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RESEARCH ARTICLE

# Reliable Data Exchange in UAV Swarm Networks Using Advanced Networking Techniques

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## Abstract

**The proliferation of unmanned aerial vehicles (UAVs) has driven the emergence of Flying Ad-hoc Networks (FANETs) as distributed cyber-physical computing systems for surveillance, disaster management, precision agriculture, and logistics. Optimizing computational and communication resource utilization within these constrained aerial systems is essential to extend network lifespan and maintain satisfactory quality of service (QoS). This study proposes integrating the Fisheye State Routing (FSR) protocol with a 3×3 Manhattan Grid mobility model as a computing-systems solution for reliable data exchange in dynamic UAV swarm networks. FSR maintains distributed topology tables and applies Dijkstra's algorithm to compute optimal routing paths, enabling adaptive resource allocation across continuously reconfiguring network architectures. Performance is evaluated across six metrics—packet delivery ratio, packet drop rate, end-to-end delay, channel utilization, throughput, and jitter—under two scenarios of twenty and thirty nodes. FSR achieves packet delivery ratios of 46% and 53% respectively, with minimal end-to-end latencies of 0.010 and 0.244 seconds and reduced jitter, outperforming five topology-based protocols (OLSR, AODV, DSR, TORA, DSDV) in resource utilization across all evaluated metrics.**

**Keywords**: UAV swarm networks, FSR, FANET, network and communication systems, internet of aerial vehicles, cyber-physical systems, resource optimization, green UAV communications, routing protocol.

## 1 Introduction

Recent global market studies approximate the present value of UAVs to be $127 billion [1, 2]. UAVs are extensively used for many purposes such as search and rescue missions, surveillance of civil fields, strategic reconnaissance, and traffic monitoring, among other applications [3–7]. They are fundamental components of the Unmanned Aerial System (UAS) or Drones, allowing Air-to-Air (A2A) and Air-to-Ground (A2G) communication. Data transfer success in A2A and

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A2G communications is heavily dependent on speed and 3D mobility capabilities [8]. UAVs are classified into two primary categories: Rotary-Wing (RW) and Fixed-Wing (FW). Unmanned Aerial Vehicles with Rotor Wings can take off from a variety of locations and fly at low altitudes. These models are classified into many categories based on their rotor configurations, including hexacopter, quadcopter, tri-copter, single-rotor, and hybrid types [9, 10]. However, Fixed-Wing UAVs are highly proficient in extended surveillance operations owing to their exceptional aerodynamic structure and wide range of flight speeds (30-460 km/h). Figure 1 depicts the predominant categories of commercially employed UAVs. From a computing-systems perspective, UAVs function as mobile, resource-constrained cyber-physical nodes that must simultaneously manage onboard computation, sensor data processing, and wireless communication within stringent energy and payload budgets.

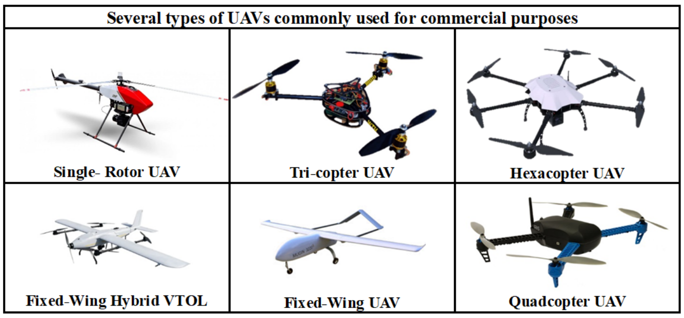


**Figure 1.** Typical types of UAVs.

These UAVs are appropriate for various deployment circumstances due to their tradeoffs in attributes including flying height, battery life, mobility, and hovering capability. Table 1 provides a brief comparison of the primary differences between RW and FW UAVs.

In recent decades, eco-friendly UAVs have opened up advanced applications in precision agriculture, product transportation, and urban monitoring, positioning FANETs as a distributed computing infrastructure for next-generation intelligent systems. Intelligent Transportation Systems (ITS) represent one prominent application domain where UAV-enabled aerial computing nodes can augment ground-based infrastructure [11–14]. The convergence of Sixth Generation (6G) wireless technologies with Intelligent Transportation Systems (ITS) is expected to enable large-scale deployment of autonomous aerial and ground vehicles in smart cities, with UAVs playing an essential role as aerial communication nodes within these emerging 6G infrastructures [15, 16]. To realize a fully automated ITS, seamless and reliable communication among aerial and ground nodes is critical; FANETs provide a promising framework for enabling such connectivity, with position-based routing protocols offering efficient data delivery in highly dynamic UAV-assisted transportation environments [17]. UAVs play a crucial role in facilitating automation in ITS, buildings, hospitals, emergency systems, and security, as illustrated in Figure 2.

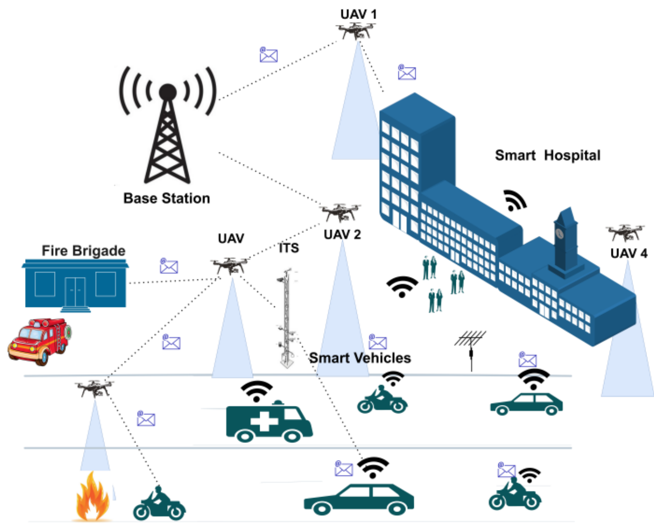


**Figure 2.** Urban automation and the role of UAVs.

FANETs have several advantages when compared to other forms of ad hoc networks, such as those

**Table 1.** Features of UAVs with fixed and rotating wings.

| Dimensions | UAV category | Energy Usage | Movability | Hovering Static | Elevation |
|---|---|---|---|---|---|
| Small UAVs | RW | Minimum | Nominal | Yes | Low |
| | FW | Maximum-Average | Rapid-Moderate | No | Med-Low |
| Large UAVs | RW | Minimum-Average | Rapid-Moderate | Yes | Med-High |
| | FW | Maximum | Nominal | No | High |

utilized in maritime vessels, automobiles, or robotics. FANETs offer advantages such as simplified hardware deployment, increased resilience in challenging environments, and decreased environmental strain. Advanced routing techniques—including reinforcement learning-based approaches and bio-inspired optimization algorithms—have further enhanced the reliability, adaptability, and energy efficiency of FANETs across diverse mission scenarios [18–22]. They are specifically used for sensitive applications that require assured data transmission, effectiveness, dependability, and extremely low latency rates. However, frequent topology changes in FANETs can cause signaling cost, packet loss, and latency problems [23].

Although FANETs have many benefits, their 3D mobility and speeds ranging from 30 to 460 km/h make it difficult to employ resources efficiently and establish connection between UAVs and target base stations [24]. The main reason for this is that UAVs need energy for both propulsion and communication, presenting a dual energy burden on UAV systems. Theoretical models for both fixed-wing and rotary-wing UAVs confirm that the energy consumed by propulsion substantially surpasses the energy utilized for communication—often by several orders of magnitude—making propulsion the dominant factor in UAV energy budgeting [25, 26]. Moreover, the implementation of mobility models significantly contributes to the improvement of Quality of Experience (QoE) and Quality of Service (QoS). This study addresses these computational and networking challenges by proposing FSR integrated with a 3×3 Manhattan Grid Mobility Model as an advanced computing architecture for distributed aerial network systems. The study of the results shows that the FSR with the Manhattan Grid (MG) routing protocol performs better than other routing methods.

This paper contributes to the advancement of network surveillance and the establishment of green UAV communications.

- Deployment of FSR as a proactive link-state computing architecture for distributed FANET resource management, enabling continuous topology awareness across dynamically reconfiguring cyber-physical UAV swarms.
- The 3x3 grid and probabilistic technique of the Manhattan Grid Mobility Model are used here; forward and backward directions each with probability 0.5, and right and left directions each with probability 0.25, respectively.
- Two case studies were conducted in the MG, using twenty and thirty nodes individually. The simulation duration in the first scenario was twenty seconds, while in the second scenario, it was thirty seconds.
- The study was conducted on six protocols employing specific performance indicators such as Packet Drop and Packet Delivery Ratio, Bandwidth Utilization, Throughput, Packet Drop Behavior, End-to-End Delay, and Jitter.
- Comprehensive performance benchmarking of FSR against five topology-based protocols within a network computing systems framework, quantifying improvements in resource utilization efficiency across packet delivery, delay, throughput, and jitter metrics.

The present study is structured into several sections to facilitate a comprehensive understanding of the proposed research. Section 2 comprises a literature review aimed at providing the necessary context for the suggested strategy. Section 3 outlines the recommended approach. Section 4 contains simulated data, comparative analysis, and discussions, while Section 5 presents the conclusion.

## 2 Related Work

Academics are concentrating more and more on creating Self-organizing and Self-healing networks as a result of the use of green UAVs in both domestic and industrial contexts [27–29]. FANETs are networks that consist of nodes capable of movement in all three dimensions [30]. Disruptions in A2A and A2G communications may arise from dynamic alterations in network architecture, including rapid topology changes, intermittent link connectivity, and high node mobility, all of which impose significant routing constraints that existing MANET and VANET protocols are ill-equipped to address in FANET environments [31]. Hence, routing protocols, categorized based on their functional methodology, are essential for preserving the effectiveness and QoS of wireless networks.

In topology-based routing protocols, nodes build a network by exchanging topology data with their neighbors. FANETs include many routing types, including Topology-based, Swarm-based, Hierarchy-based, Position-based, Delay-tolerant, Heterogeneity-based, and Energy-based [32]. Several routing protocols belonging to these classes have been established and evaluated in various network scenarios, as demonstrated in different research articles. This group of routing protocols typically have three operational steps: neighbor and route discovery, route exchange messages (RREP and RREQ), and topology table updating by identifying and sharing IP addresses with surrounding nodes. Routing protocols can be classified as static, hybrid, proactive, as well as reactive [33].

The proactive routing strategy known as Optimized Link State Routing (OLSR) has proven to be effective in both 2D and 3D environments. Link State (LS) techniques, derived from the network's topology, are employed by the system to build connections between nodes. This is achieved by transmitting a specific data packet referred to as the 'H-Packet.' The exchange of TT information among nodes is vital for maintaining all crucial network information. The protocol employs the Multi-Point Relay (MPR) technique to resolve challenges associated with looping and point-to-point communication [34, 35].

Directional antennas are incorporated in Directed Optimized Link State Routing (D-OLSR), an advanced version of OLSR as described by [36]. The implementation of this approach enables a decrease in MPR counts and effectively tackles concerns associated with overhead. An activation occurs if the Maximum Distance/2 exceeds half of the value among the initial and final nodes; otherwise, traditional OLSR is employed. In [37], the proactive routing approach known as the Distance Sequence Distance Vector (DSDV) was detailed. In this technique, nodes verify their sequence numbers before exchanging information with nodes in the surrounding area. The topology database only updates the most recent sequence number because every node communicates its current position to every other node. In large-scale networks, reactive routing methods are employed to connect specific groups of UAVs; multicast extensions of on-demand distance vector protocols have been explored for this purpose, as surveyed in the context of UAV communication challenges and protocol limitations [38].

Dynamic Source Routing (DSR) is a reactive on-demand source routing protocol based on topology that uses Self-regulating and Self-restoring procedures. This protocol employs the minimal vertex cost in conjunction with hop counts to determine routes for forwarding data packets. The most efficient route from the source UAV to the ultimate destination is ascertained with the D-Bellman Ford algorithm. As part of communication, the network routinely receives route requests and uses them to keep track of the paths that go from the source to the destination. In order to communicate updated route information, UAVs send a route error packet message whenever the topology is modified [39].

The reactive topology-based routing protocol, Temporally Ordered Routing Algorithm (TORA) is developed for dynamic networks. The system utilizes a technique that locally modifies information, using control packets to efficiently manage overhead. TORA incorporates multipath routing algorithms in order to reduce the impact of connection failures. Furthermore, it guarantees that any alterations in the physical position of a UAV are rapidly transmitted to nearby nodes in order to avoid excessive data flow in the network. The network functions similarly to a Directed Acyclic Graph (DAG), allowing UAVs to communicate through the broadcasting of route requests that include the IP address of the destination in order to establish a routing path [40]. An alternative routing class, Swarm-based Routing, applies concepts from ant and insect swarm behavior to unmanned aerial vehicle (UAV) systems [41]. The Bee-Ad hoc routing protocol, inspired by bees' living and communication ways, assigns equal obligations to nodes, which are separated into two groups: the Forager Bee and Scouting Stage. The networked UAVs communicate with each other in both directions, sending their unique identification numbers, energy levels, and Topology Tables. This allows them to choose the best route from their starting point to their final destination. Finally, a response is delivered via Forager Bees to initiate the conversation [42].

To reduce latency between nodes, hierarchically structured routing protocols use UAV locations to separate the network into clusters; the development and evaluation of such hierarchical protocol stacks for disaster monitoring and similar mission-critical FANET deployments have been extensively documented in the literature [43, 44]. Utilizing the geographic coordinates of UAVs, the Position-Based Ant Colony Routing Algorithm (POSANT) finds the shortest and most efficient communication pathways as a multi-agent protocol. Node clustering efficiently diminishes energy consumption and enhances resource usage in UAVs. A hierarchical routing design, the UAV Mobility Prediction Clustering Algorithm (MPCA) divides the network into clusters and makes location, velocity, and speed predictions for UAVs. This forecast takes into account the vocabulary's composition and the termination of connections. The initial stage involves evaluating the speed and position of UAV pairs, thereafter calculating the likelihood of their remaining inside specified geographical areas, hence extending the network's longevity. The types of communication used for both inter- and intra-cluster communication include route requests, which are necessary for communication among UAVs in a cluster, and direct packet broadcasting inside the same zone. A three-tier approach is used by the Extended Hierarchical State Routing Protocol (EHSR) for UAV networks. The cluster head at each level is responsible for data transmission among the different levels of the cluster [45–47]. The UAVs in subordinate clusters select an intermediary cluster that forms a backbone network for transmitting data to upper tiers. The EHSR system utilizes a proactive methodology to routinely oversee the connectivity status of each UAV inside a cluster. To achieve this, it exchanges routing tables with neighboring cluster leaders and creates a hierarchical structure that associates all possible routes [48].

The Disruption Tolerant Mechanism (DTM) is a kind of delay-tolerant routing that deals with problems like node connectivity issues caused by things like mobility, energy limitations, long distances, and spotty radio coverage. Clusters are established in DTM by employing the AODV routing algorithm, which leads to minimal network overhead. The cluster formation considers position, velocity, and speed, while each cluster head maintains link awareness through hello packet exchanges with neighboring heads. The suitability of a delay-tolerant routing mechanism such as DTM is inherently tied to the specific FANET application scenario and the mobility model adopted; different mission contexts—ranging from urban surveillance to search and rescue—impose distinct communication requirements that directly shape routing performance [49–52].

Table 2 outlines the basic constraints of current routing protocols that are not sufficiently discussed in the literature. A number of studies have attempted to improve the QoS and QoE of FANETs by addressing issues with propulsion and energy consumption. While performance analysis metrics including PDR, throughput, end-to-end delay, and jitter are routinely employed to evaluate routing protocols, real-time networks like FANETs often fail to meet these requirements due to their unique operational constraints; moreover, the broader technological and societal implications of deploying FANETs at scale further motivate the pursuit of more robust and efficient routing solutions [53–55]. Reliable routing protocols are crucial in FANETs to maximize UAV resource utilization and improve the QoS and QoE in these networks.

## 3 Proposed Approach

FSR is a proactive link-state computing protocol that manages distributed network state information across resource-constrained UAV nodes, improving data packet flow while maintaining routing table consistency within the topology-based class of protocols. As a computing-systems solution, FSR introduces a hierarchical scope mechanism that reduces inter-node signaling overhead, directly lowering the computational burden on individual aerial nodes. Integrating FSR with the 3×3 Manhattan Grid mobility model creates an advanced network computing architecture tailored to the cyber-physical constraints of FANETs, directly addressing the overhead and latency limitations of earlier topology-based routing protocols.

Each UAV must handle essential components, including the Neighbor List (Ln), Topology Table (TTL) and Routing Table, via FSR, as illustrated in Figure 3.

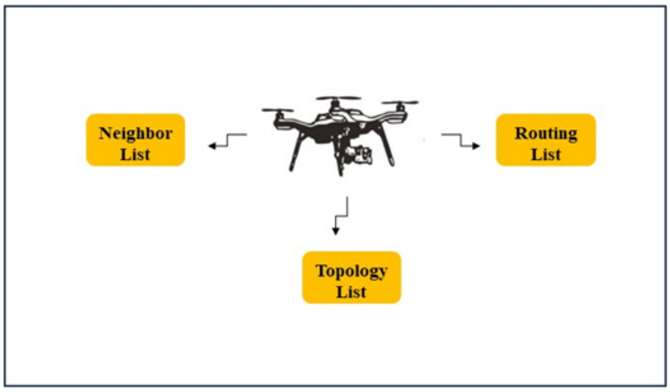


**Figure 3.** UAV with FSR technology.

A node is immediately deleted from the list if it fails to transmit link state data to its neighbors for a specific amount of time. Furthermore, when the position of mobile nodes changes, their IP addresses are distributed by neighboring nodes in a similar approach. To manage the network's scalability, FSR employs a sub-scope decision-making strategy that minimizes routing cost by executing several exchange cycles in the routing tables. As the range

**Table 2.** Advantages and disadvantages of routing protocols.

| Categories | Protocols | Merits | Limitations |
|---|---|---|---|
| Topology Based | AODV | On-demand route discovery reduces control overhead | UAVs detected within a network result in significant data delay. |
| | DSDV | Loops are eliminated from networks | When a network has congestion and delays, it becomes unsuitable for critical or real-time applications. |
| | OLSR | Multipoint relay helps to reduce overhead issues inside a network. | Data delivery delays and overhead make it ineffective in dense (FANET) networks. |
| | TORA | Enhances the nodes' organization | Unsuitable for high mobility |
| | DSR | Establishing a complete route to the destination | A network's increased latency |
| | D-OLSR | Overhead is minimized by using a limited quantity of Multipoint relays | Network longevity, which is affected by higher energy and bandwidth use, is another indicator of network performance. |
| Swarm Class | POSANT | Fragmentation of networks is also supported | The topology is based on quasi-static |
| | Bee Ad-hoc | The UAVs have enhanced memory | Sophisticated UAV network modeling |
| Energy Efficient Class | CBLADSR | Get a high percentage of packets delivered | This leads to severe delays and overhead |
| Hierarchical Class | DTM | Improves the throughput and packet delivery ratio (PDR) | It is decided to handle delay-related issues |
| | EHSR | A network's scalability is taken into account | The network as a whole will be interrupted if the backbone fails |
| | MPCA | Potential connectivity failures between UAVs are predicted. | Ignoring the UAVs' moments caused problems to arise |

decreases, data is transmitted at higher frequencies by neighbors. The major steps in FSR involve identifying neighboring nodes and calculating routes using Dijkstra's algorithm.

UAVs initiate the neighbor discovery phase by means of a hello packet (Ba), which is a unique and specific message. This packet is exclusively received by adjacent nodes that have response times falling within the range of the aerial vehicle. In the second step, the information flooding approach is used to distribute link-state packets in order to assemble the full topology table (TTL). At the same time, a UAV broadcasts a weighted function and the highest sequence (Seq) number to all neighboring nodes whenever its physical location changes. The best network path is determined by selecting edge nodes with the fewest weighted connections. The data in the topology table is updated by UAVs using Equations 1 and 2.

$$d[u] + c(u, v) < d[v] \tag{1}$$

$$d(v) = d[u] + c(u, v) \tag{2}$$

The flow chart illustrating the FSR protocol technique is depicted in Figure 4. Algorithm 1 and its corresponding notation specification are included in Table 3.

**Table 3.** Notational Index.

| Annotations | Description |
|---|---|
| TTL | Topology table |
| $L_L$ | Neighbor list |
| $B_c$ | Broadcast message |
| Nx-hop | Next hop |
| Seq | Sequence no. of packets |

### 3.1 Simulating Environment

The development of effective wireless networks in real-time applications relies heavily on mobility models [56]. The movement of UAVs is controlled using the Manhattan Grid mobility concept in this scenario. This model utilizes a Probabilistic method, where probabilities of 0.5 are assigned for forward and backward movement for forward and backward movement, and probabilities of 0.25 are assigned for right and left directions for the UAVs, as depicted in Figure 5.

The omnidirectional antenna properties of each UAV ensure that radiation covers the geographical area

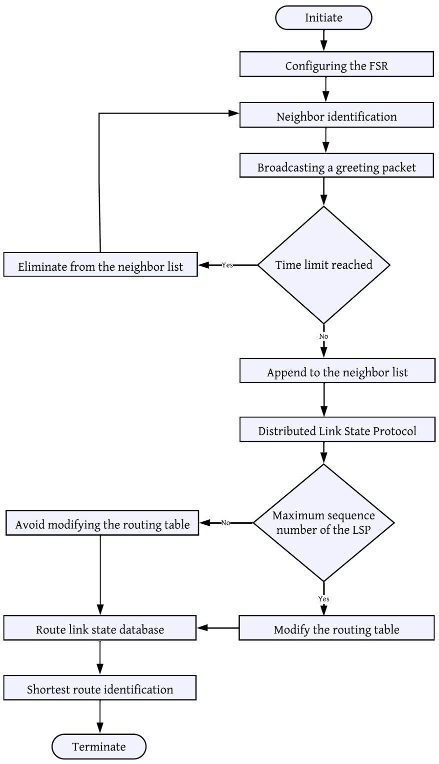


**Figure 4.** Fisheye state routing protocol flow chart.

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**Algorithm 1:** FSR

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**Input:** –
**Output:** The most efficient path from the origin to the destination
**Objective:** Ascertain the most efficient path from the origin to the destination;
Configure $L_L$, seq, TTL, Nx-hop;
**if** $L_L = empty$ **then**
    $B_c \leftarrow$ Broadcasting of a message within the spatial range of UAVs;
    **if** $UAVs = Acknowledgments$ **then**
        $L_n \leftarrow$ Append neighbor;
    **else**
        $L_L \leftarrow$ Eliminate UAVs;
**else**
    $L_L \leftarrow$ Table update;
Broadcast LA to every single network;
**if** $seq > previous\ seq$ **then**
    Revision;
**else**
    $TTL \neq$ Revision;
$I =$ Dijkstra's route search;
Iterate $L_L =$ empty;
Close;

---

uniformly, as determined by Equation 3.

$$U = [\sin(\theta)], \quad 0 \leq \theta \leq \pi, \quad 0 \leq \phi \leq 2\pi \qquad (3)$$

The approach suggested in the MG mobility model, which was put into operation on a $3 \times 3$ grid, has been validated using two case studies. Two scenarios were considered: one with twenty UAVs and a twenty-second simulation time, and another with thirty nodes and a thirty-second simulation time. The simulations require additional parameters, which are shown in Table 4.

This paper compares the performance of FSR with the topology-based routing approaches listed below.

- Optimized Link State Routing (OLSR)
- Ad-hoc On-Demand Distance Vector (AODV)
- Dynamic Source Routing (DSR)
- Temporally-Ordered Routing Algorithm (TORA)
- Distance Sequence Distance Vector (DSDV)

## 4 Outcomes and Analysis

The network parameters employed to analyze the optimal routing protocol are detailed in this section.

**Table 4.** Configuration of simulation.

| Specification | Value |
|---|---|
| Simulator | NS-2 (2.3 version) |
| Area of Topology | 1000 x 1000 (m) |
| Mobility Model | Manhattan Grid |
| Simulation time | 20 s in first scenario & 30 s in second scenario |
| Number of nodes | 20 & 30 |
| Traffic Type | CBR |
| Radio frequency | Two rays grounded |
| Pause Time | One s |
| Total Bases | One |
| Minimum Velocity | One m/s |
| Maximum Velocity | 10 m/s |

### 4.1 Ratios of Packet Delivery and Dropped

A crucial parameter in FANETs is the PDR, defined as the aggregate of all packets successfully transmitted by each UAV within a specified timeframe. The packet drop ratio is the percentage of packets dropped to the total number of transmitted packets.

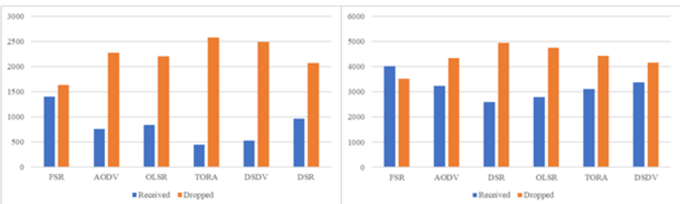
The FSR protocol proved to be superior to alternative routing protocols in both cases when comparing dropped and delivery ratios. In the first scenario, the FSR attained a drop rate of 53.88% and a data delivery ratio of 46.11%. In the second scenario, it achieved a Drop Ratio of 46.85% and a Packet Delivery Ratio (PDR) of 53.14%. The efficacy of these routing

**Figure 5.** Manhattan grid-based UAV mobility model.

**Table 5.** Routing protocol PDR containing 20 nodes.

| Protocol | Transmit | Acknowledged | Dropped |
|---|---|---|---|
| TORA | 3040 | 456 | 2584 |
| DSDV | 3040 | 536 | 2504 |
| OLSR | 3040 | 832 | 2208 |
| AODV | 3040 | 761 | 2279 |
| DSR | 3040 | 965 | 2075 |
| FSR | 3040 | 1402 | 1638 |

protocols exceeded that of the alternative protocols, as demonstrated by the data in Tables 5, 6, 7, 8 and the graphical representations in Figures 6(A) and 6(B). The high PDR of FSR in networks with dynamic topologies underscores its efficiency.




(A) Twenty Nodes (B) Thirty Nodes

**Figure 6.** Analysis of received and dropped packets in routing protocols.

**Table 6.** Percentages of PDR and Drop Ratio for Routing Protocols having 20 nodes.

| Protocol | Percentage of PDR | Percentage of Drop Ratio |
|---|---|---|
| TORA | 15 | 85 |
| DSDV | 17.63157895 | 82.36842105 |
| AODV | 25.03289474 | 74.96710526 |
| OLSR | 27.36842105 | 72.63157895 |
| DSR | 31.74342105 | 68.25657895 |
| FSR | 46.11842105 | 53.88157895 |

**Table 7.** Routing protocol PDR with 30 nodes.

| Protocol | Transmit | Acknowledged | Dropped |
|---|---|---|---|
| DSR | 7540 | 2602 | 4938 |
| OLSR | 7540 | 2794 | 4746 |
| TORA | 7540 | 3085 | 4455 |
| AODV | 7540 | 3216 | 4324 |
| DSDV | 7540 | 3377 | 4163 |
| FSR | 7540 | 4007 | 3533 |

**Table 8.** Packet Delivery Ratio (PDR) and Drop Ratio Percentages for Routing Protocols having 30 nodes.

| Protocol | Percentage of PDR | Percentage of Drop Ratio |
|---|---|---|
| TORA | 40.9151194 | 59.08488064 |
| AODV | 42.6525199 | 57.34748011 |
| OLSR | 37.0557029 | 62.94429708 |
| DSR | 34.5092838 | 65.49071618 |
| DSDV | 44.7877984 | 55.21220159 |
| FSR | 53.1432361 | 46.85676393 |

### 4.2 End-to-End delay

A data packet's overall transit time across a network is called the End-to-End Delay (D), which is also called the one-way delay. The calculation is carried out using Equation 4, which takes into consideration the packet's receiving time ($t_r$) and transmitting time ($t_s$).

$$D = t_r - t_s \tag{4}$$

The FSR protocol has a lower end-to-end latency than topology-based routing approaches in both scenarios, as illustrated by Figures 7(A), 7(B) and Tables 9 and 10.

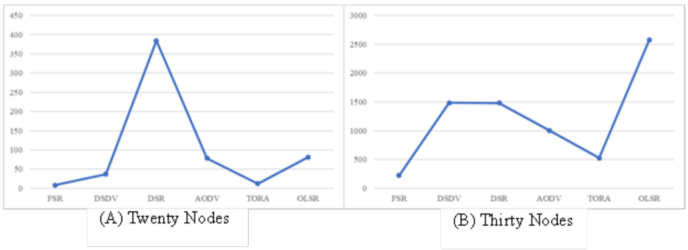



**Figure 7.** End-to-End delay of all routing protocols.

**Table 9.** End-to-end routing protocol delay with 20 nodes.

| Protocol | Delay (ms) |
|---|---|
| DSR | 382.8846867 |
| OLSR | 80.60518873 |
| AODV | 77.8061071 |
| DSDV | 40.93648628 |
| TORA | 12.5727104 |
| FSR | 10.49642941 |

**Table 10.** End-to-end delay routing protocol with 30 nodes.

| Protocol | Delay (ms) |
|---|---|
| TORA | 531.78 |
| OLSR | 1013.89 |
| AODV | 1482.48 |
| DSDV | 2570.13 |
| FSR | 243.53 |
| DSR | 1480.41 |

### 4.3 Bandwidth Utilization

It is crucial for wireless networks to optimize the use of available bandwidth over time. The assessment is based on the optimal use of a connection for a certain duration, calculated using Equation 5. In this context, the variables $P$ and $T$ represent the total amount of packet delivered and total time length respectively, and the channel's bandwidth utilization, measured in packets per second (PPS).

$$U = \sum \frac{P_s}{T_{(pps)}} \tag{5}$$

The available bandwidth has been effectively utilized by FSR throughout a restricted time frame, as illustrated in Figures 8(A) and 8(B).

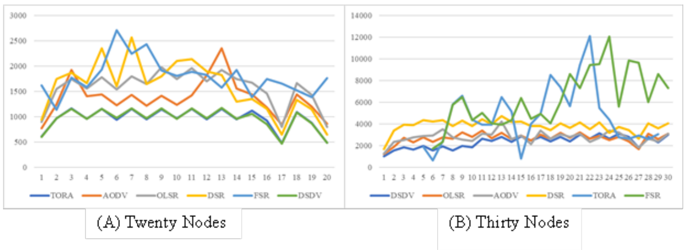



**Figure 8.** Bandwidth utilization in routing protocols.

### 4.4 Analysis of Packet Drop Rates

Packet drop behavior reflects the stability of a routing protocol under dynamic network conditions. As illustrated in Figures 9(A) and 9(B), FSR consistently exhibits the lowest packet drop counts in both the twenty-node and thirty-node scenarios. In the twenty-node case, FSR maintains drop values predominantly below 100 packets per step, while TORA, DSDV, OLSR, DSR, and AODV show considerably higher and more volatile drop behavior throughout the simulation. In the thirty-node scenario, although all protocols experience increased absolute drop counts due to higher network density, FSR remains the most stable, with values generally between 100 and 200 packets per step. By contrast, DSR and OLSR exhibit sharp isolated spikes exceeding 400 packets per step, consistent with route invalidation events caused by frequent topology changes. The low and stable drop behavior of FSR is attributed to its proactive fisheye scoping mechanism, which maintains up-to-date routing tables and avoids the stale route entries and route discovery delays that lead to burst packet losses in other protocols.

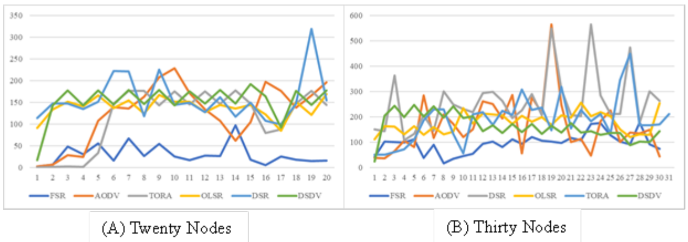


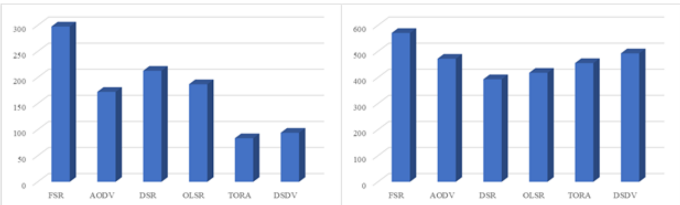

**Figure 9.** Protocols for Routing and Their Packet Drop Behavior.

### 4.5 Throughput

The throughput of a routing system is its ability to efficiently and reliably send packets over a communication media, be it a wireless or wired connection. In Equation 6, the quantification is shown in kilobytes per second (Kbps), with throughput denoted as $G$ and the total number of packets received during time $T$ represented by $\sum P_r$.

$$G = \sum \frac{P_r}{T_{(Kbps)}} \tag{6}$$

Figure 10(A) and 10(B) show that in both cases, the FSR routing protocol outperforms the competition and allows for the maximum amount of data transfer.

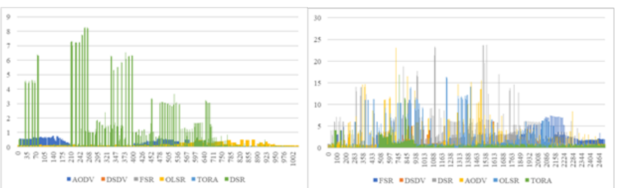



(A) Twenty Nodes (B) Thirty Nodes

**Figure 10.** The rate of throughput for routing protocols.

### 4.6 Jitter

Jitter is a complex phenomenon that arises when there is a discrepancy between the sending and receiving periods of successive packets. This discrepancy can be caused by several circumstances, including network congestion, the choice of the longest data routing route, or connections with limited bandwidth. This leads to a significant increase in network latency and the ratio of packet loss, both of which have a significant effect on the overall efficacy of a routing system. As shown in Figures 11(A) and 11(B), FSR effectively reduces congestion through the usage of network scopes, which improves network performance by reducing packet jitter.



(A) Twenty Nodes (B) Thirty Nodes

**Figure 11.** Routing Protocol Jitter.

The update mechanism of FSR protocol is mostly reliant on the system's mobility. Due to scope interval updates, this may result in quick changes to the network's architecture, which may affect routing efficiency. Nevertheless, FSR has shown significant enhancements in routing efficiency when compared to alternative routing protocols predicated on topology or table-driven approaches.

## 5 Conclusion

FANETs constitute an expanding class of distributed cyber-physical computing systems, extending wireless network architectures into three-dimensional aerial environments and offering significant capabilities for autonomous IoT applications. Unlike MANETs and VANETs that predominantly operate in two-dimensional environments, FANETs introduce unique resource constraints that demand efficient routing solutions. This study addressed these constraints by deploying the FSR protocol within a 3×3 Manhattan Grid Mobility Model across twenty-node and thirty-node scenarios. Analysis of six performance metrics—throughput, end-to-end delay, jitter, packet drop behavior, bandwidth utilization, and packet delivery ratio—consistently demonstrates that FSR outperforms five topology-based protocols in resource utilization efficiency. The effectiveness of FSR has greatly improved network adaptability while decreasing energy consumption related to connectivity and propulsion. Future research will investigate data encryption methodologies and attack mitigation strategies to enhance the security and resilience of FSR-based aerial computing systems, as well as the integration of machine learning-driven adaptive routing to further optimize resource allocation in dynamic FANET environments.

## Data Availability Statement

Data will be made available on request.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## Conflicts of Interest

James Adu Ansere served as an Associate Editor of the ICCK Transactions on Advanced Computing and Systems at the time of manuscript submission. To ensure the integrity of the peer-review process, James Adu Ansere was not involved in the editorial handling, peer review, or decision-making process for this manuscript, which was handled independently by another editor. The remaining authors declare no conflicts of interest.

## AI Use Statement

The authors declare that no generative AI was used in the preparation of this manuscript.

## Ethical Approval and Consent to Participate

Not applicable.

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