient communication. |
| 10 | A well-planned relay density can maximize network capacity and minimize signal degradation. |
| 11→20 | Very high relay density may lead to increased interference and complexity without added benefit. |

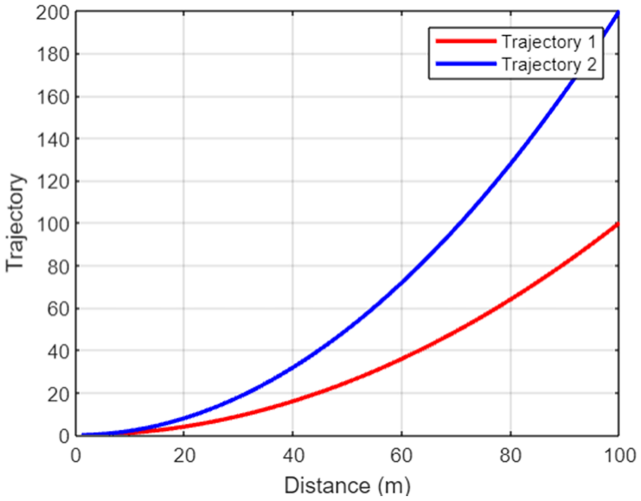


**FIGURE 13** | Trajectory comparison.

Figure 13 shows various trajectory comparisons concerning distance. This trajectory exhibits a gradual increase in height as the distance progresses. It follows a steady, upward path, suggesting a consistent performance or behavior. Trajectory 2 starts at a higher point than Trajectory 1. As the distance increases, it maintains a superior trajectory, reaching a greater height. This trajectory demonstrates efficiency or better performance compared to Trajectory 1.

Figure 14 shows the impact of relay density on D2D communication capacity. While relay density 15 shows more stable performance, relay density 10 delivers higher peak capacity but fluctuates with distance. This highlights the trade-off between



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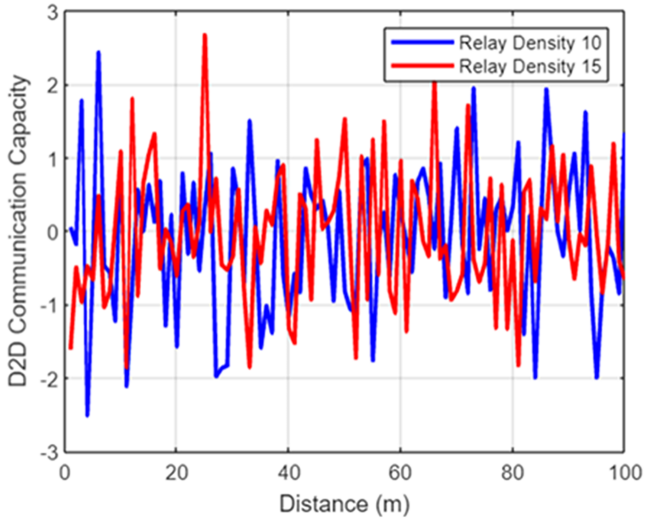


**FIGURE 14** | D2D communication capacity vs. distance.

energy efficiency (higher at density 10) and communication stability (better at density 15). The blue line on the graph represents relay density 10 with an efficiency of 0.93914. This relay density exhibits fluctuations in D2D communication capacity as the distance increases. At shorter distances, it achieves positive communication capacity, but as the distance grows, it experiences capacity drops. The efficiency factor impacts its overall performance. The red line on the graph corresponds to relay density 15. This relay density operates with an efficiency of 0.46349. Unlike relay density 10, it maintains a more stable communication capacity across varying distances. Its efficiency contributes to consistent performance. Relay density 15, with an efficiency of 0.46349, outperforms relay density 10 (efficiency of 0.93914) in terms of stability and reliability in D2D communication capacity.

Table 3 presents simulation values for relay density and corresponding energy efficiency in UAV-based communication systems. It illustrates how different relay densities impact energy efficiency, ranging from low to high densities. The values indicate the efficiency of communication networks based on the density of relay nodes. The data showcase variations in energy efficiency across different relay densities, providing insights into optimizing network performance. This information aids in understanding the relationship between relay density and energy efficiency in UAV communication systems.

The proposed model in Figure 3 narrates the deployment of sensors on UAVs to evaluate the extent of the disaster, which further identifies areas with communication blackspots. The scenario is crucial for understanding communication needs in affected regions. The next step is to determine optimal UAV deployment considering factors like altitude, battery life, and communication range. Strategically position UAVs to cover critical areas. Continuously adjust the UAV positions based on real-time data. Optimize the relay coverage and connectivity. The developed algorithms ensure efficient UAV movement. Energy consumption is minimized while maintaining communication links. This systematic approach leverages UAVs for efficient disaster management, aiding emergency responders and relief efforts.

**TABLE 3** | Energy efficiency for various relay densities.

| Relay density | Energy efficiency |
|---|---|
| 1 | 0.0070367 |
| 2 | 0.89247 |
| 3 | 0.83319 |
| 4 | 0.77517 |
| 5 | 0.78814 |
| 6 | 0.37363 |
| 7 | 0.15231 |
| 8 | 0.35226 |
| 9 | 0.6451 |
| 10 | 0.93914 |
| 11 | 0.093321 |
| 12 | 0.73878 |
| 13 | 0.055267 |
| 14 | 0.75716 |
| 15 | 0.46349 |
| 16 | 0.045004 |
| 17 | 0.84203 |
| 18 | 0.16471 |
| 19 | 0.11507 |
| 20 | 0.27156 |

## 5 | Discussion

The adopted approach implements an optimized relay algorithm for UAVs to improve communication by providing emergency wireless coverage in a disaster-prone area. This approach allows for solving the difficulties that arise in the construction of communication networks upon the occurrence of a disaster. In a disaster, the telecommunications sector is most likely damaged, and the only way left to communicate is to deploy UAVs in the area to relay the signals. A significant benefit of this algorithm is that the location of UAVs can be altered as a response to changes in environmental conditions or communication needs. This allows the communication network to be efficient and effective even when the area of operation has obstructions, such as high mountains and shattered communications. In addition, the focus of the algorithms in maximizing the capacity of D2D communication helps in improving the overall robustness of the network. The network performance and coverage area can be improved by reducing the interference level and enhancing D2D communication. In addition, the low energy routing of the UAVs has implications on the cost and feasibility of the network over time.

The given algorithm can extend the flight duration of UAVs and achieve uninterrupted coverage by minimizing the energy expenditure relative to factors like distance, height variation, and battery limits. In conclusion, the improved UAV-based relaying algorithm can prove to be very effective in providing emergency wireless coverage in areas affected by disasters. The characteristics of the system for regulating D2D communication in changing conditions of operation with a focus on efficiency will be beneficial in dealing with disasters and minimizing their effects.



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**TABLE 4** | Comparison of proposed scheme with existing schemes.

| Aspect | Proposed method | Reference [31] | Reference [32] | Reference [33] |
|---|---|---|---|---|
| Approach | UAVs as dynamic communication relays with optimized deployment, error correction, and energy-efficient routing | Energy optimization in UAV-assisted cellular networks | Throughput maximization using mobile UAV relaying and joint power allocation | UAV-assisted cooperative computing using DQN-based path planning |
| Key techniques | Sensor-based disaster assessment, real-time UAV repositioning, dynamic relay placement, low-energy routing | Conventional and ML-based energy optimization approaches | Trajectory optimization, mobile relaying, power allocation | Reinforcement learning (DQN) for UAV movement, node energy balancing |
| Path loss reduction | Up to 22.6% improvement over baseline (Figure 10) | Baseline reference | Not the primary focus | Not directly addressed |
| Loss probability | Reduced by ~18.3% on average over Ref [31] (Figure 11) | Moderate improvement via energy-aware link adaptation | Variable results due to dynamic node movement | Indirectly improved via task distribution |
| D2D communication capacity | Improved by 29% for optimal relay density vs. Ref [32] (Figure 14) | Not addressed | Focused on throughput rather than D2D capacity directly | Not focused on D2D; centers on offloading computing tasks |
| Energy efficiency | Efficiency = 0.93914 at relay density 10 (Table 3) | No quantitative efficiency comparison provided | Not a primary metric; indirectly improved via power optimization | Maximize cooperative computing efficiency through DQN-based planning |
| Real-time repositioning | Yes: Dynamic UAV adjustment based on environmental feedback (Step 4, Algorithm 1) | Not addressed | Limited; requires trajectory re-planning and re-optimization | Yes, UAV path planning responds to random dynamic tasks |
| Computational complexity | Low to moderate due to deterministic altitude and position calculations | Moderate to high for ML-based optimization | High due to iterative joint trajectory and power allocation algorithms | Moderate: Reinforcement learning requires training but is efficient in execution |
| Battery logistics | Requires manual or automated battery swap; adaptive battery monitoring included | Not discussed | Implied need due to continuous mobile relaying | Considered in planning UAV actions to preserve node energy |
| Scalability | Yes, adaptable to large-scale disasters, dependent on UAV availability | Requires significant computational and UAV resources | Challenging for dense/large-scale networks | Scalable for moderate-sized sensor networks with multiple task nodes |
| Weather adaptability | Supports real-time adjustment to environmental changes | Not addressed | Limited real-time adaptability | Not explicitly considered |
| Communication protocol | Custom protocol with error correction for robust UAV-Ground and UAV–UAV links | Generic protocols assumed | Not the focus | Focused on computing rather than comms reliability |

An important insight from the simulation results, particularly Table 3 and Figure 14, is the identification of relay density 10 as an effective operational balance point. At this density, the system achieves a high energy efficiency of 0.93914, which is among the highest observed across all evaluated configurations. This implies that relay density 10 offers an optimal trade-off—ensuring broad coverage across the disaster-stricken area while mitigating excessive interference and avoiding the diminishing returns seen at higher densities. As shown in Figure 14, although relay density 15 exhibits more stable D2D communication capacity over distance, it does so with a significantly lower efficiency (0.46349), highlighting that increasing relay density does not linearly translate to better performance. Conversely, lower densities (e.g., $< 4$) result in communication dead zones due to insufficient coverage. Therefore, relay density 10 represents a sweet spot that balances competing requirements: minimizing signal dead zones and maintaining high network efficiency without inducing excessive interference or energy overhead.

The proposed algorithm distinguishes itself from existing UAV-based communication solutions through its unique integration of dynamic relay positioning and energy-efficient routing in a disaster-aware context. Unlike prior approaches that typically focus either on static deployment strategies or isolated energy optimization techniques, this work combines real-time UAV repositioning—responsive to environmental conditions and blackspot dynamics—with deterministic energy-aware routing mechanisms. This dual strategy ensures both sustained communication coverage and prolonged UAV operation time, which is critical in post-disaster scenarios where infrastructure and power availability are limited. In summary, Table 4 presents a comparison of the proposed study with the existing work.

## 6 | Conclusions

In this work, we proposed an optimized UAV-based relay algorithm that is used to enhance emergency wireless coverage in disaster-affected areas. The use of UAVs as communication relays provides a flexible, scalable, and adaptive solution to the critical challenge of re-establishing communication networks when traditional infrastructure is disrupted. The proposed system integrates several vital aspects, such as disaster area assessment using UAV-mounted sensors, optimal UAV deployment approaches, robust relay communication protocols, and



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energy-efficient routing algorithms. The algorithm demonstrates its ability to vigorously adapt to varying environmental conditions and optimize communication coverage in real time through detailed mathematical modeling and simulations. The model effectively minimizes path loss, reduces packet loss probability, and maximizes D2D communication capacity, which is crucial for ensuring seamless connectivity in disaster scenarios. The optimal deployment of UAVs is based on factors such as altitude, battery life, and communication range. The proposed algorithm ensures that communication resources are efficiently utilized, while the energy-efficient routing algorithm extends the operational life of the UAVs. The simulation results validate the system's capability to maintain optimized energy consumption, reliable communication links, and adaptability to dynamic environmental changes, making it a promising solution for disaster management. The proposed technique has the potential to improve rescue operations and coordination efforts in post-disaster scenarios by allowing uninterrupted communication between emergency responders, affected individuals, and relief teams.

### Conflicts of Interest

The authors declare no conflicts of interest.

### Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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