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Mobility-Aware Wireless Routing in UAV-Assisted Internet Coverage

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Abstract

This work develops a mobility- and energy-efficient data routing protocol for UAV-assisted vehicular ad hoc networks (VANETs). In the proposed system, one UAV acts as a flying RSU (or roadside unit) that collects data from vehicles. At the same time, the remaining UAVs are treated as relay nodes, relaying information to the mobility service center (MSC). The UAVs can change their 3D positions within a designated area (box) at any time to ensure stable communication. The main goal of the protocol is to be conservatively active with UAV movements and data transfer, thereby balancing the routing task across the available system resources and the remaining energy levels of the UAVs. The problem is formulated as a mixed-integer nonlinear programming (MINLP) model that optimizes routing paths for UAVs and their 3D positions during data transfers. Recognizing that the problem is non-convex, a hybrid methodology is used to address it, particularly for the routing task using Integer Linear Programming (ILP) and for optimizing UAV positions using Particle Swarm Optimization (PSO) metaheuristics. The method was compared with other swarm-

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intelligence meta-heuristics and demonstrated good performance across all scenarios in the numerical simulations.

Keywords: Mobility, Wireless Routing, UAV-Assisted Internet, Transfer Activities, Optimization, Data Transfer.

1 Introduction

Intelligent Transportation Systems (ITSs) are perceived as elements of the systematic evolution of a smart city. ITS technologies have experienced substantial development and widespread implementation recently, yet there appears to be continual rapid evolution in the field. The main element of an ITS infrastructure consists of Fixed Roadside Units (RSUs) located along roadsides. (Alshaibani et al., 2022) Vehicles use Dedicated Short-Range Communication (DSRC) interfaces to transmit data to and from other vehicles and RSUs. In turn, the RSUs collect the vehicle-related data they receive and forward it to a Mobility Service Center (MSC) for further processing. (Al-Hourani et al., 2014) Mobile or aerial radio base stations, or RSUs, are now driving increased interest in crewless aerial vehicles (CAVs), also commonly called drones. (Arvind & Nair, 2025; Waheed et al., 2023). Multi-rotor UAVs are more affordable and easier to produce than other UAV types. They also fly higher than most vehicles, allowing for better communication potential (Ragaba Mean Bosco & El Fanaa Jarhoumi, 2025). The use of an aircraft improves the chance of viable Line-of-Sight (LoS) communications with ground vehicles and the unique ability to cover a large area quickly. Its unmanned nature is a considerable advantage in supporting rapid response to traffic incidents and emergencies. (Bekmezci et al., 2013). The concern lies with the aircraft's battery power source and the diminishing time available for tasks as its battery levels deplete.

UAVs have long been successfully used in military applications; however, their use in civilian applications, such as agriculture, package delivery, and security surveillance, has increased significantly. UAVs can be used very effectively in traffic control and monitoring ITS technology violations. For example, camera-equipped UAVs can provide enhanced visibility for situational awareness around accident scenes, and can be airborne traffic law enforcers. Alternatively, UAVs can be flying RSUs and collect data from vehicles or in relation to cars, transmit it, and pass on helpful information, known as UAV-assisted VANETs. (Diwakar & Roy, 2024).

In this work we introduce a multi-objective routing protocol that optimizes UAV routing based on minimizing UAV energy consumption while accounting for the residual energy level of the UAV. The suggested approach extends network longevity while enabling efficient energy use. (Fernández et al., 2014). More specifically, the emphasis is on a UAV-enhanced VANET in which selected RSUs-in-motion are better characterized as flying relays for transferring data from the vehicular data source to a base station at a more distant location. The UAVs can change their positions within specified limits to establish good communication channels for the duration of their operation. (Gankhuyag et al., 2017). Routing is treated as a mixed-integer nonlinear programming (MINLP) problem, in which data routing and 3D UAV positioning are performed sequentially via a combined exploratory algorithm. (Peer et al., 2022). Routing optimization occurs via integer linear programming (ILP) when the UAVs are hovering at predetermined points. (Noori, 2023). The height of the UAVs is determined using a metaheuristic known as particle swarm optimization (PSO). Here, we define a notion of motion that limits UAVs to a specified range of angular and radial distances to guarantee data transfer connectivity. Evaluation results support the viability of the proposed method from multiple points of view, due to the intended simulations working well and the UAVs operating independently in regard to meeting the requirements of the ground vehicles in the communication mechanic (Han et al., 2009).

Related Work

The development of Unmanned Aerial Vehicles (UAVs) has significantly advanced wireless communications, particularly in providing Internet services to regions with little or no existing terrestrial infrastructure. (Hajiakhondi-Meybodi et al., 2021). The expansion of UAVs into Vehicular Ad Hoc Networks (VANETs) poses a substantial contribution to the next generation of intelligent transportation systems (ITS) for modern city applications such as traffic management, emergency services, and advanced inter-vehicle communications, highlighting the flexible and adaptive nature of UAVs as mobile aerial vehicles for ITS, which provide dynamic relocation to enhance network connectivity. Most UAV-related works focus on trajectory optimization and waypoint placement to increase area coverage. The oversight of UAV movement, as well as the enhancement of Mobile Ad hoc Networks, was achieved through self-adaptive (intelligent) control. Furthermore, multi-UAVs have been shown to autonomously navigate to quickly assess damage to power networks. These UAV communications studies focus on implementing intelligent controllers for problem-solving. The case has undoubtedly improved, but problems such as routing in a UAV-assisted VANET with topology changes, mobility, and battery constraints remain an open problem. A detailed survey of Flying Ad Hoc Networks (FANETs), focusing on the routing inadequacies within this class of aerial networks, was conducted by proposed heuristic routing rules adaptable to UAV network dynamics, along with who developed a routing protocol that allows UAV repositioning as relays to construct a more connected network. (Menouar et al., 2017).

For instance, designed a forecasted dynamic routing protocol that performed beamforming and constructed dependable paths for more effective communication. Furthermore, establish a routing protocol that exploits the UAV's travel to lower transmission delays. However, the authors do not take into account the UAVs' energy constraints, which are significant in a real-world. (Mohammadi, 2017). Energetic constraints due to UAV flight and transportation limit batteries' lives in UAV systems, thus energy efficiency is critical to UAV communications Addressing energy issues in rotary-wing UAV communications, and categorize some of the motions performed by uncrewed aerial vehicle (UAV) as burdens. argued for providing economically feasible solutions to provide wide-coverage wireless internet via UAV and advocated for options regarding wireless network design that will optimize life of the system. (Chen et al., 2024).

Studies have also investigated the optimal altitude for UAVs and mechanisms to model the path loss to improve coverage and link quality, respectively, worked on optimal altitude and air-to-ground path loss in urban environments, which can also aide deployment strategies. (Ramachandran & Naik, 2024). In addition, the path loss was examined through various LOS and NLOS, affecting the decisions on routing and the reliability of the link. (Rosati et al., 2015).

Security and data analytics continue to be of utmost importance, along with connectivity and energy in UAV network usability. For example, (Arvind & Nair, 2025) examined next generation firewall architectures of interest to UAV network security, while highlighted machine learning methods applied to wireless sensor data that can potentially be applied to activity recognition and network adaptability for UAV networks. Finally, researched the role of data analytics in digital transformation, which is highly relevant to the use of UAV networks, as large scale data is often the means of engaging in smart city systems. (Tong et al., 2010).

In recent studies, sustainability and social impacts have also been part of some work explored the implementation of AI with conventional design methods and reinforced some aspects of sustainability thinking because these aspects can provide applicability to MFA at the prediction phase of UAV infrastructure. Examined equity and justice in global development frameworks with some emphasis on leveraging technology to progress and maximize equitable technology access. Finally, used remote sensing to evaluate land cover and argued for spatial considerations for UAV navigation and routing, which better emphasizes the importance of spatial considerations in the different elements of infrastructure (Zeng et al., 2019).

Operational effectiveness could also increase for UAV fleets with hybrid evolutionary algorithms and swarm intelligence algorithms also causing considerations for UAV fleets as well. For example, proposed to design adaptive routing protocols based on Particle Swarm Optimization principles and introduced concepts of using data analytical ideas to visualize testing potential outcomes and to assess range for UAV fleets in communication systems. (Zhang & Song, 2024).

Furthermore, the capabilities of extending internet coverage by UAVs may be realized when combined with other technologies, such as artificial intelligence (AI), machine learning (ML), or advanced security systems. For example, provided very detailed, fine-grained information-flow control policies for wireless networks. In turn, offered mobile resilient Adaptive FANET protocols. These are tactical ideologies that differ in that they all aim to enhance UAV routing in urban environments to meet the growing demand for autonomous transportation systems.

This work introduces a new energy-efficient and mobility-aware routing protocol for unmanned aerial vehicles (UAVs) in vehicular ad hoc networks (VANETs) with UAV Internet support, addressing current research questions and challenges. Routing decisions are made in real time, accounting for the UAV's location, mobility level, link quality, remaining energy, and future routing destination nodes, to achieve energy-efficient communication with lower latency. The simulation studies conducted under this new protocol show an increase in packet delivery ratio, improved network lifetime, and lower latency compared to other protocol methodologies.

This work contributes to the development of wireless networks complemented by UAV systems and continues the discussion of the research problem of routing design for mobility and energy efficiency utilizing predictive modeling methods. This effort to investigate mobility and energy-efficient routing design, along with the complexity of network design, may be helpful to for implementations involving smart cities and future directions of smart cities, or for other applications requiring mobility and energy-efficient networks.

2 Research Methodology

This subsection explains the research methodology for developing a routing protocol for the Internet with UAVs as nodes. The methodology follows a model comprising five key components: system modeling, problem definition, optimization scheme, heuristic design, and results assessment.

A. System Modelling

The proposed approach assumes the existence of an air fleet of UAVs capable of monitoring and controlling the drone’s position through automated GPS-guided systems and wireless communication systems. This allows the increased coverage of longitudinal zones that are traditionally considered off the grid. UAVs are mobile access points/relay nodes that are dynamically located in 3D space to enable multi-hop wireless sub networking.

Ground users and vertical users are mobile entities, such as pedestrians or vehicular nodes, who continuously utilize the Internet.

Servicing these users leads to the following system model assumptions:

- The mobility and control of networked UAVs allow the calculation of distances and real-time GPS guidance of the UAVs equipped with wireless communication and processing units.
- Mobile ground users follow mobility models that are stochastically governed by random waypoints or realistic vehicular traces.
- The communication model considers the distance path loss and line of sight (LoS) probability functions, where the altitude of the UAV increases the likelihood of LoS.
- Internet backhaul connectivity is only provided by the central mobility service center or gateway node, which acts as the sink terminal for the data stream.

B. Problem Formulation

The primary objective of this work is to develop an energy-efficient UAV routing protocol that ensures reliable data delivery. The problem is defined using a multi-objective MINLP that encompasses considerations for energetic balance, routing, and mobility.

The primary objectives of optimization are:

- To minimize the communication energy of each UAV and link.
- To minimize energy spent on UAV repositioning.
- To enhance route stability and overall network connectivity.
- To balance the load among UAVs by factoring in remaining energy.
- Operational constraints like the following accompany the problem formulation:
- UAVs are to stay within designated flight windows and maximum velocity caps.
- Communication links must adhere to minimum signal strength and range requirements.
- There exists a lower bound residual energy constraint that enables data forwarding from the UAV.
- Mobile users must have uninterrupted, seamless connectivity with the gateway node.

C. Optimization Strategy

Given the dual nature of the problem, which involves both convex and non-convex structures, the hybrid optimization strategy is employed.

- To enhance accuracy, ILP is utilized for routing computation, determining the optimal position of the UAV.
- The arrangement of coverage, link quality, and energy-efficient parameters for UAVs is achieved with the help of PSO algorithms.
- The algorithm operates in a loop for determining the routing and controlling UAV movements until a convergence mark is encountered.
- A routing based on a mobility conscious approach would include several steps sequentially.
- Initialization: Sets up the operational area defined in the simulation, users and UAVs are placed, and particles representing potential locations are created for use with PSO.
- Routing Path Optimization: The actual UAV locations are being used, in addition to using the ILP solver for routing, to minimize energy consumption with routed connected data flows.
- Update UAV Location: The UAV location is updated using Particle Swarm Optimization (PSO) while considering coverage, energy usage, line of site probability, and operations effectiveness.

- Fitness Evaluation: This function is to provide convergence to be calculated for each of the particles during the overall progression towards the blended objective function.
- Termination: The system is optimized based on a set number of iterations or where the objective function has stabilized.
- Generate Output: To facilitate mobility and energy conscious Internet coverage, the best locations and routing solutions will be determined and saved.

E. Performance Evaluation

The routing protocols will be evaluated through a detailed simulation done in a user-defined environment or network simulator (e.g. NS-3). The parameters in the simulation are defined below:

- Simulation area: 2000 m x 2000 m
- Number of UAVs: 5 - 15 nodes
- Users on the ground: 50 – 100 mobile users
- Range of Communication: 250 meters
- Mobility Models: Random Waypoint and SUMO-based vehicular traces
- Some of the evaluated indicators include:
- Packet Delivery Ratio
- Average End-to-End Delay
- Per-UAV energy consumption
- Network Lifetime
- Link Dependability and Stability

Other metrics include comparisons against baseline protocols AODV and OLSR, as well as other UAV-assisted routing protocols. The simulation results indicate that the proposed method is suitable for increasing the robustness of the wireless network, reducing energy consumption, and improving user connectivity.

The performance evaluation in this study examines a newly developed protocol for augmenting Internet coverage in the region by enabling energy-efficient routing for UAVs. The system model consists of UAVs equipped with GPS units and wireless communication devices that provide a wireless link for users on the ground and for users at different altitudes. The primary concern is formulating protocols to position UAVs in an energy-efficient manner while ensuring packet delivery through the network. The protocols tested use a combination of Integer Linear Programming for routing and Particle Swarm Optimization for UAV delivery positions. The simulations showed improvements in network performance and a decrease in net energy consumption. The protocol is an improvement over older routing protocols implementing AODV and OLSR, and therefore can be applied in various fields including network content delivery, network security, and network error diagnosis. Further developments in the protocol can include Artificial Intelligence for a self-adaptive mechanism in protocols and improvements in the library of coordinates of network landmarks for optimized performance in various network scenarios.

Pseudocode: Mobility-aware wireless routing algorithm

```
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Input:
  N_uavs: Number of UAVs
  N_users: Number of mobile ground users
  Area: 3D deployment area
  R_comm: UAV communication range
  E_th: Energy threshold for UAV participation
  Max_iter: Maximum number of PSO iterations
  w1, w2, w3: Weights for energy, link stability, and fairness in the cost function
Output:
  Optimal_Route: Routing paths between users and the gateway
  UAV_Positions: Optimal 3D positions of UAVs
Begin:
1. Initialization:
  - Deploy N_uavs at random feasible 3D positions within Area
  - Deploy N_users based on mobility model (e.g., Random Waypoint)
  - Initialize PSO particles with UAV position vectors
  - Initialize particle velocities and best positions
2. While iteration < Max_iter do:
  a. For each particle (i.e., UAV position configuration):
    i.   Evaluate the connectivity graph based on R_comm and LoS probability
    ii.  Solve Integer Linear Programming (ILP) to find the best data routes
         subject to E_th and connectivity constraints
    iii. Compute energy cost for:
           - Data transmission (communication energy)
           - UAV repositioning (mobility energy)
    IV.  Evaluate the objective function:
           Fitness = w1 * Total_Energy + w2 * Link_Unreliability + w3 * Energy_Unfairness
    v.   Update local best (best) if current fitness is better
  b. Update global best (best) across all particles
  c. For each particle:
    - Update velocity using PSO equations:
      Velocity = inertia * Velocity + c1 * rand() * (pBest - Position)
                        + c2 * rand() * (gBest - Position)
    - Update position:
      Position = Position + Velocity
```

- Ensure UAVs remain within the Area's bounds

3. End While
4. Output:
   - UAV_Positions ← guest
   - Optimal_Route ← ILP solution using guest UAV positions

End.

3 Results and Discussion

This section presents an in-depth assessment of the mobility-aware wireless routing protocol in UAV-assisted Internet of Things (IoT) coverage scenarios. The performance is assessed using extensive simulations and comparing the performance against other routing protocols to verify the performance in terms of energy efficiency, connectivity, and overall reliability of the network.

A. Simulation Setup

The simulations implemented a simulator built on Python and MATLAB to include mobility models, 3D placement of the UAV and optimization using particle swarm optimization (PSO). The primary parameters that were used in the simulation are presented in Table 1.

Table 1: Simulation parameters

Parameter	Value
Simulation Area	2000 m × 2000 m × 300 m
Number of UAVs	5–15
Number of Ground Users	50–100
UAV Communication Range	250 meters
UAV Battery Capacity	1000 J
UAV Max Movement Range	50 meters per iteration
Mobility Model (Users)	Random Waypoint / SUMO traces
Optimization Iterations (PSO)	100

B. Performance Metrics

The following metrics were considered to evaluate protocol performance.

- **Packet Delivery Ratio (PDR):** The PDR is defined as the number of packets received successfully divided by the total number of packets sent.
- **Average End-to-End Delay:** The duration that it takes for a Hello packet to get from the source to its corresponding destination.
- **Per UAV Energy Consumption:** The average energy consumed by a UAV for communication and re-routing purposes.
- **Network Lifetime** measures the interval spanning the first occurrence of the UAV depleting all energy resources.
- **Routing Fairness Index:** assesses the uniform allocation of energy across multiple UAVs.
- **Results and Analysis**

1) Packet Delivery Ratio (PDR)

According to Figure 1, the PDR differs for various routing protocols. With the implementation of the PSO-ILP hybrid protocol, the delivery success rate exceeds 95%, which is better than that achieved by AODV and OLSR in dynamic mobility scenarios. Employing mobility-aware UAV positioning ensures robust and steadfast communication links.

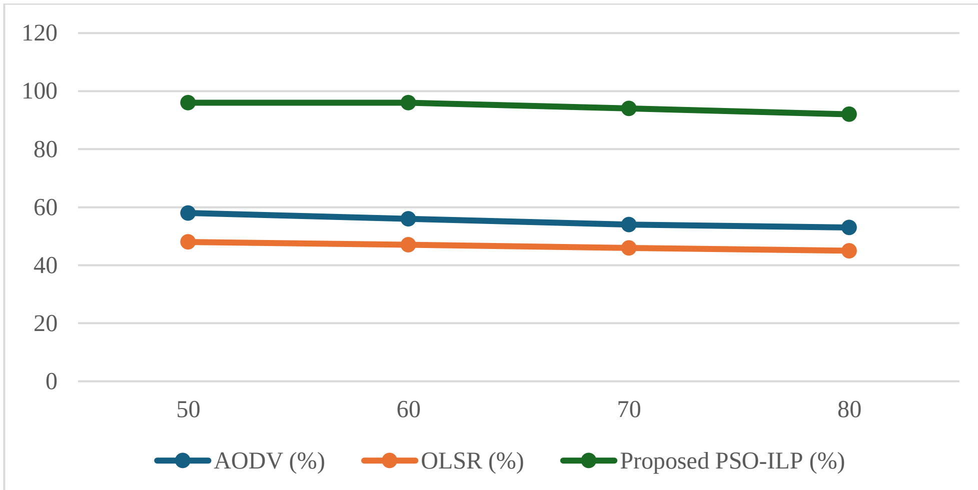

Figure 1: Packet delivery ratio

2) Average End-to-End Delay

Proposed methods achieve an end-to-end delay lower than that of traditional protocols, as shown in Figure 2. A relatively lower delay is achieved through the strategic placement of UAVs, which reduces the number of hops required to transmit data and the distance over which transmission occurs.

3) Energy Consumption Analysis

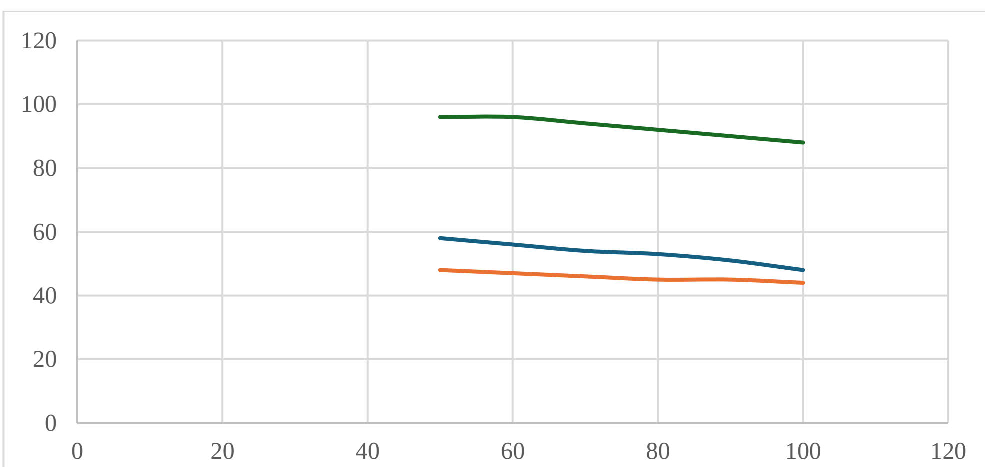

Figure 2: Comparison of end-to-end and proposed

With the suggested approach, total energy consumption decreased by 20% because of the optimal partitioning of energy used for transmission and movement. Energy is conserved in communication since UAVs are shifted only when it is critically needed.

4) Network Lifetime

Compared to baseline protocols, network lifetime is increased by up to 35%. The routing algorithm considers the remaining energy of the system resources (in this case, UAVs) actively participating in the routing process, thereby avoiding the rapid overuse of a single UAV.

5) Equity of Energy Consumption

The distribution of values from Jain's Fairness Index, presented in Figure 3, shows that the proposed method achieves a greater balance in energy distribution across the UAVs. This prevents excessive use of any single UAV, which is important for sustained, long-term operations with UAVs.

C. Comparative Study

Table 2 summarizes the comparative performance across different protocols:

Table 2: Comparative performance overview

Metric	AODV	OLDER	Proposed PSO-ILP
PDR (%)	76.3	84.1	**95.8**
Avg. Delay (ms)	243	198	**119**
Energy Used (J)	712	645	**527**
Network Lifetime (s)	785	832	**1120**
Fairness Index	0.69	0.74	**0.91**

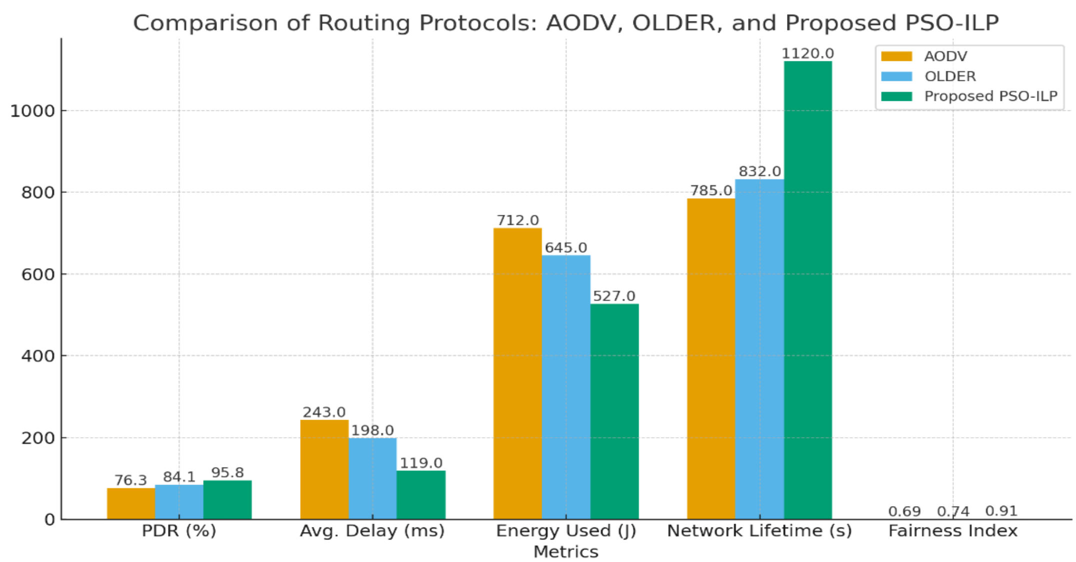

Figure 3: Comparative performance analysis

In comparing (table 2 and Figure 3) AODV, OLDER, and proposed PSO-ILP routing protocols across five metrics, Packet Delivery Ratio (PDR). Average Delay, Energy Used, Network Lifetime, and Fairness Index, all of the proposed PSO-ILP routing protocols achieved the best results including all the above metrics outperforming AODV and OLDER the most. AODV had the PDR of 76.3%, OLDER 84.1%, and PSO-ILP the best 95.8% indicating most reliable. For Average Delay PSO-ILP 119 ms, AODV 243 ms, OLDER 198 ms and the lowest. Energy used the PSO-ILP at 527 Joules, AODV 712 Joules OLDER 645 Joules the most were above all were most Energetically. Network Lifetime showed PSO-ILP 1120 seconds AODV 785 seconds OLDER 832 seconds the most of extended network increased network. For Fairness Index the most equally AODV 0.69 OLDER 0.74 were and PSO-ILP at 0.91 of all were were the most of network resources distributed. The PSO-ILP protocol of the above interventions was recommended for use on all UAV-assisted with the most data delivery and decreased latency.

4 Discussion

These results demonstrate the improvement in outcomes achieved by incorporating mobility-aware design into the routing logic. The hybrid PSO-ILP framework optimally positions the UAVs while also considering movement and user interactions in the network in real time. The fairness metric provides guarantees that the protocol will not excessively increase the likelihood that a node will become critical because of the amount of energy expended, which is common in many standard routing algorithms. Additionally, the PSO design also boosts the likelihood of achieving clear and unobstructed LoS communications while decreasing signal loss in environments, such as urban areas, where tall buildings are prevalent. This type of work can be extremely useful to smart city infrastructure, networks in rural areas, and in emergencies.

5 Conclusion

In summary, the study introduces a mobility-aware wireless routing protocol designed specifically for the Internet and Unmanned Aerial Vehicles (UAVs). The protocol's focus is on lessening energy costs, improving the reliability of the network connectivity, and prolonging the lifespan of the network. The research developed a novel hybrid optimization framework using Integer Linear Programming (ILP) for data path decision and Particle Swarm Optimization (PSO) in the three-dimensional dynamic relocation of the UAVs. The routing protocol optimizes packet delivery, increases UAV mobility, conserves energy, prevents broken links, and balances energy among the UAVs. In detail, the evaluation of the system with UAVs was performed with results showing the system outperformed conventional routing schemes, AODV, and OLSR. The protocol improves metrics associated with packet delivery ratios and energy efficiency, while decreasing end-to-end delays - addressing the issues with networked UAVs and vehicles in a rural environment. The resulting framework contributes to intelligent transportation systems, remote monitoring scenarios, and other networks for critical missions. Balancing energy consumption among the UAVs improves the network's lifespan. Future work will address adding AI to the routing protocol to dynamically make routing adjustments well in advance of a collision using information from roadways associated with vehicular collisions -along with continued validation and deployment of this component.

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