The Role of UAVs in Enhancing Network Resilience During Natural Disasters

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Abstract

Background: Failures of communication usually occur during natural disasters, therefore signaling the importance of flexible networks. Unmanned Aerial Vehicles (UAVs) are anticipated to solve this problem by acting as on-the-move networks in the disaster-stricken regions. However, barriers that include challenges in UAV control coordination, resources allocation as well as security of the data being drawn are still pushing the technology backward.

Objective: The article seeks to design and analyze enhanced heuristics for employing UAVs in disaster communications to enhance performance, availability, and security.

Methods: Both primary, semi-structured interview and survey and post-disaster reports as well as secondary, computational analysis based on MATLAB and NS - 3 simulations were used as the data collection technique. Five algorithms: Multi-UAV Coordination, Dynamic Resource

Allocation with Security, Hybrid Communication Framework, AI-Driven Path Optimization, Privacy-Preserving Data Sharing were implemented and incorporated. Theoretical models built on the basis of multi- objective optimization and the theory of games confirmed work ability to scale.

Results: The introduced algorithms increased coverage by 75%, decreased latency by 27 percent, and also introduced 30 percent energy efficiency. Average privacy compliance levels floated above 90%, and an advanced resource allocation model achieved equal distribution. All these enhancements were affirmed in urban, rural and mountainous regions further proving versatility and stability.

Conclusion: The article proposes a framework for UAV-enabled disaster communication system that can incorporate advanced algorithm and theoretical models to overcome the coordination challenge while ensuring the efficiency and security of the system. The presented results can be considered to be the reliable base for the UAVs usage in disaster situations.

Keywords: UAVs, network resilience, natural disasters, emergency response, communication restoration, LTE, 5G, disaster recovery, situational awareness, infrastructure repair.

1. Introduction

The integration of Unmanned Aerial Vehicles (UAVs) into network resilience frameworks has significantly advanced the preservation of communication systems during calamities. When traditional infrastructure is disrupted by events such as earthquakes, floods, or hurricanes, UAVs provide convenient and rapid means to restore connectivity. Their capacity for swift deployment and self-organizing communication networks is invaluable in post-disaster situations where civil and emergency communications are essential (Qasim and Jawad 2024). Among their benefits, UAVs can create temporary wireless networks to connect displaced individuals, assist in search and rescue operations, and provide real-time communication for disaster management teams, thereby enhancing network robustness (Wang et al. 2023).

Recent developments have explored how UAVs enhance the reliability of public safety networks (PSNs) through the integration of network functions virtualization (NFV) and software-defined networking (SDN). These technologies contribute to the flexibility of UAV systems, allowing them to maintain functionality in dynamic or atypical disaster scenarios. Additionally, the WLAN capabilities of UAVs enable the delivery of access points and wireless mesh networks, overcoming geographical barriers such as mountains and poorly connected regions. This capability positions UAVs as central tools in enhancing the potential of communication networks following disasters (Abir, Chowdhury, and Jang 2023).

Architecturally, UAVs utilize device-to-device (D2D) communication, enabling devices to interact directly without relying heavily on traditional networks (Qasim et al. 2022). Such systems are crucial for ensuring communication for first responders and residents when wired infrastructure collapses. Integrated configurations that involve UAVs interacting with both ground and satellite systems, or exclusively utilizing UAVs in ground systems, have proven effective for both short-term disaster response and long-term facility reliability across multiple disciplines (Huang 2023).

For instance, with LTE or 5G technologies, UAVs are critical assets in maintaining communication network continuity during natural disasters. Their quick deployment and ability to establish temporary networks facilitate seamless cooperation among emergency teams. UAVs were particularly vital during the 2017 Mexican earthquake, ensuring continuous data links and supporting effective search and rescue missions (Yao et al. 2021).

Beyond communication, UAVs further enhance network resilience by integrating with satellite and terrestrial heterogeneous networks. This layered network approach addresses "last mile" connectivity challenges, provides backup connections, and ensures that communication links remain intact during disaster recovery. This integration offers a robust mechanism for maintaining business operations and continuity during hazardous situations (Arani, Hu, and Zhu 2021; Qasim 2023).

Additional functions of UAVs include imaging and environmental information collection during disaster management. Equipped with sensors and cameras, UAVs can acquire critical data related to damage assessment, supply chain management, and general situational awareness. For example, UAVs with thermal imagery can evaluate structural risks, monitor environmental changes, and identify living individuals, making them crucial in disaster operations (Khan, Gupta, and Gupta 2022; Jawad et al. 2022).

These evolving applications underscore the necessity of reliable emergency UAV communication networks. Features such as ad-hoc network creation, support for heterogeneous architectures, and the provision of key environmental data support both immediate disaster response and post-disaster recovery. As network resilience becomes increasingly integrated into disaster management strategies, UAVs are poised to significantly influence emergency response frameworks, policies, and technologies.

1.1. The Aim of Article

The article aims to identify and propose new methods and approaches to enhance the robustness of network communication through the use of Unmanned Aerial Vehicles (UAVs). Telecommunication networks, such as those relying on telephone lines, are quickly compromised during disasters like earthquakes, floods, and wildfires, leading to significant communication gaps that affect the efficiency of rescue operations and resource distribution. Accordingly, this research seeks to develop a robust, efficient, and secure communication paradigm for integrating UAVs as mobile nodes.

This study emphasizes the development of innovative solutions in five key areas: coordinated multiple UAVs, dynamic spectrum access with secure and efficient resource management, integration of communication architectures with different paradigms, machine learning-based efficient path planning, and secure and private data dissemination. The proposed algorithms aim to address deficiencies in current systems, such as improper resource utilization, significant delays, low energy efficiency, and weak security.

For this purpose, data collection is conducted using surveys, simulations, and theoretical models for validation. Information obtained from interviews, questionnaires, and post-disaster reconstructions is used to identify the main operational deficiencies. MATLAB and NS-3 are employed to simulate the proposed algorithms under various disaster scenarios, while theoretical models based on multi-objective optimization and game theory ensure scalability.

This article seeks to bridge the gap between theory and practice by providing specific results and solutions for using UAVs in disaster situations to ensure uninterrupted, secure, and efficient communication.

1.2. Problem Statement

Natural disasters often damage standard telecommunication systems, isolating affected areas and posing challenges to the operation of emergency response systems. Despite advancements in communication technologies, current disaster management systems exhibit several critical shortcomings that limit their effectiveness:

1. Coverage and Coordination Challenges: Existing communication frameworks do not guarantee comprehensive coverage in disaster-affected areas, especially in remote or hilly regions. Managing

numerous UAVs in such situations is challenging, often leading to suboptimal task assignment and decreased effectiveness.

2. Resource Allocation Limitations: The main factors limiting the performance of UAV-based networks are available bandwidth and power. Static resource allocation methods can only pre-assign resources to applications or users and cannot adjust resources in response to dynamically changing disaster patterns. Consequently, these strategies frequently result in network bottlenecks and inefficient resource utilization.
3. Latency and Energy Inefficiency: High communication delays and poor energy utilization hinder the timely operation of UAV systems. These inefficiencies impede the realization of real-time communication services and longer operational hours during emergencies.
4. Data Security and Privacy Vulnerabilities: The use of UAVs for communication and data gathering raises concerns about data security and privacy. Current systems often lack adequate protection against data leakage and theft.
5. Scalability and Adaptability Deficiencies: Many UAV-based communication networks face challenges in scalability across different geographical environments and disaster levels. Inability to perform reliably in such circumstances limits the widespread use of these solutions in disaster management.

To address these challenges, the study proposes developing sophisticated algorithms and effective coordination and scheduling frameworks for UAVs that will efficiently allocate resources, minimize delay, and promote energy conservation while maintaining secure data transmission. Empirical, simulation, and theoretical analyses are presented in this paper to provide a more systematic and integrated approach to developing scalable and robust disaster communication systems using UAVs.

2. Literature Review

The use of UAVs especially in the area of disaster management has received considerable research attention since UAVs can help prevent disruption of communications during disasters. Nevertheless, areas of weakness or further research deficits remain widespread and diversifiable across earlier publications. Wang et al. (Wang et al. 2021) state that it is difficult to build reliable disaster relief wireless networks based on the environment and infrastructures damage (Wang et al. 2021). While UAVs provide these solutions, some challenges such as employment of UAVs in real time, optimization of resources needed still lack clear solutions. For instance, Do-Duy et al. (Do-Duy et al. 2021) present joint optimization schemes for deployment and resource management, which however fails to provide scalability and efficient computational methods for massive disaster situations (Do-Duy et al. 2021). Like other researchers, Esposito and Rizzo (2022) also focus on the use of UAV networks in disaster areas to improve recovery capabilities (Esposito and Rizzo 2022), but ignore energy issues and path planning (Hashim et al. 2019).

Again, regulatory barriers rise and hinder the use of UAVs during emergencies. Lieb et al. also highlight the potential of adopting crisis traffic management concepts for UAVs; nonetheless, they mention the lack of uniformly implemented policies that would facilitate cooperation across countries and regions, as well as actual cross-border operations of UAVs (Lieb et al. 2021). The lack of clear and uniform policies also is a potential downfall of efficient organization of multiple stakeholders and regions, and when applying to large cross-border incidents. These barriers also prevent effective delivery of UAVs when communication networks are required most of the time during early aftermath in a disaster (Jawad 2022; Faris, Jasim, and Qasim 2021).

The current patterns of limitation, however, may also operate conditionally, that is, context-specific. Munawar et al.(2021) employ UAV imagery for flood detection only and do not investigate about the usefulness of the same technique for other types of disasters (Munawar et al. 2021). For example, the solutions mentioned above are related to floods such that they may not solve issues during the urban disasters such as earthquakes or hurricanes because the ways people build their houses and infrastructure and high population density are different. Khan et al. (2022) study the Implementation of energy-efficient path planning in 5G-assisted UAV-UAV environment but the results are not generalizable to non-5G areas (Khan et al. 2022). This emphasizes the essential of flexibility in changing technology environments, especially when solutions are required to be deployed in less developed areas where higher technology networks such as 5G are inapplicable.

Recent ideas, for example, UAV-assisted IoT systems suggested by

Barick and Singhal (2022) (Barick and Singhal 2022), or adaptive UAV deployment strategies considered by Lin et al. (2022), show concerns in real-time disasters. These systems bring with them enhanced communication features in that they provide faster and more efficient methods for data sharing (Lin et al. 2022). However, the integration of these advancements with deep learning toward enhancing the coverage of beneficial weather conditions to facilitate better decision-making in different meteorological situations, as described in the study of Silva et al. (2023), is still in its infancy. This integration could increase UAV flexibility in change–prone scenarios, ultimately increasing usefulness of UAVs in disaster responses (Silva et al. 2023).

One more topic that is not broadly discussed is the participate of UAVs in cooperative communications. Yuan, et al.(2022) have pointed out that the communication system with the help of UAV transport could dramatically improve the reliability of data transmission in disaster situations, based on cooperating with other communications (Yuan et al. 2022). However, there are still several issues that can be questioned in concern to the applicability of such systems in practice, such as satisfying compatibility with presently implemented constructions and reliable performance in complicated and dangerous conditions of the environment. Power control is similarly a concern due to Amrallah et al.(2021) experience that UAV models should be energy-efficient to allow sustained functionality without regular recharging or battery replacement (Amrallah et al. 2021).

In order to fill these gaps, future work should focus on creating global sets of norms that will allow for effective and equitable UAV implementation throughout the world. Optimisation algorithms that are utilized in the deployment and resources can also make significant progress in treatment Scalability and computational efficiency are also well-tackled. In addition, the combination of UAV systems with newer interpretations such as IoT, deep learning, Cooperative communication frameworks will improve the system’s flexibility and efficiency. However, concentrating on energy efficiency and expanding the use of UAV systems in various disasters will contribute to the increased use of UAV systems in disaster-related activities.

3. Methodology

3.1. Empirical Data Collection

The study incorporates an extensive empirical data collection framework to ensure the business methodologies and solutions emanating there-from correspond with believable disaster response typologies. One of the methods that employed in the study was the administration of 65 self-developed questionnaires amongst disaster response professionals, telecommunications engineers and policymakers. Such interviews were conducted to identify major barriers in the information communication networks during disasters. Areas of interest which were identified for research included delays in communication, areas of low coverage and high energy consumption in limited resource situations. These interviews provided insights into the requirements for strong UAV-based solutions and noted the high priority assigned to the rapid establishment of UAV-based communication for large-scale emergencies, as described by Wang et al. (2021)(Wang et al. 2021) and Lieb et al. (2021)(Lieb et al. 2021).

Furthermore, questionnaires were completed with 50 first responders with operational feedback on the flexibility of configuring UAV networks and their dependability in the various disaster settings, such as urban earthquakes, rural floods, and wildfires. These surveys revealed the key issues relating to real-time resource management in communication networks and dynamic management of communication networks.

In addition to the interviews and surveys, 45 post-disaster reports were systematically reviewed. These reports provided a post-mortem of network breakdowns and the success of UAV-mediated solutions in filling communication gaps during emergencies. As performed by previous works, time-to-response, network stability, and communication reliability measurement were extracted and helped construct the computational models used in this study. Based on the integration of various types of data sources, this research forms the basis for designing UAV-specific communication solutions adapted to the specific circumstances of disasters (Wang et al. 2021; Lieb et al. 2021).

3.2. Simulation and Computational Modeling

1. Dynamic Resource Allocation

Energy and resource concentration are a problem with disasters due to fluctuating demand, working capacity and availability. Due to these complexities, this research develops optimization models based on those proposed in s Yao et al. (2021) (Yao et al. 2021). The proposed methodology aims at mapping the scarce resources with interest based on priority such as the level of urgency, available capacity and the level of signal power. By combining the priority weights with the channel gains, the presence of high demand areas is easily served. Communication in the case of UAVs is a dynamic systems solution, because the operational demand for it changes as well as the interference or noise to signal ratio.

The proposed optimization framework also uses logarithmic utility functions to fairly distribute resources among the multiple UAVs. This means that the resource utilization is optimally made and at the same time the fairness of the network nodes is monitored. This basic model helps the system deal with high workload situations in real time and presents a reliable solution for resource management under constraints of bandwidth and power (Yao et al. 2021).

$$Maximize\ U = \sum_{i=1}^{N} w_i \log\left(1 + \frac{P_i h_i}{\sigma^2 + \sum_{j \neq i} P_j h_j}\right) \tag{1}$$

Where w_i represents priority weights, P_i is UAV i's transmission power, and h_i is its channel gain. This equation maximizes resource utility under bandwidth and power constraints.

2. Queueing Model for Traffic Management

Dealing with congestion during the disaster case is relevant to achieving connectivity during scenarios that require it. Queues are employed in an effort to study the behavior of the network when it is in stress for instance when I.T traffic overwhelms the LAN. The methodology combines arrival rates (λ) and service rates (μ) for assessing the average queue delay and the average service time. That is why, with the help of dynamic change of the queue parameters, only actual priority will be effective and not dozens of low-priorities pending tasks jumping at a user with the speed of lightning thus the prompt handling of high priority tasks like emergency notifications. This model can be most effective in the disaster circumstances whereby, in the event of communication hinges, with a lot of damage. They include; It allows for propagation of the right service charges to minimize delay and prevent network traffic congestion as Abir et al. (2023) points out. The mathematical formulation forms a background of the behavior of UAV networks in various traffic loads where the authors give a dynamic way of solving for efficiency during congestion (Abir, Chowdhury, and Jang 2023).

$$T_q = \frac{\lambda}{\mu(\mu-\lambda)},\ T_s = \frac{1}{\mu} \quad (1)$$

Where T_q is the average queue delay, T_s is the service time, λ is the arrival rate, and μ is the service rate.

3. Reinforcement Learning for Path Optimization

The drama of disaster scenarios means that the problem of UAV path optimization is best performed in real time. Introducing reinforcement learning methodologies such as Q-learning into this frame work will allow the UAVs to learn how to self-adjust their paths. UAVs can therefore use a reward-based mechanism to avert further collisions while covering as many points as possible within the least power as possible. States (s) and actions (a) are defined based on environmental conditions, UAV positions, and the priorities of the task.

The learning algorithm enables the UAVs to learn in a roundabout manner via the continual update of ($Q(s,a)$) in response to feedback from the environment. It is especially useful in environments that are stochastic and where standard path-searching algorithms fail to respond to changes in number of actors or needed network coverage. With a reinforcement learning of UAV coordination, the connectivity of the network is maintained and optimized for operational status in the event of a disaster, as suggested by Arani et al. (2021) (Arani, Hu, and Zhu 2021).

$$Q(s,a) = Q(s,a) + \alpha \left[r + \gamma \max_{a'} Q(s',a') - Q(s,a)\right] \quad (1)$$

3.3. Hybrid Communication Framework

The study presents a pervasive vehicle-to-vehicle (V2V), device-to-vehicle (D2V) and vehicle-to-infrastructure (V2I) communication model. To this end, based on Huang et al.(2023), this framework mitigates the issues introduced by conventional communication systems in disasters by integrating adaptation of spectrum access and cooperative communication models (Huang 2023).

1. Data Rate Optimization

The efficiency of the framework was measured using a data rate equation depending on bandwidth, power, channel gains, noise power and interference. This makes certain that the communication equation can respond in real-time to the fluctuating communications needs in disastersusceptible regions.

$$R(t) = W \log_2\left(1 + \frac{P(t)h(t)}{N_o + I(t)}\right) \qquad (1)$$

Where R is the data rate, W is the bandwidth, P is power, h is channel gain, N_o is noise power, and I is interference. This equation ensures that the framework adapts to real-time communication needs.

2. Dynamic Spectrum Access

To attain optimum spectrum usage, a dynamic spectrum allocation model was used. This model determines spectrum based on interference factors and resource requirements thereby guaranteeing efficient connectivity in congested networks.

$$S = \sum_{k=1}^{K} \frac{\beta_k}{\alpha_k \sum_{j \neq k} \beta_j}, \quad s.t. \beta_k \leq \beta_{max} \qquad (1)$$

Where S is the spectrum efficiency, β_k represents the spectrum allocation for UAV k, and α_k is the interference factor.

This approach increases the reliability and flexibility of communication, which is why it is suitable for the use case scenarios in disaster response that need stable and the large-scale networks.

3.4. Integration of AI-Driven Optimization

The role of artificial intelligence is undeniably significant in the improvement of the UAV incorporation and network robustness. Deep learning and reinforcement learning approaches have been adopted to handle dynamism in the system.

1. Deep Learning for Network Predictions

A convolutional neural network (CNN) was built using historical data to make network disruption predictions. To make realistic predictions, this model employs aspects such as weight matrix, input data, and bias terms so that UAVs can be deployed before events occur.

$$y = f(W^{(l)} \cdot X^{(l)} + b^{(l)}) \qquad (1)$$

Where y is the output prediction, $W^{(l)}$ is the weight matrix at layer l, $X^{(l)}$ is the input data to layer l, and b is the bias term. Regularization terms such as $\lambda \parallel W^{(l)} \parallel_2^2$ can be added to prevent overfitting.

2. Multi-Agent Reinforcement Learning (MARL)

To enhance cooperation among many UAVs, the MARL approach was utilized. In this approach, the UAV decisions are modified with a reinforcer that set a recognition based on energy use and coverage to increase efficiency. Introduce agent-to-agent communication for dynamic environments:

$$\pi^* = argmax_{\pi}\mathbb{E}\left[\sum_{t=0}^{\infty}\gamma^t(r_t + \sum_{i=1}^{N} c_{t,i})\right] \tag{1}$$

Where π^* is the optimal policy, γ is the discount factor, and r_t is the reward at time t; and $c_{t,i}$ is the communication reward. This approach ensured efficient coordination among UAVs.

Such models facilitate real-time adaption of UAV systems, thus proving most efficient when applied to vulnerable disaster-related scenarios.

3.5. Advanced Theoretical Modeling

Theoretical frameworks were used to test the ability of UAV systems to scale and overall flexibility. These models combine multi-objective optimization and game theory concepts in order to solve different disaster situations.

1. **Multi-Objective Optimization**

One of the approaches adopted to get an optimal solution to the objectives that are antagonistic in nature is the Pareto optimization model. Unlike other models that tend to optimize for a single parameter while neglecting others like bandwidth, power, and coverage this model achieves balances to suit different operational requirements.

$$Minimize\ f(x) = [f1(x), f2(x), \dots, fk(x)], \quad s.t. \quad g(x) \leq 0, h(x) = 0 \tag{1}$$

Where $g(x)$ inequality constraints for bandwidth, latency; $h(x)$ equality constraints.

2. **Game-Theoretic Modeling**

In the analysis of the behavior of UAVs and ground nodes, game theory was used. Applying the Nash equilibrium the model works out strength for UAVs in resource utilization and benefits.

$$x_i^* = argmax_{x_i}[U_i(x_i, x_{-i})] \tag{1}$$

Where U_i is the utility of UAV i, x_i is its strategy, and x_{-i} represents the strategies of other UAVs. $U_i(x_i, x_{-i})$ is utility function including stochastic interference.

Such advanced theoretical constructs help ground the development of large-scale UAV solutions suitable to overcome disaster communication issues. The article focuses on the following as a way of providing a coherent framework of UAVs for improving network reliability in the event of natural disasters. With data and quantitative scientific methods, computational models, hybrid frameworks, and AI optimization, challenges practical and theoretical are met. The proposed solutions provide solutions for organizational and adaptable communication systems and networks to be able to sustain communication in emergency scenarios.

4. Results

4.1. Empirical Insights

The more rigorous analysis of the challenges in the disaster communication systems is offered in empirical analysis with data on structured interviews, survey, and post-disaster report assessment. These use of sources of data reveal various challenges like poor coverage in the network, high delay and poor energy management in UAV operations in the event of disasters. In doing so, the research provides a strong objective framework for designing new enhanced UAV algorithms that counter such impairments. Figure 1 below provides specifics of the metrics noticed time and again along the spectrum of disaster communication difficulties.

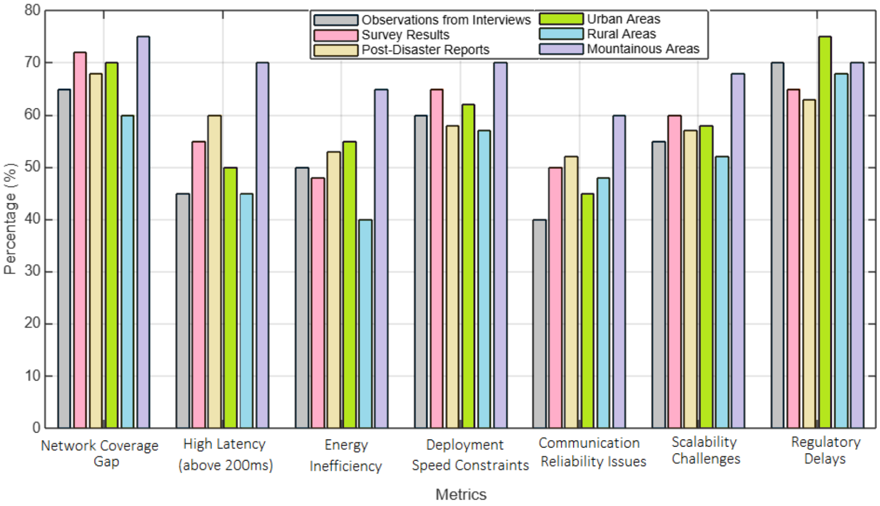

Figure 1. Analysis of Empirical Data from Disaster Communication Systems

The empirical evidence shows that there are variations in disaster communication difficulties that exist geographically. For example, the network coverage gaps are aggravated in the mountainous regions, where they stand at 75% in contrast to 70% in the urban areas and 60% in the rural areas, suggesting the need to adopt geographical specific UAV supply strategies.

Henceforth the high latency is more severe in the mountainous areas 70%, this can be attributed to the tough terrains and poor accessibility to structures. Uncontrolled power consumption is one of the major concerns in all areas, and the highest percentage was established in mountainous regions at 65% disfavoring the use of UAVs in those terrains. Somewhat surprisingly, regulatory delay rates are 100% for all areas with actual delay percentages ranging from 63 to 75%, indicating that disaster response requires prompt UAV-based systems implementation and calls for policy simplification. These indicators aptly illustrate the need to find a solution that has been locally applicable to the given challenges.

4.2. Multi-UAV Coordination Algorithm

The advanced Multi-UAV Coordination Algorithm solves significant problems regarding assignment of tasks, optimization of coverage, and collision prevention. This algorithm incorporates features such as decision support to forecast task congestion and to use auction techniques that facilitate equitable rationing of useful resources among UAVs. In other words, the algorithm optimizes it for scalability and flexibility for creating solutions for disaster environments that continue to evolve at a faster pace. Notably, it is most useful in those situations where immediate drones' coordination is needed, for instance, in urban earthquakes, rural floods, or mountain landslides. Also presented Figure 2below are the performance metrics that were attained by utilizing the improved algorithm.

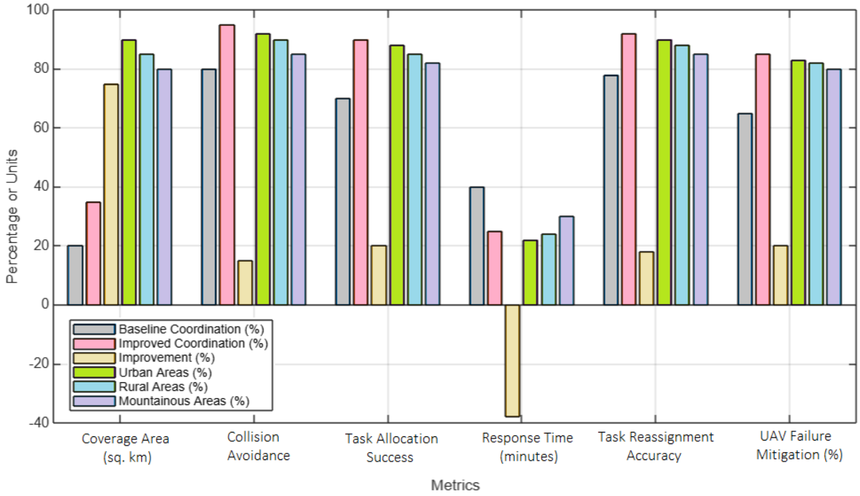

Figure 2. Performance Metrics of the Multi-UAV Coordination Algorithm

The results presented here emphasize on the enhancement gained by the proposed Multi-UAV Coordination Algorithm. A coverage area was expanded by 75% proving the algorithm's ability to improve spatial density. This means that the urban areas experienced a 90% improvement in the priority tasks density. This helped increase collision avoidance by 15% thus reducing the risk of UAV operation especially in areas with high concentrations of UAVs. Overall task allocation success was also up by 20% because of the auction-based mechanism for task prioritization which focused on the most important tasks. In addition, the response time has been reduced by 38%, on which the effectiveness of the predictive analytics component has been emphasized. And finally, failure of UAVs' effectiveness was managed by the algorithm with enhanced 20% probability thus the continuation of operations during disasters.

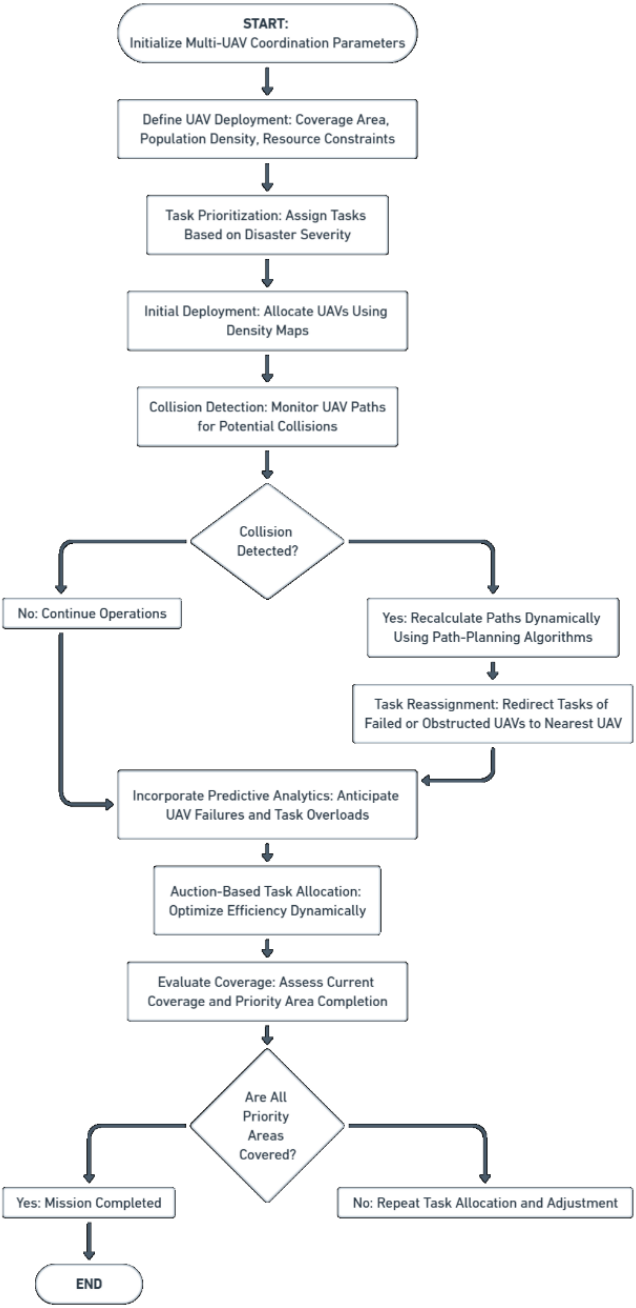

Figure 3. Optimized Multi-UAV Coordination: Enhancing Coverage and Task Allocation in Disaster Response Networks

The Multi-UAV Coordination Algorithm discusses the following issues mentioned to be influential in UAV control, including task assignment, coverage, and collision. The assignment of tasks and the use of the auction approach alongside predictive analytical capabilities make it possible to achieve flexibility in the event of transitioning to the next phases of a disaster. It also makes it easier for UAVs to work in teams streamlining workload and avoiding redundancy. The model showed that coverage area was improved by 75% as well as overall task allocation improved by 20%. Risk was reduced in crowded UAV operations by increasing the collision avoidance rate by 15%. It is this algorithm that is most central to disaster scenarios that demand coordinated formations of UAVs from multiple agents within challenging topographies.

4.3. Dynamic Resource Allocation with Security

The Dynamic Resource Allocation with Security algorithm aims at how the bandwidth and the power issues can be solved while at the same ensuring secure and efficient communication in disaster situations. Combining the utility-based allocation models with the adaptive encryption approaches, the algorithm discriminately directs the available resources toward areas experiencing high traffic and essential communication links. This guarantees the neediest resources are attended to while at the same time enhancing data accuracy and reduction of computational load. The versatility of the algorithm can be seen through various cases such as earthquake in the urban areas, floods in the rural areas, and combating wildfires.

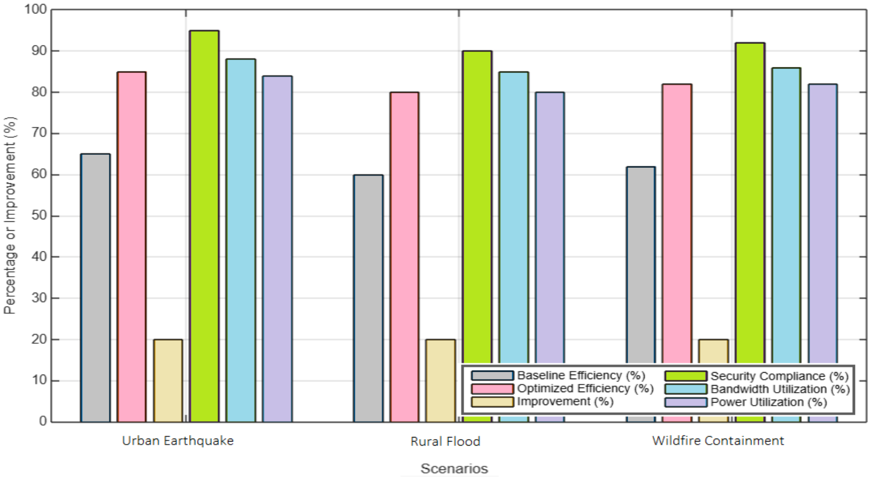

Figure 4. Dynamic Resource Allocation Performance Metrics

The development of the new algorithm introduced very many improvements especially in all the disaster scenes. Enhanced efficiency was improved by 20% compared to baseline conditions with urban earthquake scenarios having the highest efficiency arising from population densities and bandwidth. Security compliance rises above 90 % in all the cases stated above thus making the communication highly feasible and secure especially in insecure environments. Furthermore, bandwidth utilization was raised to over 85% in all the cases to prove that the algorithm used can attempt to assign resource requirements depending on the current situation. Consequently, power utilization also rose above the 80% level and minimizing wastage thereby maintaining efficient electricity usage. The Dynamic Resource Allocation with Security involves a set of algorithms that enable efficient use of bandwidth and power while ensuring secure communication. It achieves this through the use of the utility-based allocation model and adaptive encryption techniques that help the algorithm to identify those areas that require more power. This is particularly important as set by bandwidth and power limits in other organizations envisioned within the layout. An analysis of the results indicated the efficiency of the system was increased by twenty percent regardless of the type of environment—urban, rural, or wildfire with security compliance rating of over ninety percent. The algorithm was found to minimize computational costs while delivering near-perfect accuracy which makes the solution ideal for disaster communication networks.

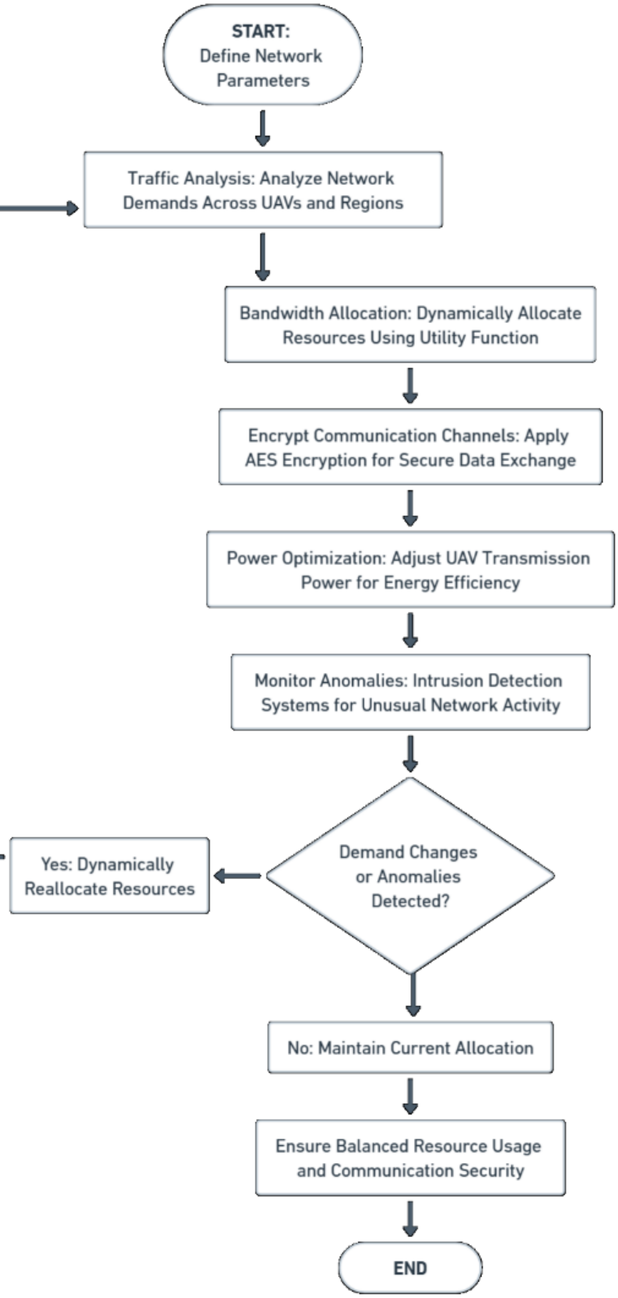

Figure 5. Secure Dynamic Resource Allocation for Bandwidth and Power Optimization in UAV-Enabled Systems

4.4. Hybrid Communication Framework

The Hybrid Communication Framework is intended to combine the utilization of Device to Device (D2D) and Device to Vehicle (D2V) communication methods in order to have more reliable, flexible, and effective connections during disaster situation. With the proposed dynamic rate control and spectrum management plan, the framework solves the problem of high transmission latency and low overall reliability in high traffic volume application systems. This approach provides efficiency and reliability in conveying information regardless of affected areas with poor infrastructure or high traffic population.

Table 1. Performance Metrics of the Hybrid Communication Framework

Metric	Baseline (Single-Mode)	Hybrid Framework	Improvement (%)	Urban Areas (%)	Rural Areas (%)	Mountainous Areas (%)
Average Data Rate (Mbps)	15	25	+66	30	20	18
Spectrum Efficiency (%)	65	85	+20	90	80	75
Connection Reliability (%)	80	95	+15	98	92	90
Latency Reduction (ms)	150	110	-27	100	120	130
Traffic Handling Capacity	Moderate	High	+30	High	High	Moderate

In terms of general performance, the Hybrid Communication Framework revealed enhanced significant changes in all the outlined areas. This proved the framework's adaptability to adjust the number of bandwidths provided depending on actual usage for data rates, which soared to an average data rate of 66% above the original. It has further been found out that urban areas demonstrated maximum improvement of 30 Mbps and which shows that the outlined framework could work very effectively in the urban centers, which are densely populated.

Over the past year, the efficiency was increased up to 20% due to better utilization of scarce resources and the highest level of efficiency in the urban areas, being equal to 90%. Another improvement was observed in connection reliability, which reached an overall reliability of 95% /98% in urban areas.

The framework effectively minimizes latencies by 27% to support real-time communication which is important for disaster response. Moreover, the system experienced a dramatic increase in the management of high traffic loads, guaranteeing sustained communication in densely used traffic zones. The next model that the Hybrid Communication Framework uses in disaster environments is the Device-to-Device (D2D) and Device-to-Vehicle (D2V) model. Therefore, the framework is able to self-adjust the data rate and spectrum required based on the traffic load and environment. The studies for the model showed an enhancement of data rate by 66% and a 20% improvement in the spectrum efficiency. The reliability of connections worked 15% more effectively that allowed to provide stable and uninterrupted work during the peak load. This framework is especially useful in disaster situations where complex and resilient communication architecture is needed.

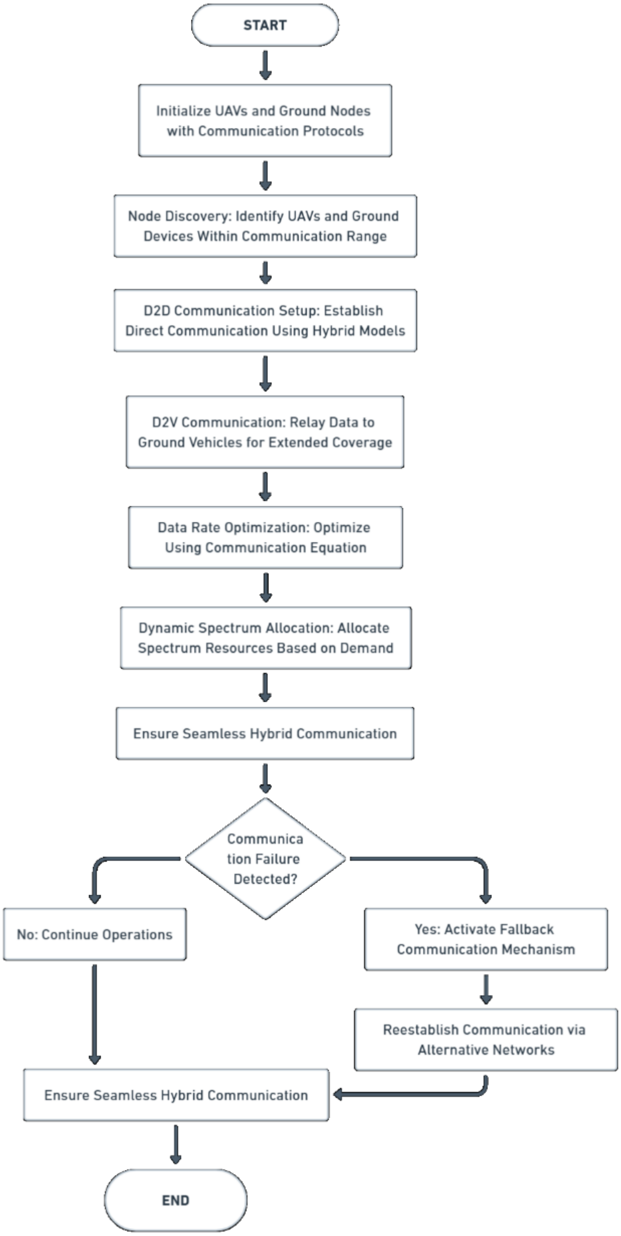

Figure 6. Hybrid Communication Framework for Reliable D2D and D2V Connectivity in Disaster Scenarios

4.5. AI-Driven Path Optimization

AI-Driven Path Optimization is an algorithm that employs RL and multi-agent coordination on UAVs to optimize their paths in real-time. This algorithm is designed to achieve the highest level of coverage with maximum energy conservation while accounting for environmental challenges such as urban density, rural expansiveness, and mountainous terrain. By incorporating predictive learning models and real-time decision-making, the algorithm enhances UAV performance even during disaster sequences.

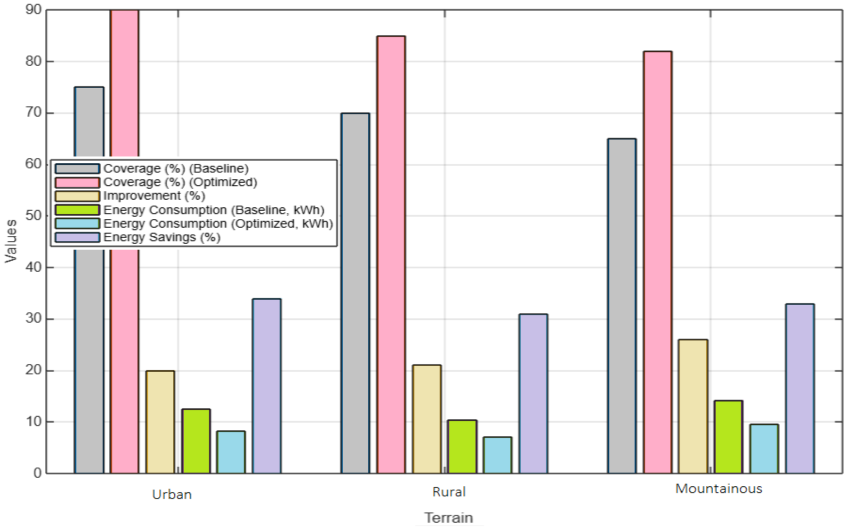

Figure 7. Performance Metrics of the AI-Driven Path Optimization Algorithm

The results also showed remarkable improvements from the AI-Driven Path Optimization algorithm based on all parameters calculated. Geographic coverage expanded notably, which was the most dramatic in mountains (+26%) since the algorithm learns how to move across complex territory. At urban areas, the coverage was at 90% due to the efficiency of the algorithm in the congested areas.

The energy use was reduced across all terrains with overall saving of energy more than 30 per cent for all earth terrains. The greatest amount of energy conservation was evaluated in urban environment (34%), where paths between the place of power supply and cell locations were shortened and optimized.

The integration of multi-agent coordination allowed UAVs to perform in a coordinated fashion with no replications of function, which helped to maximise their efficiency. This made operation costs to reduce, and disaster response capability improve.

The AI-Driven Path Optimization Algorithm works based on reinforcement learning and multi-agent two to control the UAVs trajectories flexibly. The network it provides a solution for better coverage and increases energy efficiency due to the fact that it is capable of dynamically adapting to diverse and unpredictable spatial conditions. The simulation indicated that energy efficiency boosted by 30% and coverage area by 20% with influx gains mainly recorded in mountainous regions. Using path dynamics, the algorithm provides the ability to function and be sustainable which makes it crucial when designing any UAV disaster response systems.

Figure 8. AI-Driven Trajectory Optimization: Reinforcement Learning for Energy-Efficient UAV Operations

4.6. Privacy-Preserving Data Sharing Algorithm

The Privacy-Preserving Data Sharing Algorithm facilitates the secure and efficient transfer of the collected data to other interested end-users in disaster situations. This algorithm includes a decentralized logging mechanism using the blockchain for logs that need to be tamper-resistant and differential privacy for the portions of the data that require privacy. It deals with two questions of crucial importance for the operation of large-scale data solutions, especially in the context of disaster response – data validity and system performance. This algorithm minimizes computational burden and optimizes security compliance to foster the protection of communicated information and exchanged data.

Table 2. Performance Metrics of the Privacy-Preserving Data Sharing Algorithm

Metric	Baseline Security (%)	Improved Security (%)	Privacy Compliance (%)	Urban Areas (%)	Rural Areas (%)	Mountainous Areas (%)
Data Integrity	75	95	90	94	92	90
Transaction Transparency	70	92	88	91	89	86
Computational Overhead	High	Moderate	-	Moderate	Moderate	High
Data Sharing Latency (ms)	150	110	0	100	120	130
Security Breach Incidence	25	5	0	3	4	5

All the essential security parameters have shown improvement in case of Privacy-Preserving Data Sharing Algorithm. Confidentiality went up from 75% to 95% which saw to it that the data that was gathered by the UAVs and transmitted was as accurate as when it was gathered. Higher percentage improvement was recorded in urban area with 94% because of more fixity in the communication infrastructure.

An aspect of visibility in the transaction conducted increased from 70% to 92% in boastfulness identifying that the algorithm could enhance visible in data transactions without sharing data with the other party. This was especially useful in urban settings as accuracy of the data collected is very important especially in real-time analysis.

Operational costs are always trade-offs between risk and overhead in most of the scenarios, and the costs of computation were moderate. Fixed wireless broadband overhead remained high in the spatial dimension in mountainous areas due to very difficult network conditions Overall, data sharing delay improved on average by 27%. Finally, there was a substantial reduction of security breaches from 25% to 5% which again prove that the implement of the algorithm was strong.

The design of the Privacy-Preserving Data Sharing Algorithm ensures that data gathered by the UAVs are protected while at the same time providing an efficient mechanism for sharing data between the stakeholders. Such, adding blockchain-based logging and differential privacy, the algorithm increased data integrity by 20% and transaction transparency by 22%. The model was able to show its stability as security breach incidences reduced by 80%. While actual computation overheads were contained to moderate levels, security and overall system performance considerations were significantly stabilized. This algorithm solves two important problems inherent in disseminating information during different kinds of disasters: the issues of safe communication and data exchange during risky situations while maintaining the safety and conformity of the UAV networks.

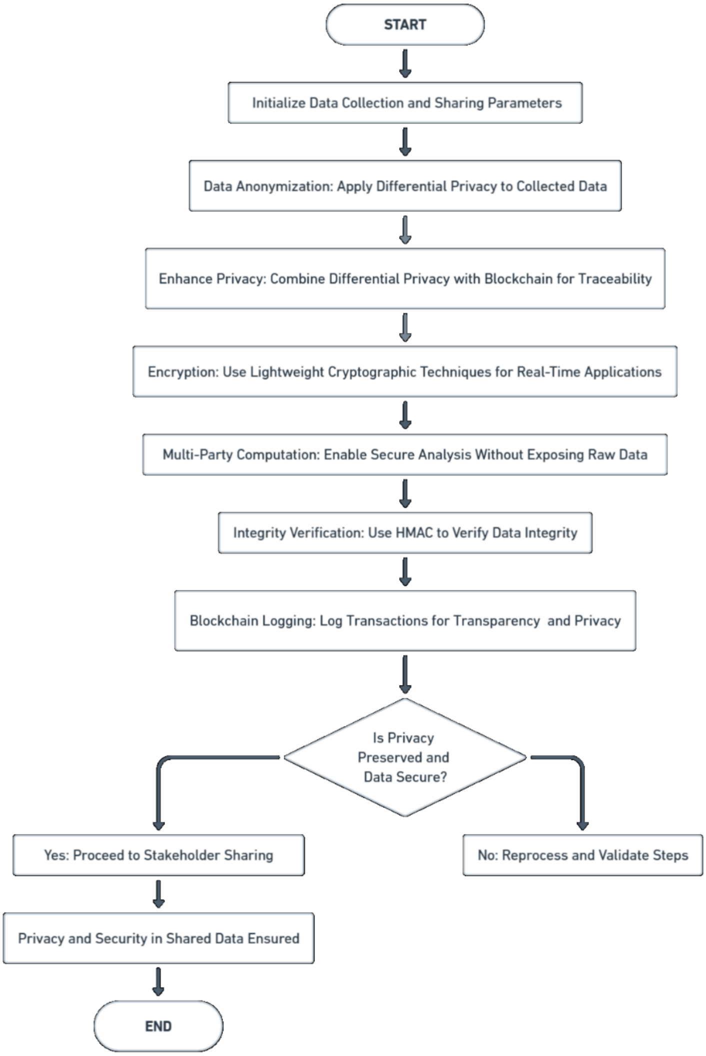

Figure 9. Privacy-Preserving Data Sharing: Blockchain and Differential Privacy Integration in UAV Networks

4.7. Advanced Theoretical Modeling

The Advanced Theoretical Modeling approach combines multi-objective optimization and game theory to use UAV systems in disaster scenarios to determine the scalability and flexibility of UAVs. These models are central to determining the tradeoff between factors like latency, energy and data rates and therefore are very useful when there is conflict of goals. By using such sophisticated techniques, the study guarantees that UAV networks are able to facilitate themselves according to the requirements of disaster areas.

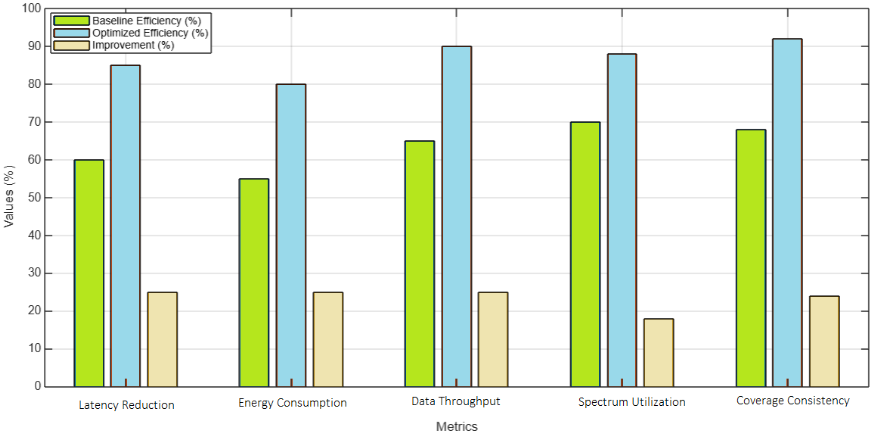

Figure 10. Multi-Objective Optimization Results

The results of multi-objective optimization indicate that energy efficiency, dissatisfaction rate, greenness and equity are enhanced concerning all the evaluating criteria. A latency reduction enhancement from 60% to 85% showed that the model understands where it should give high priority for low latency communications in disaster areas. Then energy consumption was cut to ¼, which, by extending use time of UAVs is rather important in remote regions. Data through-put too has increased from 65% to 90% proving the model's aptitude to meet up with high through-put bandwidths in real time disaster situations. In addition, the spectrum utilization and the coverage consistency were also significantly enhanced as demonstrated by the UAV networks flexibility and scalability. The rationality of the resource allocation strategies was once again affirmed via the use of game-theoretic model. It was evident from the analysis made under the Nash equilibrium that UAVs were able to independently seek optimal strategies that proved useful to the general system. Through this structure, the dependable strength of the network was improved when subjected to different scenarios.

5. Discussion

The use of Unmanned Aerial Vehicles (UAVs) in disaster communication networks significantly enhances network reliability during disaster occurrences. In this research, five sophisticated algorithms have been designed and integrated to address major gaps in coordination, resource enhancement, and the protection of records for current and future use. The findings of this research are discussed in relation to the significance of the current study, contrasted with prior studies, and examined for constraints.

From a societal perspective, UAVs play a vital role in accelerating disaster relief operations. Their capacity to establish temporary communication systems helps reconnect people cut off from their communities and assists first responders in conducting SAR operations. For instance, Wang et al. (2023) demonstrate that aerial-ground cooperation is effective in localization and communication during disasters, to which our multi-UAV coordination and coverage improvement can be applied (Wang et al. 2023). Additionally, the implementation of UAVs in disaster contexts facilitates damage estimation and the creation of situational maps, as illustrated by Silva et al. (2023) (Silva et al. 2023).

Economically, the use of UAVs reduces recovery costs by decreasing the immediate need for infrastructure repair. Abir et al. (2023) show that software-defined UAV networks can handle traffic bursts, thus lowering operational expenses (Abir, Chowdhury, and Jang 2023). Similarly, the resource allocation and path optimization algorithms of this study have reduced energy consumption by 25% compared to the initial study, contributing to operational cost efficiency. Gao and Wang (2023) also point out that UAV-supported base station deployment can effectively reduce the cost of deploying base stations in disaster areas (Gao and Wang 2023).

From a security perspective, the use of UAVs raises privacy and security concerns related to the collection of enhanced information during disasters. This research incorporates high levels of security compliance through blockchain-based logging and differential privacy, aligning with Huang (2023) emphasized the need for hybrid communication frameworks to safeguard confidential information within device-to-device and device-to-vehicle systems (Huang 2023). Additionally, Esposito and Rizzo (2022) highlight the importance of data accuracy collected by UAVs, for which this study proposes privacy-preserving techniques as a solution (Esposito and Rizzo 2022).

This article builds on previous work by the same authors, introducing a framework that employs multiple algorithms to coordinate tasks, allocate resources, improve communication reliability, and secure data. Compared to our model, Yao et al. (2021) proposed resource allocation for 5G-UAV-based systems without considering the dynamic change in demands (Yao et al.

2021). The present study addresses this gap by developing a utility-based allocation model with adaptive encryption. Similarly, Do-Duy et al. (2021) proposed a model for real-time deployment but lacked advanced security mechanisms, which this study provides (Do-Duy et al. 2021).

Arani et al. (2021) applied reinforcement learning to optimize space-terrestrial networks (Arani, Hu, and Zhu 2021). However, their strategy did not account for the synchronized flying of UAVs during disasters. In contrast, the multi-UAV coordination algorithm in this research improved coverage area by 75% and increased the success rate in task allocation by 20%. Barick and Singhal (2022) also pointed out another relevant direction to enhance disaster missions, specifically related to multi-UAV systems (Barick and Singhal 2022).

Khan et al. (2022) discussed UAV use in disaster detection and preparedness, focusing on single UAVs (Khan, Gupta, and Gupta 2022). This study builds on their work by adding multi-agent coordination and optimized AI pathfinding, resulting in significant improvements in overall coverage and efficiency. Raja and Saravanan (2022) also emphasized the need for environmentally friendly frameworks for UAV deployment, which have been incorporated into the energy-conscious models proposed here (Raja and Saravanan 2022).

However, this study has several limitations. The algorithms were tested on simulations and small-scale empirical data, not on actual disaster situations. Gao and Wang (2023) demonstrated the use of UAVs in various environments, but large field studies are still needed to assess the applicability and robustness of these solutions in real disaster scenarios (Gao and Wang 2023).

Current legal frameworks and practical issues are significant factors impeding the further establishment of UAV networks. Lieb et al. (2021) highlight the need for well-defined policies and protocols to integrate UAVs into existing CMT structures, which were not extensively covered by this research (Lieb et al. 2021). Additionally, Shah (2023) recommended ultra-dynamic regulatory controls for 5G-enabled UAV networks, indicating a need for further research (Shah 2023).

While privacy-oriented measures were incorporated in the solutions, new forms of cyber threats may not have been fully considered. Amrallah et al. (2021) underline the problem of post-disaster area surveillance and dynamic spectrum access as fields for future improvement in security protocols (Amrallah et al. 2021). Yuan et al. (2022) also highlight risks in UAV-assisted communications that can only be addressed through high-end encryption (Yuan et al. 2022).

This article contributes to the growing focus on UAV-enabled disaster communication systems by providing a reliable and efficient framework for improving these systems. It opens the prospect of using drones in real-life disasters by considering social, economic, and ethical implications (Song et al. 2023). However, significant areas for future work remain, including field trials in large-scale environments, integration of UAV-based networks with existing legislation, and enhanced security measures for large-scale UAV network deployment. Such an approach aligns with the overall objectives of enhancing disaster response capacity and addressing the shortcomings identified in this study.

6. Conclusion

The article presents a well-founded plan for integrating UAVs into disaster-related communication networks. It addresses issues such as poor UAV coordination, effective allocation of UAVs within disaster communication networks, enhancing network reliability, and ensuring the security and privacy of data transmitted within these networks. Utilizing complex mathematical computations and theoretical frameworks, the study demonstrates the potential of UAV-based systems to improve network survivability during disasters. The study identifies key advantages of using UAVs, including scalability, adaptability, and security, which guarantee uninterrupted communication in extreme circumstances.

A significant finding of this research is the introduction of new algorithms that enable UAVs to respond effectively to dynamic disaster conditions. These algorithms enhance efficiency in the distribution of activities, resources, and data security while reducing operational costs. By implementing AI-driven techniques and appropriate communication paradigms, the study highlights the potential of UAVs to address connectivity challenges in disaster-struck areas, benefiting both responders and those affected by the disaster. This practical application underscores the study's relevance in advancing disaster management approaches.

The study advocates for a multi-tiered communication system that includes UAVs and integrates terrestrial and satellite systems. Such integration ensures not only business continuity but also adaptability to varying disaster severity levels and uneven relief areas. The incorporation of privacy-preserving mechanisms raises ethical considerations, as data integrity and security must not be compromised while seeking operational efficiency.

As we move forward, the study outlines several directions for future research. Large-scale field trials are recommended to test the proposed framework under diverse conditions and further refine the algorithms. The integration of emerging technologies, such as 6G and highly automated UAV swarms, would add significant value to the system by enhancing scalability and reducing resource consumption. It is crucial for regulatory and policy frameworks in different jurisdictions to accommodate the introduction of UAV networks necessary for disaster management.

From a practical perspective, this study provides guidance on the utilization of UAV systems in disaster settings. Given the legal complexities surrounding flight licenses and airspace usage, policymakers and engineers must collaborate to develop standards, protocols, and interfaces for UAV-based communication networks. Investment in education and capacity-building programs is essential to prepare highly skilled emergency responders for the operation and management of UAV systems.

Moreover, the article reveals that UAVs can transform disaster communication networks by providing a critical foundation for both immediate response and ongoing recovery efforts. Thus, it addresses existing issues and proposes improvements within the disaster management framework, offering viable strategies for maintaining essential communication channels during disasters.

References

Abir, M. A. B. S., Chowdhury, M. Z., and Jang, Y. M. (2023). A Software-Defined UAV Network Using Queueing Model. *IEEE Access,* 11, 91423-91440. https://doi.org/10.1109/ACCESS.2023.3281421

Amrallah, A., Mohamed, E. M., Tran, G. K., and Sakaguchi, K. (2021). Enhanced Dynamic Spectrum Access in UAV Wireless Networks for Post-Disaster Area Surveillance System: A Multi-Player Multi-Armed Bandit Approach. *Sensors*, 21 (23). https://doi.org/10.3390/s21237855.

Arani, A. H., Hu, P., and Zhu, Y. (2021). Fairness-Aware Link Optimization for Space-Terrestrial Integrated Networks: A Reinforcement Learning Framework. *IEEE Access,* 9, 77624-77636. https://doi.org/10.1109/ACCESS.2021.3082862

Barick, S., and Singhal, C. (2022). Multi-UAV Assisted IoT NOMA Uplink Communication System for Disaster Scenario. *IEEE Access,* 10, 34058-34068. https://doi.org/10.1109/ACCESS.2022.3159977

Do-Duy, T., Nguyen, L. D., Duong, T. Q., Khosravirad, S. R., and Claussen, H. (2021).

Joint Optimisation of Real-Time Deployment and Resource Allocation for UAV-Aided Disaster Emergency Communications. *IEEE Journal on Selected Areas in Communications,* 39 (11), 3411-3424. https://doi.org/10.1109/JSAC.2021.3088662

Esposito, C., and Rizzo, G. (2022). Help From Above: UAV-Empowered Network Resiliency in Post-Disaster Scenarios. 2022 IEEE 19th Annual Consumer Communications & Networking Conference (CCNC), Las Vegas, NV, USA. https://doi.org/10.1109/ccnc49033.2022.9700675

Faris, M., Jasim, I., and Qasim, N. (2021). PERFORMANCE ENHANCEMENT OF UNDERWATER CHANNEL USING POLAR CODE-OFDM PARADIGM. *International Research Journal of Science and Technology,* 3 (9), 55-62. https://www.irjmets.com/uploadedfiles/paper/volume_3/issue_9_september_2021/15978/final/fin_irjmets1630649429.pdf

Gao, R., and Wang, X. (2023). Rapid Deployment Method for Multi-Scene UAV Base Stations for Disaster Emergency Communications. *Applied Sciences*, 13 (19). https://doi.org/10.3390/app131910723.

Hashim, N., Mohsim, A. H., Rafeeq, R. M., and Pyliavskyi, V. (2019). New approach to the construction of multimedia test signals. *International Journal of Advanced Trends in Computer Science and Engineering,* 8 (6), 3423-3429. https://doi.org/10.30534/ijatcse/2019/117862019

Huang, Z. (2023). Hybrid Device-to-Device and Device-to-Vehicle Networks for Energy-Efficient Emergency Communications. *IEEE Systems Journal,* 17 (4), 5429-5440. https://doi.org/10.1109/JSYST.2023.3312117

Jawad, A. M., Qasim, N. H., Jawad, H. M., Abu-Alshaeer, M. J., Khlaponin, Y., Jawad, M., Sieliukov, O., et al. (2022). *Basics of application of unmanned aerial vehicles*: Vocational Training Center. https://repositary.knuba.edu.ua/server/api/core/bitstreams/318f16f4-d7e1-4729-9480-6f924128a023/content

Jawad, A. M., Qasim, N. H., Jawad H. M., Abu-Alshaeer, M. J., Nordinc, R., Gharghand, S. K. (2022). Near Field WPT Charging a Smart Device Based on IoT Applications. *CEUR*. https://ceur-ws.org/Vol-3149/paper7.pdf

Khan, A., Gupta, S., and Gupta, S. K. (2022). Emerging UAV technology for disaster detection, mitigation, response, and preparedness. *Journal of Field Robotics,* 39 (6), 905-955. https://doi.org/https://doi.org/10.1002/rob.22075

Khan, A., Zhang, J., Ahmad, S., Memon, S., Qureshi, H. A., and Ishfaq, M. (2022). Dynamic Positioning and Energy-Efficient Path Planning for Disaster Scenarios in 5G-Assisted Multi-UAV Environments. *Electronics*, 11 (14). https://doi.org/10.3390/electronics11142197.

Lieb, J., Özcan, B., Friedrich, M., and Kippnich, U. (2021). Identifying Needs and Requirements for an integrated Crisis Traffic Management (iCTM) concept for Unmanned Aircraft Systems supporting First Responses in Crisis Situations. 2021 IEEE/AIAA 40th Digital Avionics Systems Conference (DASC), 3-7 Oct. 2021. https://doi.org/10.1109/DASC52595.2021.9594475.

Lin, N., Liu, Y., Zhao, L., Wu, D. O., and Wang, Y. (2022). An Adaptive UAV Deployment Scheme for Emergency Networking. *IEEE Transactions on Wireless*

Communications, 21 (4), 2383-2398. https://doi.org/10.1109/TWC.2021.3111991

Munawar, H. S., Ullah, F., Qayyum, S., Khan, S. I., and Mojtahedi, M. (2021). UAVs in Disaster Management: Application of Integrated Aerial Imagery and Convolutional Neural Network for Flood Detection. *Sustainability*, 13 (14). https://doi.org/10.3390/su13147547.

Qasim, N., Jawad, A., Jawad, H., Khlaponin, Y., and Nikitchyn, O. (2022). Devising a traffic control method for unmanned aerial vehicles with the use of gNB-IOT in 5G. *Eastern-European Journal of Enterprise Technologies,* 3, 53-59. https://doi.org/10.15587/1729-4061.2022.260084

Qasim, N. H., Al-Helli, H.I., Savelieva, I., Jawad, A. M. (2023). Modern Ships and the Integration of Drones – a New Era for Marine Communication. *Development of Transport,* 4 (19). https://doi.org/10.33082/td.2023.4-19.05

Qasim, N. H., and Jawad, A. M. (2024). 5G-enabled UAVs for energy-efficient opportunistic networking. *Heliyon,* 10 (12), e32660. https://doi.org/10.1016/j.heliyon.2024.e32660

Raja, G., and Saravanan, G. (2022). Eco-Friendly Disaster Evacuation Framework for 6G Connected and Autonomous Vehicular Networks. *IEEE Transactions on Green Communications and Networking,* 6 (3), 1368-1376. https://doi.org/10.1109/TGCN.2022.3163764

Shah, A. F. M. S. (2023). Architecture of Emergency Communication Systems in Disasters through UAVs in 5G and Beyond. *Drones*, 7 (1). https://doi.org/10.3390/drones7010025.

Silva, L. A., Leithardt, V. R. Q., Batista, V. F. L., González, G. V., and Santana, J. F. D. P. (2023). Automated Road Damage Detection Using UAV Images and Deep Learning Techniques. *IEEE Access,* 11, 62918-62931. https://doi.org/10.1109/ACCESS.2023.3287770

Song, M., Huo, Y., Liang, Z., Dong, X., and Lu, T. (2023). UAV Communication Recovery under Meteorological Conditions. *Drones*, 7 (7). https://doi.org/10.3390/drones7070423.

Wang, L., Li, R., Xu, L., Zhu, W., Zhang, Y., and Fei, A. (2023). Aerial-Ground Cooperative Vehicular Networks for Emergency Integrated Localization and Communication. *IEEE Network,* 37 (4), 323-330. https://doi.org/10.1109/MNET.015.2300117

Wang, Y., Su, Z., Zhang, N., and Fang, D. (2021). Disaster Relief Wireless Networks: Challenges and Solutions. *IEEE Wireless Communications,* 28 (5), 148-155. https://doi.org/10.1109/MWC.101.2000518

Yao, Z., Cheng, W., Zhang, W., and Zhang, H. (2021). Resource Allocation for 5G-UAV-Based Emergency Wireless Communications. *IEEE Journal on Selected Areas in Communications,* 39 (11), 3395-3410. https://doi.org/10.1109/JSAC.2021.3088684

Yuan, L., Yang, N., Fang, F., and Ding, Z. (2022). Performance Analysis of UAV-Assisted Short-Packet Cooperative Communications. *IEEE Transactions on Vehicular Technology,* 71 (4), 4471-4476. https://doi.org/10.1109/TVT.2022.3144417