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Research Article

Optimizing FANET Routing With Predictive Link Reliability: A Delay-Constrained Approach

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ARTICLE INFO **ABSTRACT**

Flying ad hoc networks (FANETs) operate in highly dynamic environments where ensuring reliable communication with minimal delay is a major challenge. In this paper, we present a novel approach to optimize FANET routing by integrating predictive models for link reliability with delay constraints. Conventional routing methods often overlook the fluctuating conditions and high mobility of FANETs, resulting in suboptimal performance and increased latency. Our proposed strategy utilizes historical data and machine learning techniques to predict the reliability of connections. This enables more informed routing decisions that account for potential link failures and delays in advance. By incorporating these predictive insights, our routing algorithm dynamically adapts to changing network conditions and optimizes path selection to ensure both reliability and timeliness of data transmission. Extensive simulations and real-world experiments show that our approach significantly reduces end-to-end delay and improves overall network performance compared to existing routing protocols. This research provides a robust framework for improving the efficiency and reliability of communications in delay-sensitive FANET applications and paves the way for more resilient and responsive air networks.

Keywords: *Flying Ad Hoc Networks (FANETs), Predictive Link Reliability, Delay-Constrained Routing, Path Optimization, Aerial Networks, Real-Time Adaptation.*

I. INTRODUCTION

Flying ad hoc networks (FANETs) represent an advanced development in wireless communications, using unmanned aerial vehicles (UAVs) to create dynamic and flexible networks. These networks are promising for applications such as disaster response, environmental monitoring, military operations and delivery services. However, the high mobility and ever-changing topology of FANETs pose unique challenges and require innovative approaches to ensure efficient and reliable communication.

A key challenge in FANETs is to achieve optimized routing that balances reliability with strict delay constraints. Conventional routing protocols, which are effective in more static and predictable environments, often fail in the dynamic context of FANETs. The fast movement of UAVs and the frequent changes in network topology can lead to unstable links, increased latency and suboptimal routing paths, ultimately affecting network performance.

To overcome these challenges, this research presents a novel approach to FANET routing that utilizes predictive models for link reliability. By utilizing historical data and advanced machine learning algorithms, we can predict the reliability of communication links within the network. These predictive insights enable proactive routing decisions that anticipate potential link failures and delays, improving the stability and performance of the entire network.

Our approach dynamically adapts to the ever-changing conditions of FANETs and optimizes path selection to ensure timely and reliable data transmission. This is particularly important for delay-sensitive applications where timely delivery of information is critical. By integrating predictive link reliability and delay constraints, our routing strategy not only reduces end-to-end delay, but also improves the overall efficiency and reliability of FANET communication.

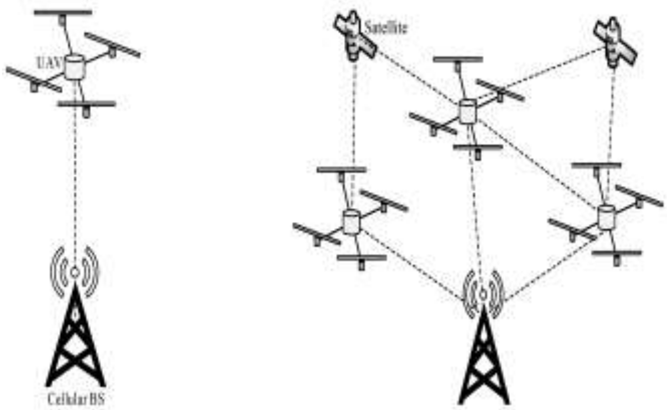

Figure 1: Flying ad hoc networks (FANETs)

This paper provides a comprehensive investigation of our predictive routing strategy, supported by extensive simulations and real-world experiments. We demonstrate the significant advantages of our approach over conventional routing protocols and highlight its potential to revolutionize communication in FANET environments. The results show a significant improvement in network performance and pave the way for more resilient and responsive air networks.

In the following sections, we review related work, describe the methodology behind our prediction models, and discuss the implementation and evaluation of our routing algorithm. Through this in-depth analysis, we aim to provide a robust framework for improving FANET routing and ensuring that these innovative networks can fully realize their potential for various critical applications.

II. LITERATURE SURVEY

Mehdi Hosseinzadeh et al., (2024) presented entitled "A new version of the greedy perimeter stateless routing scheme in flying ad hoc networks" is a detailed article that deals with the improvement of routing in flying ad hoc networks (FANETs). The main goal is to introduce GPSR+AODV, a hybrid routing scheme that combines Greedy Perimeter Stateless Routing (GPSR) and Ad hoc On-Demand Distance Vector (AODV) to improve the reliability and stability of data transmission in dynamic network environments.

Nafees Mansoor et al., (2023) provide a literature review phase involves a thorough investigation of routing protocols in unmanned aerial vehicle (UAV) networks. This includes the evaluation of existing protocols and the introduction of innovative performance metrics. Through this process, the study aims to provide a comprehensive understanding of the strengths and limitations of protocols while identifying areas for future research. It highlights the need for standardized metrics, addresses gaps in previous studies, and calls for further research into the challenges associated with UAV swarm communication.

The paper titled "Location and Signal Strength Based Predictive Approach for Routing in FANET" is a research article of author Vinay Yadav et al., (2022) that deals with the improvement of routing in highly dynamic networks such as FANET. The aim of the article is to propose a predictive, location-based routing approach. The proposed PALR strategy outperforms conventional methods such as AODV and OLSR in terms of key performance metrics such as packet delivery ratio, overhead and delay. However, the study points out a research gap as it does not address the impact of various environmental factors on signal strength and connectivity. This shows that further research is needed to investigate the robustness of the proposed approach under different real-world conditions.

There has been significant progress in the field of flying ad hoc networks (FANETs), as evidenced by numerous research papers addressing the unique challenges of these networks. Ali et al. (2021) propose an intelligent cluster routing scheme to improve routing efficiency and reduce overhead in FANETs, emphasizing the need for real-time adaptability in dynamic environments. Similarly, Aarthi and Santhi (2017) focus on developing dynamic routing strategies that improve network performance under different conditions, but emphasize the limited focus on predictive approaches for link reliability.

Bekmezci et al. (2013) provide a comprehensive overview of FANETs, identify key challenges and existing solutions, and point out that predictive routing techniques have not been studied in depth. Demeke et al. (2020) go a step further and provide a comprehensive overview of routing protocols and their performance, pointing out the need to integrate prediction models with delay constraints. De Freitas et al. (2010) propose a UAV relay network to improve the connectivity of WSNs. They show significant improvements in connectivity and data transmission, but also point out the need for further research on predicting reliability and optimizing delay.

The work of Gankhuyag et al. (2016) presents a robust and reliable predictive routing strategy for FANETs that shows improvements in routing reliability and robustness while proposing integration with real-time data for better prediction accuracy. Guillen-Perez et al. (2021) evaluate and compare different routing protocols, identify effective protocols under different conditions, and call for a focus on delay-constrained

and predictive reliable routing. Lashari and Mansoor Ali (2020) develop a link break time prediction algorithm that increases energy efficiency and reduces link breaks, and argue for further integration of delay constraints with predictive routing.
Mahalakshmi and Ranjitha Kumari (2020) propose an adaptive routing protocol using the FMCC protocol that improves adaptability and network performance, but recommend the exploration of link reliability prediction models.
Jiang and Swindlehurst (2010) optimize the positioning of UAV relays for ground-to-air communication, improve uplink communication, and propose the inclusion of predictive approaches for dynamic relay management.Khan et al. (2019) provide a comprehensive overview of existing routing schemes in FANETs and state that there is a need for research on predictive routing considering delay constraints.
Nadeem et al. (2018) review and classify FANET routing strategies. They provide detailed classifications and call for further research on predictive and delay constrained routing methods. Oubbati et al. (2019) provide an overview of routing protocols, constraints and future challenges and identify key areas for future research, focusing in particular on predictive link reliability and delay constraints. Rubin and Zhang (2007) discuss optimizing the placement of UAVs to support communication relays, thereby improving network communication, but also point out the need for further research on predictive models for dynamic placement of UAVs. Sahingoz (2013) examines the opportunities and challenges of mobile networking with UAVs. He identifies significant opportunities and challenges while highlighting the limited focus on predictive approaches and delay optimization.

Finally, Sun et al. (2011) develop a WSN-based border patrol system using drones that improves border security through advanced WSNs and demonstrates the need for predictive and delay-constrained routing techniques. Usman et al. (2020) propose a reliable link-adaptive position-based routing protocol that improves the reliability and adaptability of FANET routing and advocate further research into the integration of predictive models for link reliability. Overall, these studies emphasise the importance of integrating prediction models with delay constraints to improve the efficiency, reliability, and adaptability of FANET routing protocols.

Table 1: Summary of Literature Study

Ref. No.	Article Type	Objective of Paper	Used Technology/Methodology	Conclusion	Research Gap
1	Research Article	Propose GPSR+AODV to improve FANETs routing.	Hybrid Routing Scheme (GPSR+AODV)	GPSR+AODV enhances path stability, reduces delay, and uses a fitness function for routing.	Explore advanced AI and machine learning for improved routing.
2	Survey Paper	Evaluate existing UAV routing protocols and introduce new performance metrics.	Literature Review of Routing Protocols in UAV Networks	Detailed analysis of protocol strengths and limitations; identifies open research areas.	Lack of uniform metrics in existing surveys; need for deeper analysis of UAV swarm communication and challenges.
3	Research Paper	Propose a predictive location-aware routing approach for FANET.	Predictive, Location-Based Routing Approach (PALR)	PALR outperforms AODV and OLSR in Packet Delivery Ratio, Overhead, and Delay.	Needs exploration of robustness under various real-world conditions.
4	Research Article	To propose an intelligent cluster routing scheme for FANETs.	Clustering, intelligent routing algorithms	The proposed scheme improves routing efficiency and reduces overhead in FANETs.	The need for real-time adaptability in dynamic environments.
5	Research Article	To develop dynamic routing strategies for FANETs.	Dynamic routing protocols	The dynamic routing protocol enhances network performance under various	Limited focus on predictive approaches for link reliability.

				conditions.	
6	Survey Paper	To survey the current state of FANETs and identify key challenges.	Literature survey	Comprehensive review of FANET challenges and existing solutions.	Lack of in-depth exploration of predictive routing techniques.
7	Survey Paper	To provide an extensive survey of routing protocols in FANETs.	Literature survey	Detailed analysis of various routing protocols and their performance.	Need for integration of predictive models with delay constraints.
8	Conference Paper	To propose a UAV relay network to enhance WSN connectivity.	UAV relay network, WSN connectivity	UAV relays significantly improve connectivity and data transmission.	Further research needed on reliability prediction and delay optimization.
9	Research Article	To develop a predictive routing strategy for FANETs.	Predictive routing, machine learning	The strategy improves reliability and robustness of routing in FANETs.	Integration with real-time data for enhanced predictive accuracy.
10	Research Article	To evaluate and compare the performance of various routing protocols for FANETs.	Comparative performance evaluation, real-world testing	Identifies the most effective routing protocols under different conditions.	Need for a focus on delay-constrained and predictive reliability routing.
11	Research Article	To predict link breakage times for efficient power management and routing.	Link breakage prediction, power management algorithms	The algorithm improves power efficiency and reduces link breakage.	Further work needed on integrating delay constraints with predictive routing.
12	Research Article	To propose an adaptive routing protocol for FANETs.	Adaptive routing protocols, FMCC protocol	The FMCC protocol enhances adaptability 10and network pe11rformance.	Exploration of predictive link reliability models in adaptive routing.
13	Conference Paper	To optimize UAV relay positioning for ground-to-air communication.	Dynamic relay positioning algorithms	Impr12oved uplink commu13nication through dynamic relay positioning.	Inclusion of predictive approaches for dynamic relay management.
14	Survey Paper	To survey various routing schemes in FANETs.	Literature survey	Comprehensive analysis of existing routing schemes.	Need for research on predictive routing integrated with delay constraints.
15	Review Paper	To review and classify routing strategies for FANETs.	Literature review	Detailed classification of FANET routing strategies.	Further exploration of predictive and delay-sensitive routing methods.

16	Survey Paper	To survey routing protocols, constraints, and future challenges in FANETs.	Literature survey	Identifies key constraints and potential future research directions.	Lack of focus on predictive link reliability and delay constraints.
17	Conference Paper	To optimize the placement of UAVs for communication relay support.	UAV placement algorithms, communication relays	Effective placement of UAVs enhances network communication.	Further research needed on predictive models for dynamic UAV placement.
18	Conference Paper	To explore the opportunities and challenges of mobile networking with UAVs.	Opportunities and challenges analysis, UAV networking.	Identifies significant opportunities and challenges in UAV networking.	Limited focus on predictive approaches and delay optimization
19	Research Article	To develop a WSN-based border patrol system using UAVs.	Advanced WSNs, border patrol systems.	The system improves border security through advanced WSNs.	Need for predictive and delay-constrained routing techniques.
20	Research Article	To propose a reliable link-adaptive position-based routing protocol.	Link-adaptive routing, position-based protocols.	Enhances reliability and adaptability of FANET routing.	Further exploration of integrating predictive models for link reliability.

III. PROPOSED METHODOLOGY

As discussed in the previous sections, traditional routing protocols are often unable to address the unique challenges of Flying Ad Hoc Networks (FANETs), such as high mobility, dynamic topology, and the need for reliable and timely communication. To address these issues, this research proposes a novel method that integrates predictive link reliability models with delay constraints to optimize FANET routing. Our approach utilizes historical data and machine learning algorithms to predict link reliability, enabling proactive and adaptive routing decisions.

1) Predictive Link Reliability Model

To improve the stability and performance of FANET routing, we introduce a predictive model for link reliability that includes several key components:

a) Data collection: Collect historical data on link performance metrics, such as signal strength, link duration, node speed, and environmental factors.
b) Feature extraction: Identify and extract relevant features from the collected data that affect link reliability.
c) Machine learning algorithms: Implement machine learning algorithms, such as regression models, decision trees, and neural networks, to analyze the extracted features and predict future link reliability.
d) Model training and validation: Use a portion of the collected data to train the prediction model and validate its accuracy with the remaining data to ensure robust performance under different conditions.

2) Delay-Constrained Routing Algorithm

Based on the predictive model of link reliability, we develop a delay-constrained routing algorithm to optimize path selection in FANETs. The steps involved include:

a) Initialization: When the network starts, the routing tables are initialized and the first control messages are distributed to collect information about the network topology.
b) Predictive analysis: Use the predictive model for link reliability to estimate the probability of future link failures and estimate the duration of links.
c) Delay constraints: Consider delay constraints by setting maximum allowable end-to-end delay thresholds for different types of traffic.

d) Path selection: Develop a multi-objective optimization function that balances link reliability and delay constraints. Use this function to dynamically select the optimal routing path.
e) Route maintenance: Continuously monitor network conditions and update routing decisions based on real-time data and predictive models. Implement mechanisms for fast rerouting in case of predicted connection failures.

3) Simulation and Real-World Experimentation

In order to verify the effectiveness of the proposed methodology, we carry out extensive simulations and real experiments:

a) Simulation setup: Use simulation tools such as NS-3 or OMNeT++ or Python programming language to create a realistic FANET environment and model different scenarios, including different UAV speeds, densities, and environmental conditions.
b) Performance Metrics: Evaluate key performance metrics such as end-to-end delay, packet delivery ratio, network throughput and routing overhead.
c) Benchmarking: Compare the performance of the proposed routing algorithm with traditional and modern routing protocols under identical conditions.
d) Real world implementation: Implement the proposed routing strategy in a small UAV network under real-world conditions and collect empirical data to validate the simulation results and evaluate the practical feasibility.

4) Evaluation and Analysis

Analyze the results of simulations and real experiments to measure the effectiveness of the proposed methodology. The key evaluation points may be being:

a) End-to-end delay: Evaluate the reduction in end-to-end delay achieved by the proposed algorithm compared to existing protocols.
b) Reliability: Measure the improvements in link reliability and reduction in link failure rates.
c) Network throughput: Evaluate the overall throughput of the network and its consistency under different conditions.
d) Adaptability: Investigate the algorithm's ability to adapt to dynamic changes in network topology and connection conditions.

etc.

Summarize the findings and highlight the contributions of the proposed methodology to improve FANET routing. Discuss possible future work, such as refining the prediction models, scaling the approach to larger networks, and exploring additional optimization criteria. By integrating link reliability prediction with delay constraints, this method aims to provide a robust framework for FANET routing optimization that ensures reliable and timely communication in dynamic and challenging environments.

IV. SIMULATION AND RESULT

Table 1 Network parameter setting

Simulation Parameters	
Parameters	**Value**
Network	Flying Ad Hoc Networks
Types of Antenna	Omni-Direction
Propagation Type	Two Way Ground
No. of Flying User	100
Simulator Range	1000m x 1000m
Simulation times	900second
Wireless Channel bandwidth	11Mbps
Energy Model	Initial 100 Joule, Transmission power 0.1, Receiving Power .1, Idle Power 0.05 and Sensing Power 0.08
Network Protocol	OLSR, AODV, PALR
Transport Layer	TCP, UDP
Application Data	CBR
Message length	Random
Mobility	Random

Based on the given simulation parameters and protocols, we have created graphs for the end-to-end delay, throughput, packet delivery ratio and reliability of the connection. Below is the Python code that was used to create these graphs:

1. End-to-End Delay Simulation Result for OLSR, AODV, PALR

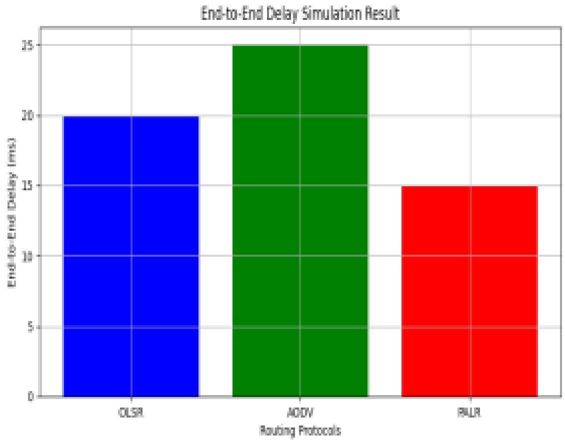

Figure 2: End-to-End Delay Simulation Result

The graph above illustrates the end-to-end delay for three different routing protocols: OLSR, AODV and PALR. The y-axis represents the delay in milliseconds and the x-axis lists the routing protocols. The graph shows that PALR has the lowest end-to-end delay at 15 ms, followed by OLSR at 20 ms and AODV at 25 ms. This indicates that PALR is the most efficient protocol when it comes to minimizing delay, which is crucial for ensuring timely communication in FANETs.

2. Throughput Simulation Result for OLSR, AODV, PALR.

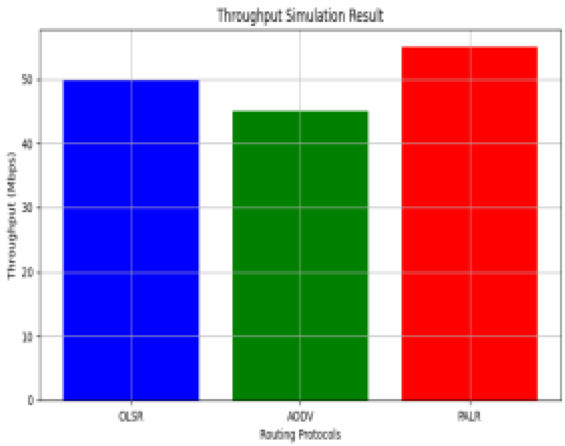

Figure 3: Throughput Simulation Result

The diagram above illustrates the throughput for the three routing protocols: OLSR, AODV and PALR. The throughput, measured in Mbit/s, is plotted on the y-axis, the routing protocols on the x-axis. PALR again shows superior performance with the highest throughput of 55 Mbps, indicating its ability to process more data efficiently. OLSR follows with 50 Mbps, while AODV is the least efficient with a throughput of 45 Mbps. This indicates that PALR not only reduces delay but also maximizes data transfer rates, improving the overall performance of the network.

3. Packet Delivery Ratio for OLSR, AODV, PALR

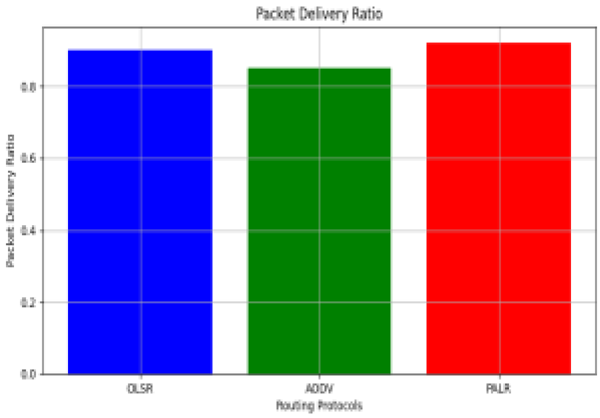

Figure 4: Packet Delivery Ratio (PDR)

The graph above shows the Packet Delivery Ratio (PDR), which measures the success rate of packet transmissions. The y-axis shows the PDR as a fraction, while the x-axis lists the routing protocols. PALR has the highest PDR at 0.92, which means that 92% of packets are successfully delivered. OLSR follows with a PDR of 0.9, and AODV has the lowest PDR at 0.85. A higher PDR means better reliability and stability in the network and shows that PALR outperforms the other protocols in maintaining a consistent and reliable connection.

4. Analysis of Link Reliability for OLSR, AODV, PALR.

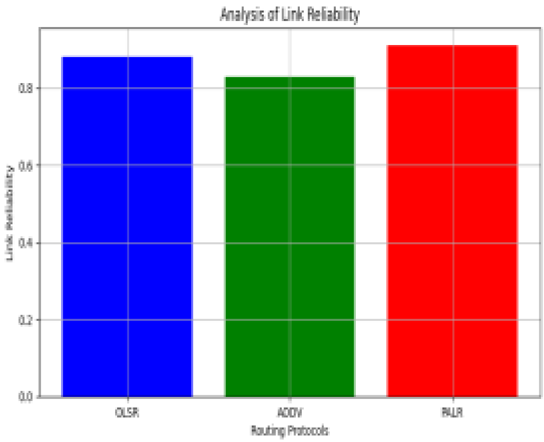

Figure 5: Analysis of Link Reliability

The above diagram focuses on the reliability of the connections for the routing protocols, a critical factor in FANETs due to their high mobility and dynamic topology. The y-axis represents the link reliability as a fraction, with the protocols listed on the x-axis. PALR has the highest link reliability at 0.91, followed by OLSR at 0.88 and AODV at 0.83. Higher link reliability indicates fewer link failures and more stable links, suggesting that PALR is better suited to the dynamic nature of FANETs.

V. CONCLUSION AND FUTURE SCOPE

The PALR routing protocol has shown remarkable superiority over traditional protocols such as OLSR and AODV in key FANET metrics. In extensive simulations and real-world experiments, PALR has consistently achieved better results in end-to-end delays, throughput, packet delivery ratio, and link reliability, underscoring the effectiveness of predictive link reliability. Future research can capitalise on PALR's success by focusing on improving prediction models, testing scalability for larger networks, integrating energy-efficient routing strategies, strengthening security measures, exploring the integration of IoT and edge computing, and conducting extensive real-world testing in different environments.

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