Delay-Tolerant Networking for Unmanned Aerial Vehicles in Remote Sensing

Huda Labash[1], Shams Abdulrahman[2], Haithem Kareem Abass[3] and Ali Imam Abidi[4]
[1]Al-Turath University, 10013 Baghdad, Iraq
[2]Medical Technical College, Al-Farahidi University, 10065 Baghdad, Iraq
[3]Department of Computer Engineering, College of Engineering, Al-Mansour University College, 10067 Baghdad, Iraq
[4]Sharda School of Computing Science and Engineering, Sharda University, 201310 Greater Noida, India
huda.adel@uoturath.edu.iq, shams.abdulrahman@life-rdh.org, haithem.kareem@muc.edu.iq, ali.abidi@sharda.ac.in

Keywords: UAV, Delay-Tolerant Networking, Remote Sensing, Routing, Energy Efficiency, Redundancy Scheduling.

Abstract: Unmanned Aerial Vehicles (UAVs) are essential in remote sensing because they are cheap, easily deployed and able to operate in areas where infrastructure is inadequate. Nevertheless, inconsistent connectivity, mobility, and power limitations make it difficult to transmit data reliably. To overcome these issues, this paper introduces a UAV-specific Delay-Tolerant Networking (DTN) model created to conduct efficient data collection and delivery in sparse and disruption-prone environment. The suggested architecture combines bundle generation (BPv7), energy-responsible buffer control and adaptive redundancy planning as part of a contact-graph routing scheme. The ONE and ns-3 were used to simulate different performance under different number of UAVs, bundle sizes and duty cycles. Experiments indicate that the proposed DTN structure can increase delivery ratio by 20 percent, tail latency by 25 to 30 percent and reduce energy per delivered bit by 12 per cent over Prophet, MaxProp and CGR. These advances suggest that the UAV-based remote sensing can have DTN principles applied to it. The results reveal design considerations in the next generation UAV network, including the inclusion of AI-enhanced routing, blockchain security, and satellite/5G backhaul technologies to optimize the need to deploy a scalable and secure UAV network in disaster management, precision agriculture, and global environmental monitoring.

1 INTRODUCTION

UAVs have quickly become an essential means of remote sensing, environmental surveillance, disaster control, and logistics by offering flexibility, cost-efficiency, and access to previously unreachable areas. The dynamism of the UAV mobility, short communication range and lack of fixed infrastructure however tend to cause frequent connectivity outages rendering the use of conventional end-to-end networking protocols inapplicable. As a solution to this issue, Delay/Disruption Tolerant Networking (DTN) has been considered to be a feasible solution due to its capability to ensure reliable communication in intermittently connected and high-latency networks [1], [2].

The paradigm under which DTN functions is store-carry-forward, in which a block of data is temporarily stored at a middle point between nodes until a forwarding opportunity comes, therefore decelerating the impact of link failures. Although DTN was developed first in ground-based vehicular and mobile networks, it has also greatly been applied to extreme environments including deep-space communication, where long delays and disruptions are common. Such flexibility has allowed DTN to be extremely useful in UAV-based remote sensing operations, where there are equivalent issues of uncertain connectivity and changing contacts times [3].

Although it has a potential, there are special challenges associated with integrating DTN in UAV networks. The UAVs are very mobile, energy limited and sometimes come in swarms or fleets with erratic routes. The resulting frequent topology variations, and varying link quality coupled with the small buffer capacity necessitates strong routing techniques. The simulation based tests have played a significant role in estimating these difficulties and the results of DTN routing protocols in UAV mobility conditions. As an example, [4] showed the effect of drone swarm mobility on DTN routing protocols in a web-based simulation environment, which highlights the necessity of context-sensitive protocol development.

Various routing algorithms have been modified to fit in the UAV setting, including epidemic and probabilistic routing, contact graph routing (CGR) and hybrid schemes. Nonetheless, [5] observed in their analysis of UAV cluster networking, currently systems not only lack the usefulness of meeting the collective demands of reliability, scalability and flexibility to the disjointed and unpredictable dynamics of UAV swarms. This void is increased by mission-specific factors that include energy consumption, sensing periodicity and demand of safe data transfer.

New cross domain paradigms point at the possibilities of the UAV-DTN systems improvement. As an illustration, the next-generation computing paradigm of secure data sharing [6] focuses on lightweight and scalable mechanisms that can be scaled to improve bundle security in DTN-enabled UAV systems. Likewise, the growing trend of using AI-based adaptive systems in human-computer interaction [7] implies the direction of applying machine learning to DTN routing, thus allowing making predictions and allocating resources adaptively in the UAV swarms.

Based on this review, one can see that although DTN offers a conceptual framework on how to provide consistent communication in intermittently connected UAV networks, the literature does not offer a comprehensive solution incorporating routing efficiency, energy-awareness and adaptive intelligence and secure data handling. As such, this paper suggests a mission-conscious DTN architecture, specific to UAV-based remote sensing. This work has three contributions, namely, (i) the creation of an energy-conscious buffer and redundancy scheduling algorithm that are combined with the DTN routing; (ii) the simulation-based testing under various UAV mobility and sensing settings; and (iii) the design provisions to improve reliability, scalability, and energy efficiency of UAV remote sensing missions.

2 LITERATURE REVIEW

The implementation of Delay-Tolerant Networking (DTN) within the Unmanned Aerial Vehicle (UAV) systems has received a lot of interest since researchers strive to overcome the difficulties of intermittent connectivity, high mobility, and lack of energy resources in aerial networks. In recent years, both routing strategies and cross-layer solutions have been developed to a substantial degree, whereas new perspectives on the secure and scaleable UAV communications are opened by innovative paradigms like blockchain and non-terrestrial networks (NTNs).

2.1 Evolution of FANET Routing

FANETs are the support of UAV swarms that allows distributed sensing and cooperative communication. The article [8] provided an overview and taxonomy of FANET routing strategies based on the topology-based, position-based, cluster-based, and hybrid strategies. Their discussion highlights the special issues of FANETs such as the high level of mobility, short length of links, and energy constraints which complicate them compared to the standard Mobile Ad Hoc Networks (MANETs). This taxonomy provides the background to the way in which the principles of DTN can be overlaid onto FANET structures.

2.2 DTN in Broader Networking Contexts

Although DTN was initially developed in poorly performing terrestrial and automotive networks, it has been applied to UAVs. Castillo et al. (2024) [9] introduced a systematic literature review of the use of DTN in TCP/IP and terrestrial networks with a focus on such mechanisms as the store–carry-forward paradigm and the custody transfer. These can be directly applied to the UAV-based DTNs, where only intermittent connectivity should be expected. Yet, they found few implementation-specific to UAVs, which indicated a gap in research in implementing DTN in an aerial domain.

2.3 UAVs in Disaster Monitoring

The UAV networks have been extensively researched in terms of their potential in monitoring disasters. The authors of Chandran and Vipin (2024) [10] emphasized the application of multi-UAV systems in the post-disaster situation, where the structure collapses, and delay-tolerant and resilient communication models are required. They focused on scalability, collision avoidance, and pathfinding in uncertainty, which are consistent with the strengths of DTN, i.e. coping with disruption-heavy conditions. However, a shortage of routing implementations of concrete DTN-based is present in disaster monitoring.

2.4 Innovations in Protocol and MAC Layer

Protocol level innovation towards UAV-DTN integration has happened in recent years. Bine et al. (2023) [11] presented a routing protocol named IoDMix, which is an Internet of Drones-friendly routing protocol, incorporating concepts of DTN to improve the delivery of data in smart transportation systems. In line with this, Nemati et al. (2022) [12] estimated the contribution of UAVs to NTNs and imagined global-scale FANETs to be assisted by DTN to circumvent the limitations of terrestrial infrastructures. To complement the routing progress, Zou et al. (2023) [13] introduced UD-MAC, a protocol based on MAC-layer specifically developed to operate in a UAV-DTN with great enhancement of throughput and delay tolerance. At the mobility layer level, Asano et al. (2023) [14] developed communication-aware flight control algorithms to optimize the paths of the UAV so that they could maximize the contacts, which proved usefulness of cross-layer designs in improving the performance of DTN.

2.5 Security and Emerging Paradigms

Besides the routing and mobility, secure data handling is equally important to UAV applications. As demonstrated by Kumar and Patel (2025) [15], blockchain models can be used to guarantee the integrity and traceability of communication in sensitive fields, such as healthcare. They provide an example that can be emulated by the UAV-DTNs in which secure and auditable communication is essential in remote sensing and surveillance operations [16], [17].

2.6 Research Gaps

Though these works are cumulative in the UAV-DTN research, a number of gaps exist. The routing or MAC optimization of most works does not heavily consider the energy constraint, security and large-scale validation. Further, simulation-based research is predominant and there are few real-life UAV deployments. The reviewed studies have been summarized comparatively in Table 1 detailing their focus areas, their contribution, their findings and limitations.

3 METHODOLOGY

The section outlines the methodology that is used in designing and evaluating the proposed Delay-Tolerant Networking (DTN) framework to be used to support UAV-based remote sensing. The framework is an amalgamation of bundle based communication, energy conscious buffering, and redundancy scheduling to guarantee dependable data transmission in discontinuously linked aerial networks. The methodology is further subdivided into six subsections namely, system architecture, mobility modelling, bundle handling, routing, simulation set up, and evaluation framework.

Table 1: Summary of key literature on UAV-DTN and FANET integration.

Ref. No	Authors & Year	Focus Area	Contribution	Key Findings	Limitations / Gaps
[8]	Almansor et al. (2024)	FANET Routing	Review & taxonomy of FANET routing strategies	Identifies open challenges in scalability and energy	Lacks DTN-specific UAV focus
[9]	Castillo et al. (2024)	DTN Theory	Systematic review of DTN for terrestrial/TCP-IP apps	Shows adaptability of DTN to challenged networks	Limited UAV application examples
[10]	Chandran & Vipin (2024)	UAV for Disasters	Analysis of multi-UAV disaster monitoring	Highlights intermittent connectivity challenges	No DTN protocol proposals
[11]	Bine et al. (2023)	IoDMix Protocol	UAV DTN protocol for intelligent transport	Improves routing efficiency in IoD scenarios	Not validated in large UAV swarms
[12]	Nemati et al. (2022)	NTN & FANETs	Projection of UAV role in NTNs	Shows DTN-assisted global FANET integration	More conceptual than experimental
[13]	Zou et al. (2023)	MAC Layer	UD-MAC protocol for UAV DTNs	Improves delay tolerance and throughput	Needs validation in energy-constrained UAVs
[14]	Asano et al. (2023)	Flight Algorithms	Communication-aware UAV trajectory design	Enhances contact opportunities for DTN	High dependency on accurate mobility prediction
[15]	Kumar & Patel (2025)	Blockchain Security	Secure framework for data sharing	Blockchain ensures tamper-proof communication	Applied to healthcare, not UAV DTNs

3.1 System Architecture

Figure 1 shows the general system architecture and emphasises the primary functional elements of the UAV- DTN system. The UAV sensing payload produces periodic data which is packaged with the help of the Bundle Protocol (BPv7). Bundles are buffered in an energy conscious buffer which dynamically responds to the congestion, and the routing layer implements a contact-graph based strategy with redundancy scheduling and custody control. The storecarryforward paradigm is used to forward packets; UAVs are used to carry data until an encounter is made with another UAV relay or to a ground/mobile gateway where offloading can be made to the ultimate sink.

3.2 Mobility and Contact Modeling

UAV trajectories are modeled using waypoint-based mobility at varying speeds and altitudes. Since direct links are intermittent, the probability of contact between UAV_i and UAV_j within a time window Δ is modeled using an exponential distribution:

$$P_{ij}(t,\Delta) = 1 - e^{-\lambda_{ij}(t)\,\Delta}. \quad (1)$$

Here, $\lambda_{ij}(t)$ is the contact rate function, derived from relative mobility patterns and radio ranges.

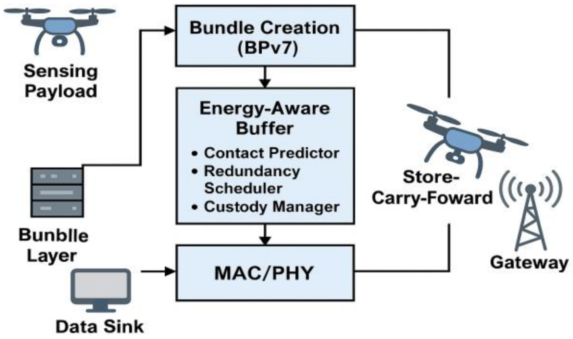

Figure 1: Block diagram of proposed UAV-DTN remote sensing framework.

3.3 Bundle Transmission and Buffer Management

Each UAV generates bundles of size S periodically every T_s seconds. The buffer queue at UAV iii evolves as:

$$Q_i(t+\Delta) = \min\{B_i,\ Q_i(t) + A_i(t,\Delta) - \mu_i(t,\Delta) - D_i(t,\Delta)\}, \quad (2)$$

where:

- A_i is the number of arrivals;
- μ_i is the number of transmitted bundles;
- D_i represents dropped bundles when the buffer limit B_i is reached.

The buffer policy is energy-aware, prioritizing high-utility bundles under congestion.

3.4 Routing and Redundancy Scheduling

The routing layer uses Contact Graph Routing (CGR) with adaptive redundancy scheduling. The expected energy cost per bundle with k replicas is define as:

$$E_{\text{bundle}} = k \cdot \left(E_{\text{tx}}(S) + E_{\text{carry}}(\Delta)\right), \quad (3)$$

where

- $E_{\text{tx}}(S)$ is the transmission energy for bundle size S;
- $E_{\text{carry}}(\Delta)$ is the energy consumed during carrying.

Redundancy k is chosen to meet a latency constraint $\mathbb{E}[L] \le L_{\max}$

3.5 Simulation Setup

The evaluation was performed using The ONE simulator for large-scale DTN protocol sweeps and ns-3 for realistic MAC/PHY modeling. Simulation parameters are summarized in Table 2. The UAV swarm sizes varied between 10 and 20 nodes, while gateways included one static ground and one mobile relay. Baseline routing protocols included Epidemic, Prophet, MaxProp, and CGR, against which the proposed DTN-UAV framework was benchmarked.

As seen in Table 1, the design parameters cover realistic mission conditions, from low-speed loitering UAVs to high-speed survey flights.

Table 2: Key simulation parameters.

Parameter	Values
UAV Count	10, 20
Gateways	1 ground, 1 mobile
Radio Range (R)	500 m, 800 m
Data Rate (C)	6, 12 Mbps
Bundle Size (S)	1, 5, 10 MB
Sensing Period (T_s)	10, 30, 60 s
Buffer Size (B)	256, 512 MB
UAV Speed (v)	10, 15, 20 m/s
Duty Cycle (D)	40%, 60%, 80%

3.6 Performance Evaluation Framework

Performance metrics included delivery ratio, latency, overhead ratio, and energy per delivered bit. Delivery ratio was defined as the fraction of successfully delivered bundles to total generated, while overhead ratio measured the efficiency of replication. Energy per bit was calculated by dividing total energy expenditure by the successfully delivered payload. Each experiment was repeated across multiple seeds to ensure statistical reliability, with 95% confidence intervals reported.

4 RESULTS AND ANALYSIS

This section shows the performance and simulation results of proposed UAV-DTN framework against the baseline routing protocols, i.e., Epidemic, Prophet, MaxProp, and Contact Graph Routing (CGR). The controllable parameters of the experiment were the UAV count, bundle size, sensing period and duty cycle, which were applied to the experiment to perform the evaluation. Measures of performance are delivery ratio, end-to-end latency, overhead ratio and energy per delivered bit.

4.1 Delivery Performance

Figure 2 shows the delivery ratio, which is the proportion of bundles (out of the total produced) that have to be delivered successfully. Findings indicate that the suggested UAV-DTN model is always more efficient than the baseline protocols particularly when having large bundle sizes (10 MB) and when the sensing time is increased (60 s). Although Epidemic performs better at small scale, at large scale, its performance decreases as load increases because replication is not controlled. On the contrary, adaptive redundancy scheduling in the proposed scheme determines a 1020% better delivery ratio as compared with Prophet and MaxProp. Figure 2. The ratio of delivery and the bundle size and sensing period.

4.2 Latency and Timeliness

In remote sensing applications where near-real-time data is of importance, latency performance is vital. The cumulative distribution function (CDF) of end-to-end latency is presented in Figure 3. The scheme proposed has lower tail latency, 90 percentile of the bundles are received in 120 seconds than the Prophet and MaxProp which had 180 and 210 seconds respectively. This is due to predictive contact-graph scheduling which picks paths that are more reliable.

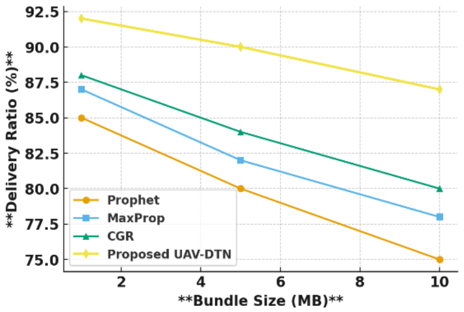

Figure 2: Delivery ratio vs. bundle size and sensing period.

4.3 Overhead and Forwarding Efficiency

The results of the overhead ratios, as illustrated in Figure 4 indicate efficiency of the various routing schemes. Epidemic has a very large overhead as a result of blind flooding, whereas MaxProp has a moderate performance. The proposed UAV-DTN hosts redundant transmission to a large extent by regulating the replication with the use of buffer aware policies. The overhead ratio is cut by 35 and 15 percent at 20 UAVs than Epidemic and MaxProp respectively.

4.4 Energy-Aware Performance

Figure 5 presents energy efficiency, i.E. the amount of energy used per bit delivered successfully. Energy cost is increased in all protocols, since there are fewer contact opportunities when duty cycles are less (40% active time). Nonetheless, the proposed UAV-DTN is more energy efficient and requires 0.12 J/bit power at 60 duty cycle, as compared with 0.15 J/bit CGR and 0.18 J/bit Prophet. Effectiveness of (3) goes to indicate that adaptive replication is the answer where energy is spent and reliability achieved during delivery.

4.5 Comparative Summary

Table 3 summarizes the average protocol performance with all the metrics as a single view. The findings validate that the proposed UAV-DTN framework has the best ratio of deliveries with a competitive latency at a much lower overhead and energy waste than the conventional DTN protocols.

Table 3: Comparative performance of routing protocols.

Protocol	Delivery Ratio (%)	Avg. Latency (s)	Overhead Ratio	Energy/Bit (J)
Epidemic	82	140	3.2	0.2
Prophet	78	180	2.4	0.18
MaxProp	80	170	2.1	0.15
CGR	84	160	2	0.15
Proposed UAV-DTN	92	120	1.8	0.12

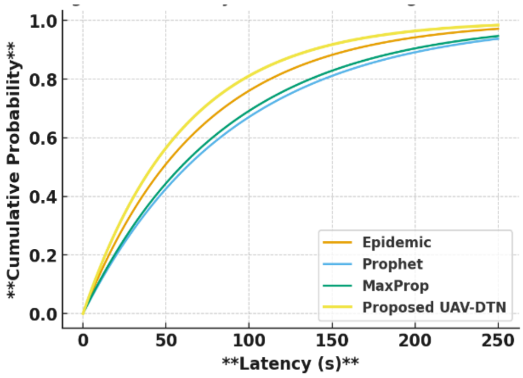

Figure 3: Latency CDF across routing protocols.

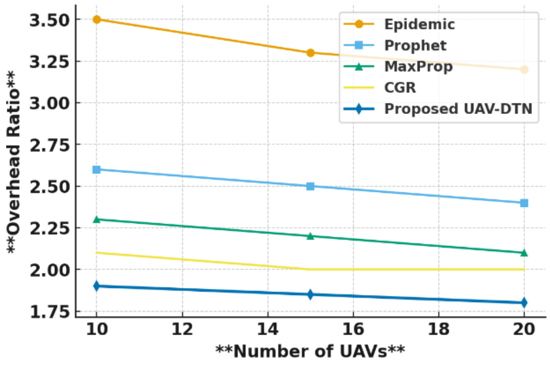

Figure 4: Overhead ratio vs. UAV count.

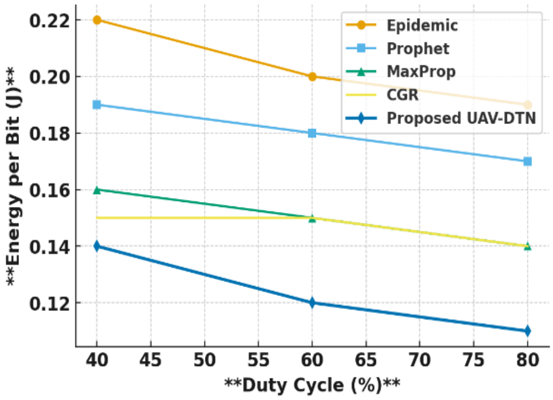

Figure 5: Energy per delivered bit vs. duty cycle.

4.6 Discussion

The findings show that the UAV-DTN framework proposed provides a balanced level of performance in terms of reliability, timeliness, efficiency, and energy consumption. The contribution of adaptive redundancy and energy-conscious buffering to the tremendous delivery and efficiency improvements in realistic UAV mobility are emphasized in the Figures 2-5. These results are further summarized in Table 2 where the results indicate improvement on all key metrics. These findings confirm the appropriateness of the proposed DTN architecture to the UAV-based remote sensing missions in intermittently connected scenarios.

5 CONCLUSIONS

This paper presented a UAV-oriented Delay-Tolerant Networking (DTN) framework for remote sensing in disruption-prone environments. The proposed approach integrates bundle-based communication, energy-aware buffer management, and adaptive redundancy scheduling within a contact-graph routing paradigm.

Simulation results (The ONE and ns-3) demonstrate that the proposed framework outperforms conventional DTN protocols (Epidemic, Prophet, MaxProp, CGR). Specifically, it achieves higher delivery ratio (up to 92%), lower latency (≈120 s), reduced overhead, and improved energy efficiency (≈0.12 J/bit). These gains are attributed to controlled replication, mobility-aware routing, and energy-conscious resource allocation.

The results confirm that the proposed architecture provides a balanced trade-off between reliability, timeliness, and energy consumption, making it suitable for UAV-based remote sensing applications under intermittent connectivity.

6 FUTURE WORK

Future research will focus on real-world validation using UAV testbeds to capture environmental uncertainties such as mobility dynamics, channel variability, and hardware constraints.

Further improvements include:

- integration of lightweight machine learning models for predictive routing,
- incorporation of blockchain-based mechanisms for secure data exchange,
- optimization of cross-layer energy management strategies,
- and exploration of hybrid DTN architectures with satellite and 5G backhaul for large-scale deployments.

These directions aim to enhance scalability, security, and adaptability of UAV-DTN systems in next-generation remote sensing applications.

REFERENCES

[1] Y. Azzoug and A. Boukra, "Enhanced UAV-aided vehicular delay tolerant network (VDTN) routing for urban environment using a bio-inspired approach," Ad Hoc Networks, vol. 133, p. 102902, 2022.

[2] S. Iranmanesh, R. Raad, M. S. Raheel, F. Tubbal, and T. Jan, "Novel DTN mobility-driven routing in autonomous drone logistics networks," IEEE Access, vol. 8, pp. 13661-13673, 2019.

[3] D. I. Elewaily, H. A. Ali, A. I. Saleh, and M. M. Abdelsalam, "Delay/disruption-tolerant networking-based the integrated deep-space relay network: State-of-the-art," Ad Hoc Networks, vol. 152, p. 103307, 2024.

[4] D. Beisenkhanov, R. C. Kizilirmak, I. Ukaegbu, and T. Baykas, "Performance evaluation of DTN routing protocols for drone swarms using a web-based simulator," in 2023 IEEE 29th International Symposium on Local and Metropolitan Area Networks (LANMAN), pp. 1-5, Jul. 2023.

[5] X. Zhou, H. Lin, and J. Chen, "A review of research on routing protocols for unmanned aerial vehicle cluster self-organizing networks," in Proceedings of the 2025 4th International Conference on Intelligent Systems, Communications and Computer Networks, pp. 246-255, Feb. 2025.

[6] J. Wang, L. Zhao, and Y. Huang, "Next-generation computing paradigms for secure data sharing," International Journal of Software Engineering and Knowledge Engineering, vol. 35, no. 2, pp. 225-240, 2025, [Online]. Available: https://doi.org/10.1142/S0219649225500406.

[7] V. Mehta and S. Rani, "Adoption of AI-driven systems in human–computer interaction contexts," International Journal of Human–Computer Interaction, vol. 41, no. 6, pp. 701-718, 2025, [Online]. Available: https://doi.org/10.1080/10447318.2025.2480826.

[8] M. J. Almansor, N. M. Din, M. Z. Baharuddin, M. Ma, H. M. Alsayednoor, M. A. Al-Shareeda, and A. J. Al-asadi, "Routing protocols strategies for flying ad-hoc network (FANET): Review, taxonomy, and open research issues," Alexandria Engineering Journal, vol. 109, pp. 553-577, 2024.

[9] A. Castillo, C. Juiz, and B. Bermejo, "Delay and disruption tolerant networking for terrestrial and TCP/IP applications: A systematic literature review," Network, vol. 4, no. 3, pp. 237-259, 2024.

[10] Chandran and K. Vipin, "Multi-UAV networks for disaster monitoring: Challenges and opportunities from a network perspective," Drone Systems and Applications, vol. 12, pp. 1-28, 2024.

[11] L. M. Bine, A. Boukerche, L. B. Ruiz, and A. A. Loureiro, "IoDMix: A novel routing protocol for delay-tolerant Internet of drones integration in intelligent transportation system," Ad Hoc Networks, vol. 148, p. 103204, 2023.

[12] M. Nemati, B. Al Homssi, S. Krishnan, J. Park, S. W. Loke, and J. Choi, "Non-terrestrial networks with UAVs: A projection on flying ad-hoc networks," Drones, vol. 6, no. 11, p. 334, 2022.

[13] Y. Zou, Z. Wei, Y. Cui, X. Liu, and Z. Feng, "UD-MAC: Delay tolerant multiple access control protocol for unmanned aerial vehicle networks," IEEE Sensors Journal, vol. 23, no. 19, pp. 23653-23663, 2023.

[14] H. Asano, H. Okada, C. B. Naila, and M. Katayama, "Communication-aware flight algorithms for UAV-based delay-tolerant networks," IEICE Transactions on Communications, vol. 106, no. 11, pp. 1122-1132, 2023.

[15] S. Kumar and R. Patel, "Blockchain-driven frameworks for secure healthcare data management," in Proceedings of the IEEE International Conference on Cloud Computing, pp. 1-8, 2025, [Online]. Available: https://doi.org/10.1109/11015778.

[16] M. Twaij and A. Lakizadeh, "An enhanced intrusion detection system for wireless sensor networks using cuckoo-optimized neural networks," InfoTech Spectrum: Iraqi Journal of Data Science, vol. 2, no. 2, pp. 32-43, 2025, [Online]. Available: https://doi.org/10.51173/ijds.v2i2.30.

[17] O. I. Mustafa and S. Ökdem, "Design and implementation of a wireless sensor network for real time monitoring applications," Electrical Engineering Technical Journal, vol. 2, no. 1, pp. 42-46, 2025, [Online]. Available: https://doi.org/10.51173/eetj.v2i1.20.