International Journal of Computer Networks and Applications (IJCNA)
DOI: 10.22247/ijcna/2024/23 Volume 11, Issue 3, May – June (2024)

RESEARCH ARTICLE

Multiple Route Selection for Avoiding Single Point Failure in Flying Ad Hoc Network (FANET)

H. Shaleena
Department of Computer Science, Kongunadu Arts and Science College, Coimbatore, Tamil Nadu, India.
✉ shaleena280385@gmail.com

K. Sumangala
Department of Computer Applications, Kongunadu Arts and Science College, Coimbatore, Tamil Nadu, India.
sumangalak_ca@kongunaducollege.ac.in

Received: 07 March 2024 / Revised: 28 May 2024 / Accepted: 04 June 2024 / Published: 30 June 2024

Abstract – In Flying Ad Hoc Network (FANET), routing is a major challenging task due to dynamic network topology and inadequate resources. This can be resolved by designing reliable Routing Protocols (RPs) that assist in boosting the network's Quality-of-Service (QoS) performance. Among many RPs, an Energy-aware and Predictive Fuzzy Logic with Consistent Link-based Copy adaptive Transmit-based RP (EPFL-CLCT-RP) has achieved high data transmission reliability and low energy utilization by limiting the redundant transmission of data duplicates over the network. However, in the case of multipath routing, there can be high delay and routing overhead when choosing an alternate route in case of link failure in the primary optimal path. Therefore, a novel Multipath EPFL-CLCT-RP (MEPFL-CLCT-RP) is proposed in this article to transfer data in multi-hop FANETs. The key goal is to reduce routing overhead and delay in multi-hop FANETs. First, the Fuzzy Logic (FL) system is used to choose multiple paths from the source to destination nodes based on near-optimal solutions for data transmission. Then, a new routing metric is determined for all available routes in the multi-path set according to the link survival probability, and the path with the highest link survival probability is elected as a backup path. During link failures, if the source node cannot create a valid alternate path by considering its nearby nodes, then the selected backup path is used for data transmission. If the source node can create a new valid reliable path, then it transmits the data duplicates through the newly created path using the CLCT method. Moreover, extensive simulations demonstrate that the MEPFL-CLCT-RP significantly reduces routing overhead and delay compared to traditional RPs in FANETs.

Index Terms – FANET, Routing Protocol, EPFL-CLCT, Multipath Routing, Multi-Cast, Link Failure, Link Survival Probability.

1. INTRODUCTION

Unmanned Aerial Vehicles (UAVs), or drones, have gained popularity due to advanced technology like Wireless Fidelity (Wi-Fi), Global Positioning System (GPS), sensors, and microelectronics. They can be controlled remotely or flown autonomously based on predetermined flight paths and are used in surveillance systems, private sectors, vehicle tracking, aerial imagery, fire observation, disaster recovery, crop administration, armed forces, and network security [1-2]. In FANETs, UAVs are mobile and move freely within the coverage area, which is becoming more prevalent. FANETs, a multi-hop wireless network, aim to improve radio coverage, boost capacity, and enable system auto-settings without a core. UAVs can be directed distantly by a Base Station (BS) control system or driven autonomously by an anchored regulation [3]. FANET supports single and multiple UAV systems. A single UAV system consists of more UAVs linked to a BS and satellites, requiring advanced hardware. A multi-UAV system includes several UAVs and a satellite, which improves longevity, dependability, workload, and heterogeneity. Multi-UAV networks are flexible since tasks can be completed with residual UAVs even if one fails, and their radius can be easily expanded by incorporating additional UAVs [4]. FANETs use five communication strategies: UAV-to-BS (UAV/BS), BS-to-BS (BS/BS), UAV-to-UAV (UAV/UAV), UAV-to-Satellite (UAV/S), and UAV-to-sensor (UAV/X). These strategies allow UAVs to transmit data like video streams or visuals to a BS. Ad hoc UAV/UAV interactions help reach equilibrium and disseminate data. UAV/S allows connections between UAVs and satellites at great distances, and sensor or mobile node data is also collected via the UAV/X link [5].

Nonetheless, FANETs, consisting of high mobility and dynamic topology among UAVs, face issues like unstable transmission paths and insufficient network resources [6]. To address these, UAVs must share data over RPs. Traditional ad hoc network RPs are impractical in FANETs due to their 3D movement, dynamic topology, finite number of UAVs, high mobility, frequent path failures, network partition, and resource limits. QoS requirements vary among FANET users, with some applications allowing delays, while others require near-instantaneous data dissemination for security and failure management [7]. Numerous studies were presented to create RPs based on the structure and peculiarities of FANETs, either as novel RPs or refined versions of conventional ad hoc RPs. The optimal path for connecting two UAVs in FANETs is crucial, and factors such as efficient use of network resources, energy savings, absence of routes, restoration abilities, and mobility must be considered [8]. RPs in FANETs would achieve minimum overhead, great dependability, minimum packet drop, manageable latency, and sufficient stability. However, achieving all goals in an RP can be challenging.

To address this issue, Lee et al. [9] created an EPFL-based RP for FANET that includes path discovery and path maintenance stages. To minimize network storms and handle control packet transmission, a method such as Route Request (RREQ) and Route Reply (RREP) was initially employed to find the score of all UAVs. This score was calculated using a variety of factors like mobility direction, remaining energy, path efficiency, and node stability. The FL was also used to select pathways with the highest fitness. The path failure was then stopped to identify and alter routes at the failure threshold, and the failed paths were replicated to swiftly substitute such paths. In contrast, data forwarding was hampered by shaky transmission links and limited resources. To address this issue, an opportunistic transmission was used as data transfer, in which the UAV can store the data if it does not reach the proper forwarding UAV and only transmit if it reaches the proper relay UAV while moving. However, sending extra data copies to incorrectly transmitting UAVs can deplete energy and weaken the Packet Delivery Ratio (PDR). As a result, adaptive copy routing is critical to dealing with UAVs' high mobility and FANETs' dynamic topology.

As a result, an EPFL-CLCT-RP [10] has been presented to achieve data transmission in FANETs. In this protocol, the data collected from each neighboring UAV was used to determine the real-time fluctuations of network connectivity. The CLCT mechanism was then adopted, which uses previous data and the transitivity of UAV interactions to select suitable relay UAVs. Also, the Transmit Prediction Value (TPV) was computed as a criterion for reducing the transmission of many data packet replicas during the data transmission activity.

1.1. Problem Statement

The EPFL-CLCT-RP protocol experienced high routing overhead and delays when link failures occurred in multipath routing due to the need to maintain multiple routes, leading to increased control message exchanges. Additionally, the protocol faced challenges in long-range FANETs with multiple hops between nodes, increasing the risk of failures and complicating route stability. In such scenarios, the likelihood of link failures rose, further impacting routing efficiency and network reliability. These factors collectively degraded network performance in managing the dynamic and extended FANET topology.

1.2. Major Contributions of the Manuscript

This manuscript develops a new Multipath EPFL-CLCT-RP (MEPFL-CLCT-RP) for data transmission in multi-hop FANETs. The key contributions of this study include:

- First, the FL system chooses multiple near-optimal routes between the source and destination nodes.
- Then, the RREQ and RREP messages are transmitted via multiple paths based on the multicast strategy. Also, the link survival probability is calculated as a routing metric for each path available in the multi-route set, and the path with the maximum probability of link survival is chosen as the backup path.
- If a link failure occurs and the source node cannot create a valid stable path using its neighboring nodes, then the source node can use a backup path for data transfer. Otherwise, the source node can create a valid path and transmit copied packets based on the CLCT method.
- According to this protocol, the routing overhead and delay can be reduced by alleviating the complexity of creating a new valid path when a link breaks during transmission.

The remaining sections are planned as follows: Section 2 covers the related works. Section 3 explains the MEPFL-CLCT-RP protocol and Section 4 verifies its effectiveness against existing ones. Section 5 abridges the findings and suggests further improvements.

2. LITERATURE SURVEY

This section reviews some of the recent RPs developed for FANETs in detail. Abdel-Malek et al. [11] presented a multi-hop multipath source routing method for UAVs to enhance link connectivity by optimally positioning many UAVs and allowing several parallel routes at the top layers. This provided alternate routes when a link failure occurs. The optimization dilemma was modeled to reduce End-To-End Delay (E2D) with a limited quantity of UAVs, and the delay analysis was executed for the received queues to determine the E2D. However, the routing overhead was high due to redundant transfers based on multipath parallel transmission. Bhardwaj & Kaur [12] presented a Secure Energy-Efficient Dynamic RP (SEEDRP) to achieve secure data transfer. Initially, a new dynamic routing scheme has been utilized to obtain a cost-effective path from the source to the destination nodes. Then, a new dynamic key generation method was used to secure the forwarded data. However, its efficiency in handling link failures was poor when increasing the number of nodes. Namdev et al. [13] developed the whale optimization-based Optimized Link State Routing (OLSR) protocol to obtain optimal routing according to the neighborhood, power, stability period, and usage of UAVs. However, it needs more objective parameters to choose the best route when link failure exists.

Mansour et al. [14] presented a Cross-Layer and Energy-Aware Ad-hoc On-demand Distance Vector (CLEA-AODV) RP to enhance FANET longevity. This protocol has three major stages: routing with AODV protocol, cluster head selection based on Glow Swarm Optimization (GSO), and cooperative Medium Access Control (MAC). However, the path was chosen only depending on the remaining power and hop count. The path survivability was not considered, which impacts data transmission when the path fails. Khan et al. [15] presented an Ant Colony Optimization (ACO) scheme named Ant-Hocnet using the optimized FL to enhance FANET routing. In this algorithm, FL was utilized to examine the data regarding the link condition, including available bandwidth, node mobility, and link quality. Then, the Ant-Hocnet was used to choose the optimal routing path according to the link status for data transfer. However, it was not effective in avoiding link or path failures, which led to degrading network throughput and dissipating more energy.

An Intelligent Clustering Routing Approach (ICRA) was developed [16] for UAVs. During the clustering phase, all nodes determine their utility and reinforcement learning-based clustering fine-tuning was applied to compute the node's utility in a particular system environment. Then, the inter-cluster forwarding nodes were chosen in the routing stage for data transfer. However, the routing process was ineffective when the network topology was impacted by link failures. Ma et al. [17] developed an aerial-ground integrated network and considered a novel mobility model for disaster environments depending on the 3D Gaussian Markov mobility. Also, routing factors and multipath stability fine-tuning operations were established. A multidimensional hypergraph matching framework for selecting multiple routes among nodes. However, it cannot find alternate routes to prevent link failures in the network.

Ren et al. [18] developed a multipath routing scheme constrained by many QoS factors depending on an intuitionistic fuzzy set of entropy weights called FMQMRP. First, a cross-layer method was used to satisfy the QoS requirements according to the multipath routing, which helps find and preserve many transmission routes. Then, intuitionistic fuzzy set theory was applied to reveal the efficiency tables of the obtained multi-routes via fuzzy regularization to form a multi-parameter multipath routing decision matrix. The weight of all factors was calculated based on the information entropy. Moreover, the TOPSIS approach was applied to determine the efficient ordering of multi-routes. However, the network delay was still high since it takes more time to recover the path when a link interruption occurs. Lansky et al. [19] developed an energy-aware RP in FANETs depending on the OLSR. Initially, the link quality among UAV nodes was determined using the percentage of transmitted/received hello packets and connection period. Then, the multipoint relays were chosen by the firefly algorithm based on the remaining energy, link quality, neighborhood degree, and willingness. Moreover, paths among nodes were formed according to the energy and link quality for data transfer. However, it was ineffective in handling link failures and had a high routing overhead. Table 1 provides a summary of the studies discussed above, outlining the methodology employed as well as the advantages and disadvantages.

Table 1 Summary of Related Works

Ref. No.	Methodology Used	Advantages	Disadvantages
[11]	Multi-hop multipath source routing method	Higher throughput and shorter delay.	The routing overhead was high due to redundant transfers based on multipath parallel transmission.
[12]	SEEDRP	Good throughput and PDR.	Efficiency in handling link failures was poor while increasing the number of nodes.
[13]	Whale-optimized OLSR protocol	Better PDR, E2D and throughput.	It requires more objective factors to choose the best route when a link failure occurs.
[14]	CLEA-AODV-RP	Reduced energy utilization and increased cluster lifetime.	The path was chosen based only on remaining power and hop count, without considering path survivability, impacting data transmission when the path fails.
[15]	Ant-Hocnet	Maximum throughput and minimum E2D.	Ineffective in avoiding link or path failures, leading to degraded network throughput and higher energy consumption.

[16]	ICRA	Reduced E2D and increased PDR.	Ineffective routing process when network topology is affected by link failures.
[17]	Multidimensional hypergraph matching framework	Higher path stability.	Unable to find alternate routes to prevent link failures in the network.
[18]	FMQMRP	Reduced routing overhead and increased PDR.	Network delay remains high as it takes longer to recover the path after a link interruption.
[19]	Energy-aware RP	Better PDR, throughput, E2D and energy efficiency.	Ineffective in handling link failures and has a high routing overhead.

Through this literature, it can be observed that the previous RPs in FANETs were ineffective in handling link failures during data transmission since they considered only a few parameters to choose the optimal routes. The path survivability such as the probability of the path's survival was not determined, resulting in redundant transmissions if the link was broken during data transfer. This may cause high routing overhead and delay. To combat this issue, this study develops a new multipath RP in FANETs, which helps to enhance the network's QoS efficiency.

3. PROPOSED METHODOLOGY

This section briefly describes the MEPFL-CLCT-RP protocol for FANETs. In this study, a homogeneous FANET is constructed as in [10], with N number of UAVs and E number of existing links at interval t. All UAVs i are aware of their position $\mathrm{a}_i = (x_i, y_i, z_i)$ and speed $\mathrm{v}_i = (v_{x,i}, v_{y,i}, v_{z,i})$ at t in the 3D space. The distance between 2 UAVs i and j at t is defined as the Euclidean distance $d_{ij}(t) = \left\|\mathrm{a}_i(t) - \mathrm{a}_j(t)\right\|_2$. Also, consider the UAV velocity is restricted to $[0, V_{max}]$, where $V_{max} > 0$ is predetermined. Assume a link e_{ij} as part of E at t when $d_{ij}(t)$ is less than the transmission range R, i.e., $E(t) = \{e_{ij}(t): d_{ij}(t) \le R\}$.

A structure of FANET considered in this study is depicted in Figure 1. As nodes in the network move, the following operations must be repeated at each time step.

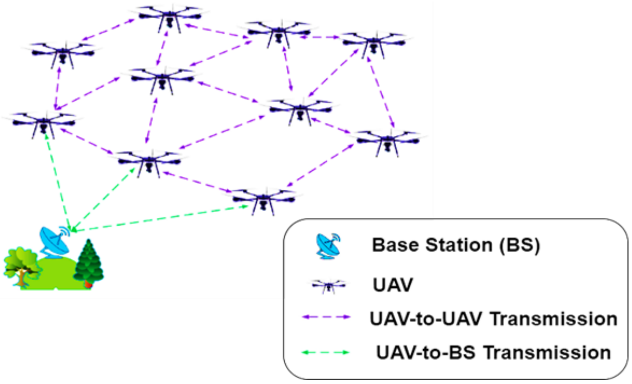

Figure 1 FANET Design

3.1. Problem Formation

Consider that the actual location a_i of all UAVs is not known by the BS. Rather, it maintains an estimation of the Probability Density Function (PDF) for the location a_i, denoted as $p(\hat{\mathrm{a}}_i = \mathrm{a})$. This PDF provides the probability of the UAV i being at a particular position a according to the BS's approximation. Then, the link survival probability $P(e_{ij})$ is defined in equation (1):

$$P(e_{ij}) = P_R(d_{ij} \le R) = \int_{B_R(0)} p(\mathrm{a}_i - \mathrm{a}_j = \mathrm{a}) d\mathrm{a} \quad (1)$$

In equation (1), $B_R(\mathrm{a})$ denotes the sphere with radius R centered at location a. Consider e is a route from a source (s) to a destination (d), and $\mathcal{E}_{sd}$ is the list of multiple routes between s and d. Subsequently, the best paths e^* are chosen by the FL system [9] as the vector of links that increase the total path survival probability as in equation (2):

$$\mathrm{e}^* = \underset{\mathrm{e}\in\mathcal{E}_{sd}}{\operatorname{argmax}}\, P(\mathrm{e}) \quad (2)$$

When every link is autonomous, $P(\mathrm{e}) = \prod_{e\in\mathrm{e}} P(e)$. It is important to note that loops are often neglected because a path with a loop may have a lower or equal probability of survival compared to a similar path without a loop. In this study, the mutual existence probability of neighboring links is also modeled.

Once the best routes e^* are chosen from available multiple paths, its best backup path $b(\mathrm{e}^*)$ is defined as in equation (3) to increase the success probability in case the links in a primary path fail (a link failure is represented by $\bar{\mathrm{e}}^*$):

$$b(\mathrm{e}^*) = \underset{b\in\mathcal{E}_{sd}|\bar{\mathrm{e}}^*}{\operatorname{argmax}}\, P(b|\bar{\mathrm{e}}^*) \quad (3)$$

In equation (3), $\mathcal{E}_{sd}|\bar{\mathrm{e}}^*$ is the set of possible routes from s and d, provided that the primary route e^* has failed. The concept of a backup path is extended to determine the best backup from a list of multiple available optimal paths, ensuring the optimal path in case all available routes fail.

The following section explains the calculation of link survival probability using the EPFL-CLCT-RP to identify the primary and backup paths.

3.2. Probability of Link Survival

Consider that the predicted location distribution for all UAVs is a multivariate Gaussian distribution $\widehat{\mathrm{a}}_i \sim \mathcal{N}(\mu_i, \sum_i)$. Also, consider that the locations of the UAVs are jointly autonomous. Note that the covariance matrix $\sum_i$ is not necessarily diagonal, as a high inaccuracy is expected in the direction of UAVs' mobility. The PDF of the location for a node i is defined as in equation (4):

$$p_i(\mathrm{a}) = \frac{1}{2\pi\sqrt{|\sum_i|}} exp\left(-\frac{1}{2}(\mathrm{a} - \mu_i)^T \textstyle\sum_i^{-1}(\mathrm{a}_i - \mu_i)\right) \quad (4)$$

Therefore, the link survival probability defined in equation (1) is rewritten as equation (5):

$$P(e_{ij}) = \int_{B_R(0)} \frac{exp\left(-\frac{1}{2}\left(\mathrm{a}-(\mu_{i-j})\right)^T \sum_{i-j}^{-1}(\mathrm{a}-\mu_{i-j})\right)}{2\pi\sqrt{|\sum_i|}} d\mathrm{a} \quad (5)$$

In equation (5), $\mu_{i-j} = \mu_i - \mu_j$ and $\sum_{i-j} = \sum_i + \sum_j$ represent the discrepancy between 2 independent multivariate Gaussian random variables. Let's assume the survival probability $P(e_{ij}, e_{jk})$ of a 2-hop route (e_{ij}, e_{jk}). The 2 links are interconnected because they share the middle node j. If the locations a_i and a_k are jointly autonomous, the links' survival probabilities become autonomous when conditioned on a_j. Therefore, using the joint probability rule, the overall probability of the survival of links e_{ij} and e_{jk} $\left(P(e_{ij}, e_{jk})\right)$ conditioned on the location of the intermediate node j is given by equation (6):

$$P(e_{ij}, e_{jk}) = \int_{\mathbb{R}^3} P(e_{ij}|\mathrm{a}_j = \mathrm{a}) P(e_{jk}|\mathrm{a}_j = \mathrm{a}) p_j(\mathrm{a}) d\mathrm{a} \quad (6)$$

In equation (6), $P(e_{ij}|\mathrm{a}_j = \mathrm{a})$ and $P(e_{jk}|\mathrm{a}_j = \mathrm{a})$ are the conditional probabilities of link survival between nodes i and j, and between nodes j and k, given the location of the intermediate node j. Additionally, p_j is the PDF of the location for node j, and $P(e_{ij}|\mathrm{a}_j = \mathrm{a})$ is provided as in equation (7):

$$P(e_{ij}|\mathrm{a}_j = \mathrm{a}) = \int_{B_R(\mathrm{a})} p_i(\mathrm{a}) d\mathrm{a} \quad (7)$$

3.3. Determination of Routing Metric

To calculate the survival probability of a certain path, it is essential to equally consider all links in that path. The probability determination is simplified by considering that connections that don't share nodes are autonomous, as represented in equation (8):

$$P(\mathrm{e}) = P(e_{12}) P(e_{23}|e_{12}) \ldots P(e_{n-1,n}|e_{n-2,n-1}) \quad (8)$$

This generalization is supported by the statement that all UAV mobility is considered to be autonomous; therefore, it is practical to assume that the joint dependency of connections that don't share nodes is insignificant. By simply taking the dependency on the directly preceding link, a negative logarithm of the link survival probability is used as a routing metric W in equation (9):

$$W(e_{jk}|e_{ij}) = -\log_{10}\left(P(e_{jk}|e_{ij})\right) \quad (9)$$

Here, the negative logarithm is used in the link routing metric W because it converts the probability into a cost that routing algorithm can optimize. Routing algorithms typically aim to find the lowest-cost path between nodes. Using the actual probability $P(e_{jk}|e_{ij})$ as the routing metric wouldn't work well, because higher probability equates to lower cost, but the routing algorithm wants to minimize the metric. By taking the negative logarithm $-\log_{10}\left(P(e_{jk}|e_{ij})\right)$, the values are flipped so that higher probability now equates to higher cost. This transforms the probability into a cost metric that the routing algorithm tries to minimize. In this manner, a path with a higher link survival probability and routing metric is selected.

3.4. Determination of Backup Paths

The selected optimal primary path may fail in dynamic scenarios, such as high-speed multi-hop FANETs. To address this issue, consider a list of backup paths that can be used in case the main path fails. This will significantly improve transmission reliability in dense UAV scenarios, as multiple optimal paths will be available to the target nodes. To determine the best backup path, consider single-link failures and calculate the conditional path survival probability when a connection is broken, as shown in equation (10):

$$b_i(\mathrm{e}^*) = \underset{b \in \mathcal{E}_{sd}|\bar{\mathrm{e}}^*}{\operatorname{argmax}} P(b|\bar{e}_i^*) \quad (10)$$

When the i^{th} link in the major path doesn't occur, the conditional mutual location PDF of nodes i and j is calculated by equation (11):

$$p\left((\mathrm{a}_i, \mathrm{a}_j) = (\mathrm{a}, \mathrm{b}) \middle| \bar{e}_{i,j}\right) = \begin{cases} \frac{p_i(\mathrm{a}) p_j(\mathrm{b})}{1-P(e_{i,j})}, & \mathrm{b} \in B_R(\mathrm{a}) \\ 0, & Otherwise \end{cases} \quad (11)$$

In equation (11), $p\left((\mathrm{a}_i, \mathrm{a}_j) = (\mathrm{a}, \mathrm{b}) \middle| \bar{e}_{i,j}\right)$ is the conditional joint PDF of nodes i and j given the absence of the i^{th} link $\bar{e}_{i,j}$. $p_i(\mathrm{a})$ is the location PDF of node i, and $p_j(\mathrm{b})$ is the location PDF of node j, when b belongs to the region $B_R(\mathrm{a})$. $P(e_{i,j})$ is the survival probability of the i^{th} link between nodes i and j. After that, other links' survival probabilities are adjusted using a conditional PDF to determine the backup path. Once the best backup $b_i(e^*)$ for all link failures is determined, evaluate them based on the probability of the link failing. The best backup path $\left(\tilde{b}(\mathrm{e}^*)\right)$ is provided as equation (12):

$$\tilde{b}(\mathrm{e}^*) = \underset{b_1,\dots,b_{N(\mathrm{e}^*)-1}}{\operatorname{argmax}} P(b|\bar{e}_i^*)\big(1 - P(e_i)\big) \tag{12}$$

In equation (12), $N(\mathrm{e})$ denotes the amount of path e. The successive backups are calculated for specific failed connections in the main path, although the output is slightly suboptimal. The flow diagram of MEPFL-CLCT-RP is shown in Figure 2, and its complete pseudocode is provided in Algorithm 1.

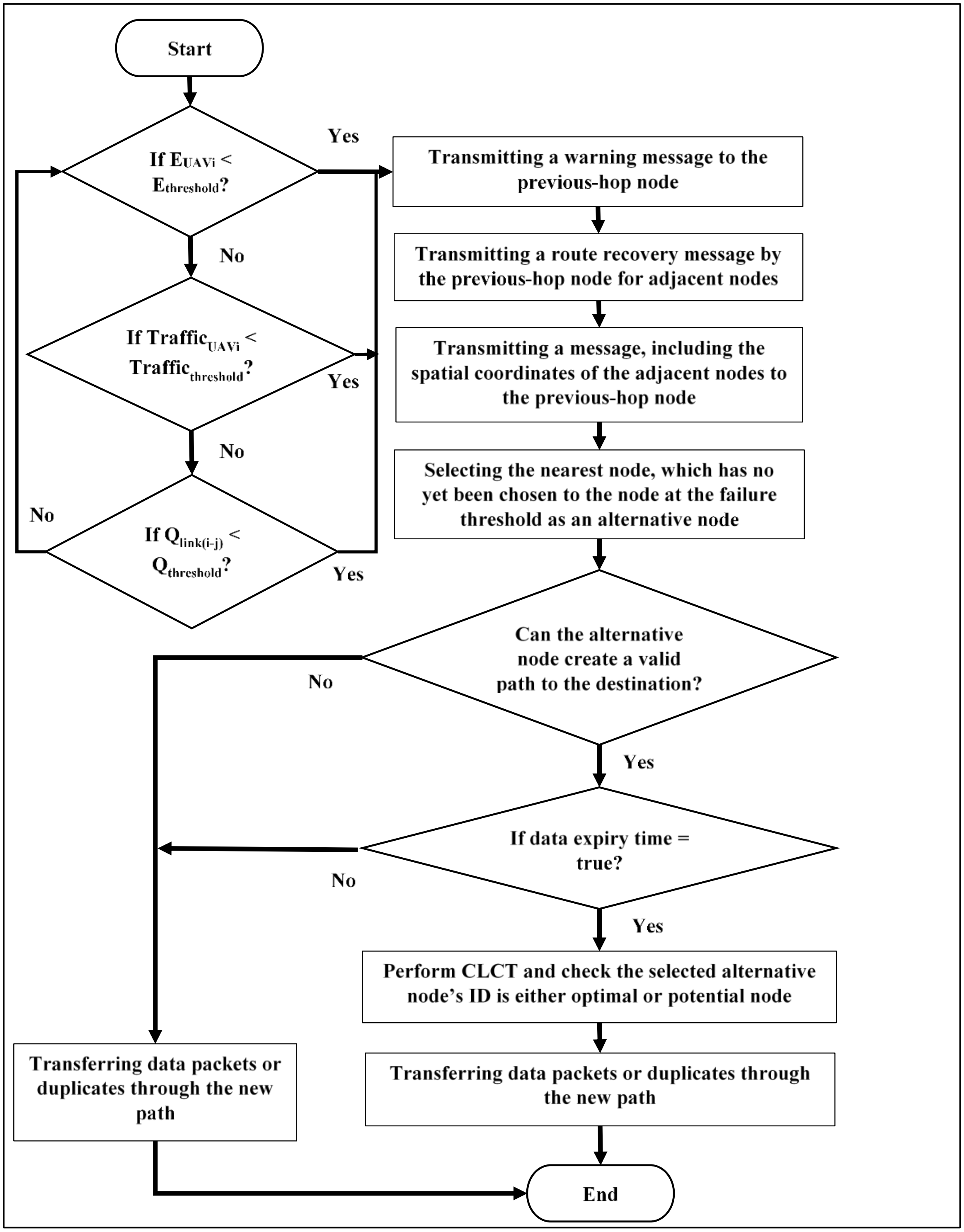

Figure 2 Flow Diagram of MEPFL-CLCT-RP

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Input: $UAV_i$, $i = 1, \dots, N$ where N represents the total quantity of UAVs, data expiry time ($Exp.T_{Data}$)
Output: Effective path between source UAV ($UAV_S$) and destination UAV ($UAV_D$)
1.  Begin
2.  Step 1: $UAV_S$ generates an RREQ packet, inserts all fields of the RREQ packet and transmits them to the adjacent UAVs;
3.  Step 2: if($UAV_i$ receives the RREQ message from one node)
        a. if(the RREQ message is not duplicated)
        b.     $UAV_i$ calculates its score related to the previous-hop UAV, updates a few fields of the RREQ packet (i.e., hop count, path fitness, path delay) and retransmits them to the adjacent UAVs;
        c. end if
4.  Step 3: else
        a. $UAV_i$ calculates its score related to the previous-hop UAVs, chooses the UAV having the maximum score as the former hop UAV, updates a few fields of the RREQ packet (i.e., hop count, path fitness, path delay) and retransmits them to the adjacent UAVs;
5.  end if
6.  Step 4: if($UAV_D$ receives the RREQ message)
        a. $UAV_D$ calculates its score, updates a few fields of the RREQ messages, and chooses the multiple near-optimal paths using the FL scheme;
        b. if(2 links do not share a similar intermediate node j)
        c.     Calculate the link survival probability for each selected path in the multipath set by equation (5);
        d.     Calculate a routing metric using equation (8);
        e. else
        f.     Calculate the link survival probability of a path using equation (6);
        g.     Compute a routing metric using equation (9);
        h. end if
        i. if(link failure exists)
        j.     Determine the conditional path survival probability as equation (10);
        k.     Calculate the conditional mutual location PDF of UAVs i and j using equation (11);
        l.     Determine the optimal backup route as equation (12);
        m. else
        n.     Go to Step 5;
        o. end if
7.  Step 5: else
        a. Go to Step 2;
8.  end if
9.  Step 6: $UAV_D$ generates an RREP packet, and multicasts them to the former-hop UAV via the chosen paths;
        a. while(ID of $UAV_i \neq$ Source IP Address field of the RREP message)
        b.     $UAV_i$ assigns the successive hop in its routing table and multicasts the RREP to the former-hop UAV via the chosen multiple paths;
        c. end while
10. Step 7: $UAV_S$ transfers data packets to $UAV_D$ via the selected multiple paths;
11. Step 8: for($i = 1:N$)
        a. if$\left(E_{UAV_i} < E_{threshold} \text{ or } Traffic_{UAV_i} < Traffic_{threshold} \text{ or } Q_{link_{i-j}} < Q_{threshold}\right)$
        b.     $UAV_i$ transmits a warning information to the former-hop UAV ($UAV_j$);
        c.     $UAV_j$ sends a path recovery data to its adjacent UAVs ($UAV_{adjacent}$);
        d.     $UAV_{adjacent}$ transmits its spatial coordinates to $UAV_j$;
        e.     $UAV_j$ chooses the adjacent UAV nearest (that has not yet been chosen) to $UAV_i$ as $UAV_{alternative}$;
        f. if($UAV_{alternative}$ cannot create a valid path)
        g. Use the optimal backup path to transmit the data packets;
        h. end if
        i. end if
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        j. if($\mathrm{UAV}_{\mathrm{alternative}}$ created a valid path && $\mathrm{Exp.T}_{\mathrm{Data}}$ == false)
        k.     Add $\mathrm{UAV}_{\mathrm{alternative}}$ as its subsequent hop UAV in the routing table;
        l.     Transmit the data packets through the new path;
        m. else if($\mathrm{Exp.T}_{\mathrm{Data}}$True&&$\mathrm{UAV}_{\mathrm{alternative}}$ cannot create a valid path)
        n.     Apply the CLCT algorithm [10];
        o. end $if$
        p. Check if $UAV_{alternative}$ is selected as the optimal UAV or potential UAV is ID;
        q. Transmit the data packets through the optimal backup path;
        r. Otherwise, forward copied packets to $UAV_{alternative}$ from the optimal UAV or potential UAV;
        s. Transmit the data packets through the backup path;
        t. $end\ for$
12. Step 9: $UAV_S$ transmits a route validation message to $UAV_D$;
        a. $if\,(path\ is\ valid)$
        b.     $UAV_D$ transmits an ACK message to $UAV_S$;
        c. $else$
        d.     $UAV_S$ receives a Route Error (RRER) message from the intermediate UAV;
        e.     Go to Step 1;
        f. end if
13. End
```

Algorithm 1 MEPFL-CLCT-Based RP

4. SIMULATION RESULTS

The effectiveness of the MEPFL-CLCT-RP is evaluated against existing protocols such as EPFL-CLCT-RP [10], SEEDRP [12], CLEA-AODV [14], and FMQMRP [18]. The essential codes for the considered existing and proposed protocols are simulated in the Network Simulator (NS2.35) under the Ubuntu platform using the parameters given in Table 2.

A comparative analysis is conducted in terms of E2D, PDR, routing overhead, path stability, hop count and energy usage to measure the performance of MEPFL-CLCT-RP against existing protocols.

Table 2 Simulation Parameters

Parameters	Values
Simulation region	1500×1500×1000 m^3
Number of UAVs	120
Simulation period	350 seconds
Velocity of UAVs	[3,30] m/s
Mobility model	Random waypoint
Initial energy of UAVs	2100 J
Transmission range	310 m
Data packet dimension	1 Kbit
Path loss type	Free-space
MAC layer	IEEE 802.11a

4.1. E2D

It is the average time required for the source UAV to broadcast data to the target UAV.

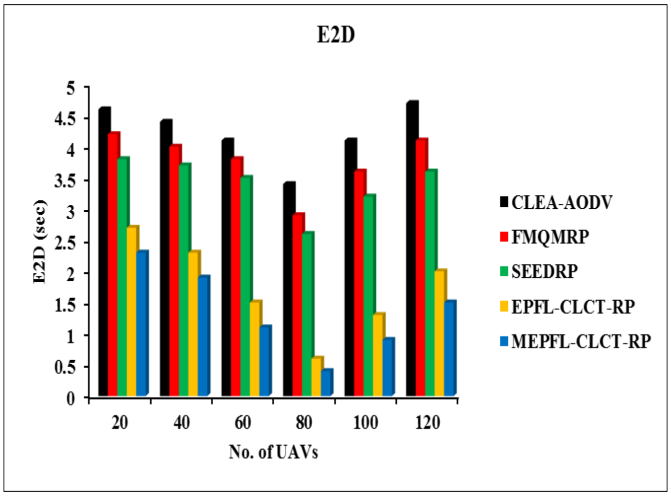

Figure 3 E2D vs. No. of UAVs

Figure 3 compares the E2D of the proposed MEPFL-CLCT-RP protocol with existing protocols for different numbers of UAVs. The data shows that MEPFL-CLCT-RP significantly reduces E2D by selecting reliable backup routes to prevent link failures during data transfer. Compared to other protocols, MEPFL-CLCT-RP demonstrates superior efficiency in handling link failures, resulting in lower E2D. For example, with 120 UAVs, MEPFL-CLCT-RP reduces E2D by 68.1% compared to CLEA-AODV, 63.4% compared to FMQMRP, 58.3% compared to SEEDRP, and 25% compared to EPFL-CLCT-RP. These findings highlight the superior performance of MEPFL-CLCT-RP in maintaining low latency and ensuring timely data delivery, especially in scenarios with a high number of UAVs in FANETs.

4.2. PDR

It is the proportion of total data delivered to the target UAV to the total data produced. Figure 4 compares the PDR results of the proposed MEPFL-CLCT-RP protocol with existing protocols for varying numbers of UAVs. The data shows that MEPFL-CLCT-RP significantly improves PDR as the number of UAVs increases by preventing link failures and utilizing multiple stable paths. For a network with 120 UAVs, MEPFL-CLCT-RP increases PDR by up to 38.8% compared to CLEA-AODV, 29.2% compared to FMQMRP, 19.2% compared to SEEDRP, and 3.3% compared to EPFL-CLCT-RP. These enhancements are crucial for ensuring successful data packet transmissions in FANETs, and improving network reliability in dense UAV environments.

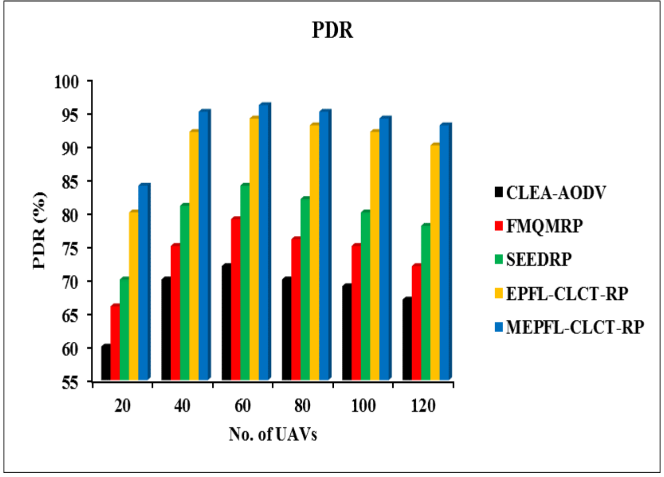

Figure 4 PDR vs. No. of UAVs

4.3. Routing Overhead

It is the percentage of each message generated in the packet forwarding task that is delivered to the target UAV.

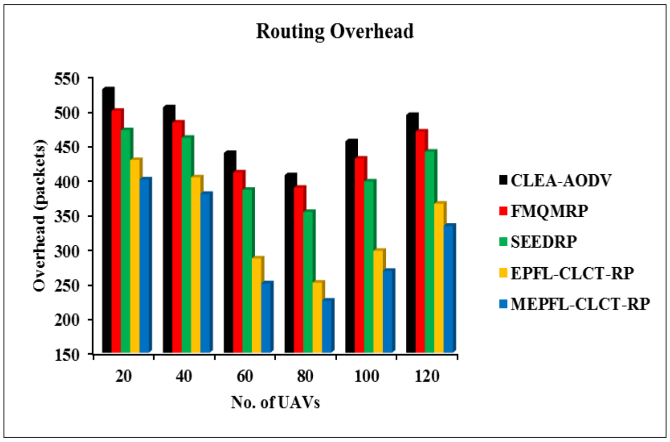

Figure 5 Routing Overhead vs. No. of UAVs

Figure 5 compares routing overhead for different protocols with varying numbers of UAVs in the network. The MEPFL-CLCT-RP protocol shows a significant reduction in routing overhead compared to other protocols due to its efficient backup route selection mechanism. For a network with 120 UAVs, MEPFL-CLCT-RP reduces routing overhead by 32.5% compared to CLEA-AODV, 29% compared to FMQMRP, 24.3% compared to SEEDRP, and 8.8% compared to EPFL-CLCT-RP. This reduction is crucial for optimizing FANET performance by minimizing control message bandwidth consumption and processing burden on UAVs, leading to faster and more reliable network operation in dynamic and high-density UAV environments.

4.4. Path Stability

It is calculated as the sum of all failed routes. When the RP decreases the number of unsuccessful routes, it creates highly resilient paths. Figure 6 compares path stability across different protocols with varying numbers of UAVs. MEPFL-CLCT-RP stands out for significantly reducing failed paths due to its effective backup route selection strategy based on link survival probability. In a 120 UAV scenario, MEPFL-CLCT-RP reduces failed routes by 96% compared to CLEA-AODV, 95.2% compared to FMQMRP, 94.1% compared to SEEDRP, and 66.7% compared to EPFL-CLCT-RP. This highlights MEPFL-CLCT-RP's ability to maintain stable and reliable routes, crucial for uninterrupted data transmission in FANETs. Its proactive approach to backup route selection enhances network reliability and efficiency, especially in high-density and long-range UAV operations.

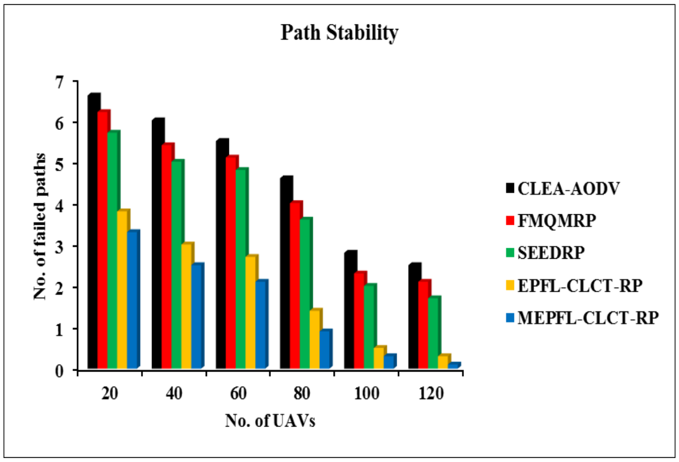

Figure 6 Path Stability vs. No. of UAVs

Figure 7 compares the path stability of different protocols during data transmission with varying node velocities. MEPFL-CLCT-RP outperforms existing protocols by significantly reducing the number of unsuccessful paths, especially at higher UAV velocities. At 30 m/s, MEPFL-CLCT-RP reduces failed paths by 45.5% compared to CLEA-

AODV, 42.3% compared to FMQMRP, 36.2% compared to SEEDRP, and 14.3% compared to EPFL-CLCT-RP. This demonstrates the protocol's robustness in maintaining stable communication paths in dynamic UAV environments. The MEPFL-CLCT-RP dynamically selects backup routes based on link survival probability, effectively mitigating link failures due to rapid movement. This capability is crucial for FANETs, where high mobility can disrupt communication links. By enhancing path stability, MEPFL-CLCT-RP improves data transmission reliability and efficiency in high-speed UAV environments, making it ideal for applications requiring uninterrupted communication in FANETs like real-time monitoring and surveillance.

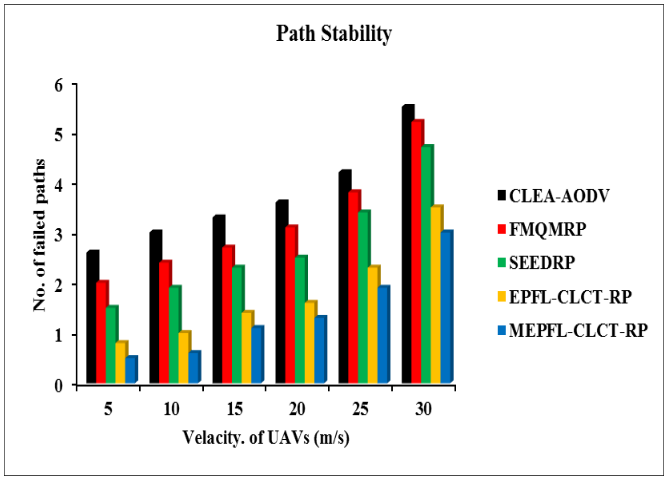

Figure 7 Path Stability vs. Velocity of UAVs

4.5. Hop Count

It specifies the average number of hops in the route during data forwarding.

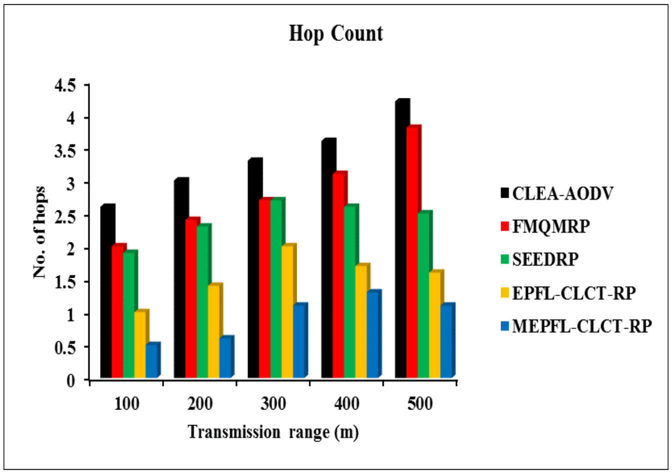

Figure 8 Hop Count vs. Transmission Range

Figure 8 illustrates a comparison of hop count between the proposed MEPFL-CLCT-RP and existing protocols under varying node transmission ranges. The results show that as the transmission range increases, the MEPFL-CLCT-RP significantly reduces the hop count by selecting optimal multi-routes with minimal hops, outperforming existing protocols. When the transmission range is set to 500 meters, the MEPFL-CLCT-RP reduces the hop count by 73.8% compared to CLEA-AODV, 71.1% compared to FMQMRP, 56% compared to SEEDRP, and 31.3% compared to EPFL-CLCT-RP. This reduction in hop count is crucial for efficient FANET operation, enabling faster data transmission, lower latency, and increased network reliability. The MEPFL-CLCT-RP's intelligent route selection mechanism prioritizes routes with the fewest hops, enhancing network performance in scenarios with extended transmission ranges. Overall, the protocol's ability to minimize hop count improves network efficiency and reliability in dynamic UAV environments.

4.6. Energy Utilization

It is the total amount of energy wasted by every UAV in the path formation and packet transfer phases.

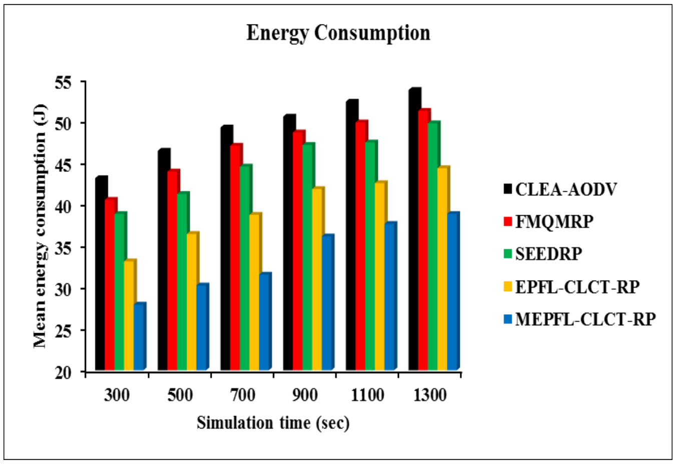

Figure 9 Energy Consumption vs. Simulation Time

Figure 9 illustrates the mean energy consumption of various routing protocols for different simulation periods. The MEPFL-CLCT-RP stands out by reducing energy consumption for data transmission through multi-path routing compared to existing protocols. At 1300 seconds, the MEPFL-CLCT-RP shows significant energy savings, with a 27.7% reduction compared to CLEA-AODV, 24.2% compared to FMQMRP, 21.9% compared to SEEDRP, and 12.4% compared to EPFL-CLCT-RP. Key factors contributing to these energy savings include efficient route selection, minimized retransmissions, balanced load distribution, and optimized control overhead. These improvements enhance the longevity of UAV networks, particularly in energy-constrained FANETs. The MEPFL-CLCT-RP's ability to reduce energy consumption makes it a valuable routing protocol for sustainable and efficient operations in UAV networks, enabling extended mission durations and improved performance in various applications.

4.7. Discussion

The MEPFL-CLCT-RP model outperforms existing routing protocols for FANETs in several key aspects:

1. Multipath selection: Utilizes the FL system to choose multiple near-optimal paths for data transmission, enhancing network reliability and fault tolerance.
2. Link survival probability: Calculates the likelihood of link survival for selected paths, considering UAV mobility and dynamic topology to prioritize stable connections.
3. Backup path selection: Identifies the best backup path based on link stability, enabling quick switching in case of primary path failure to minimize disruptions.
4. CLCT mechanism: Adapts data transmission through newly created paths after link failures, ensuring reliable delivery and minimizing data loss.
5. Routing overhead reduction: Proactively selects backup paths and employs CLCT to reduce route rediscovery and control message exchanges, conserving network resources.
6. Energy efficiency: Efficient route selection, minimized retransmissions, and optimized control overhead contribute to reduced energy consumption, extending UAV operational lifetime in energy-constrained scenarios.

Thus, the MEPFL-CLCT-RP model's comprehensive approach results in improved performance metrics, including reduced E2D, higher PDR, lower routing overhead, enhanced path stability, and energy efficiency in dynamic FANET environments.

5. CONCLUSION

This study developed the MEPFL-CLCT-RP data transmission scheme for multi-hop FANETs. Initially, the FL system was applied for multi-path selection based on near-optimal solutions. Based on link survival probability, a new routing metric was then calculated for each selected path, and the path having the greatest link survival probability was decided as a backup path. Such a backup path was used as an alternate path when the link was broken and the source node could not form a new valid path. Alternatively, if the source node can form an alternate reliable path, then the data duplicates were transferred using the CLCT mechanism via the created path. Finally, the simulation outcomes revealed that on average, the MEPFL-CLCT-RP achieved 1.35 sec E2D, 92.83% PDR, 309 packets of overhead, 2 failed paths, 1 hop count, and 33.68 J mean energy consumption, compared to earlier RPs in FANETs.

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Authors

H. Shaleena, I completed my BSc in Computer Science at Avinashilingam Deemed University, Coimbatore during the academic year 2003-2006. I pursued my postgraduate studies in MCA and M. Phil at Bharathiar University affiliated colleges during the academic years 2006-2009 and 2012-2014, respectively. Currently, I am pursuing a PhD in Computer Science at Bharathiar University.

K. Sumangala, Research Supervisor and Associate Professor at Kongunadu Arts and Science College, Coimbatore, has over 25 years of teaching experience and more than 15 years of research experience.

How to cite this article:

H. Shaleena, K. Sumangala, "Multiple Route Selection for Avoiding Single Point Failure in Flying Ad Hoc Network (FANET)", International Journal of Computer Networks and Applications (IJCNA), 11(3), PP: 363-374, 2024, DOI: 10.22247/ijcna/2024/23.