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ENERGY-AWARE CONSISTENT LINK-BASED FUZZY ROUTING PROTOCOL IN FANET

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ABSTRACT—
A Flying Adhoc Network (FANET) is a novel ad-hoc network that clusters tiny Unmanned Aerial Vehicles (UAVs) in an ad-hoc manner. Such networks have many issues while designing an effective Routing Protocol (RP) because of high node (UAV) mobility, limited resources, low UAV densities, etc. To tackle this problem, an Energy-aware and Predictive Fuzzy Logic (EPFL)-based RP was designed, which computes the score of each UAV based on the different parameters and applies the fuzzy logic to select the best route. However, data transmission is influenced by unstable transmission links and inadequate resources. This can be solved by opportunistic transmission based on the store-copy-forward strategy. But, it degrades Packet Delivery Ratio (PDR) by transmitting more data copies to improper relay UAVs. Hence, this article designs an EPFL with a Consistent Link-based Copy adaptive Transmit (EPFL-CLCT)-RP to regulate the data transmission in FANETs. In this protocol, the real-time variations of network connectivity are initially determined by the data gathered from every adjacent UAV. Then, the CLCT mechanism is proposed, which utilizes the historical data and transitivity of the UAV interactions to choose suitable relay UAVs. Also, the Transmit Prediction Value (TPV) is determined as the measuring criterion to reduce the transmission of multiple data packet replicas during the data transmission task. Finally, the simulation outcomes illustrate that the EPFL-CLCT-RP outperforms other classical RPs.
Keywords—FANET, Unmanned aerial vehicle, Routing, Fuzzy logic, Network connectivity, Copy adaptive routing, Dynamic topology

I. INTRODUCTION

UAVs also called drones to become popular in modern decades due to the fast adoption of smart technologies like low-cost Wi-Fi, Global Positioning System (GPS), sensors and embedded components [1]. UAV is an unmanned aircraft that is propelled by a jet or piston engine and may be operated remotely or driven automatically depending on preprogrammed route information [2]. UAV applications have grown over the last centuries, from radar systems to commercial domains [3-6]. The most well-known applications are traffic surveillance, remote sensing, wildfire monitoring, crisis control, agricultural management, military services and relaying networks.

Currently, Adhoc networks deploying UAVs have received great significance. An ad hoc network does not contain a stable structure, wherein all UAVs are movable and may travel from a specific location to the other location within the network's coverage region. The concept of multi-hop wireless networks called FANETs is motivated by the idea of increasing wireless coverage, enhancing total output and allowing network auto-settings without backbone support [7]. UAVs can remotely operated by a Base Station (BS) controller or autonomously controlled by an implanted regulator.

In FANET, UAVs will be split into single and multi-UAVs [8]. A single-UAV system is often comprised of a big UAV, which is directly linked to the BS and/or satellites. It has been repeatedly used to conduct specialized operations. To maintain interaction with the BS, this UAV has to be equipped with complex hardware technology [9]. The function may be canceled when the UAV does not succeed. A multi-UAV network connects numerous UAVs, on top of a BS, sensors and satellite. It outperforms a single-UAV network regarding durability, reliability, task duration and diversity, implying that although one of the UAVs malfunctions while operating; the function might be finished with the remaining UAVs [10]. In multi-UAV networks, UAVs can be configured in a range of configurations as desired. Also, the scope of a multi-UAV network's connectivity can be simply modified by adding new UAVs to the network.

Transmission paths in FANETs are classified into 5 categories: UAV-to-BS paths (UAV/BS), BS-to-BS paths (BS/BS), UAV-to-UAV paths (UAV/UAV), UAV-to-Satellite paths (UAV/S) and UAV-to-sensor paths (UAV/X) [10]. UAV/BS transmission paths send information like real-time video or photos from a UAV to the BS. BS/BS paths permit many BSs to transmit multi-media data. UAVs will interact ad hoc in UAV/UAV, in which they should engage with each other to establish a consensus and distribute information. UAV/S enables a high-altitude transmission path between UAV and satellite. Moreover, the UAV/X path collects data from sensors or mobile nodes.

Conversely, with the high mobility and dynamic topology, data transmission in FANETs, i.e. among UAVs experienced various problems like unstable transmission paths/connections and inadequate resources in the network. To combat these problems, information sharing among UAVs requires the use of an RP. Standard ad hoc network RPs developed for MANETs and VANETs seem to be ineffective for FANETs [11]. FANETs possess specific aspects, which create designing effective RPs difficult, including 3D movement, dynamic topology, a limited number of UAVs, high mobility, frequent path failures, network partition and resource constraints [12]. Further, distinct FANET users have different Quality-of-Service (QoS) needs that must be modified [13-15]. While certain uses like information gathering and modeling can accept latencies, others like surveillance and disaster management require real-time information sharing with negligible latencies [16].

As a result, a few types of research were performed to develop RPs, which focus on design properties and the unique qualities of FANETs. Such are either new RPs or improvements to standard ad hoc RPs. While developing RPs, it is extremely essential to choose a suitable path. This is a vital problem to interact with 2 UAVs in FANET. In contrast, it is often complex to select the best route. So, when creating RPs for FANETs, different criteria should be considered such as effective usage of network resources (e.g., bandwidth, memory and energy), power efficiency, lack of paths, recovery abilities and flexibility [17]. As well, RPs in FANET should be effective, which means they ought to have minimal overhead, strong dependability, less packet drop, tolerable latency and adequate stability. But, satisfying all criteria specified in an RP is extremely challenging.

To combat this problem, Lee et al. [18] developed an EPFL-based RP for FANET, which contains path discovery and path maintenance stages. Initially, a method was used to determine the score of all UAVs to avoid the network storm issue and handle the control packet transmission such as Route Request (RREQ) and Route Reply (RREP). This score was determined according to many factors like mobility direction, remaining energy, path efficiency and node stability. Also, a fuzzy system was adopted to choose paths having more fitness. After that, the path failure was prevented to identify and alter routes at the failure threshold and the failed paths were recreated to rapidly substitute such paths. Conversely, the data forwarding was affected by unstable transmission links and restricted resources. To solve this problem, an opportunistic transmission has been conducted as data transmission, wherein the UAV can store the data if it did not reach the proper forwarding UAV and only performs the transmission if it reaches the proper relay UAV during movement. But, the transmission of more data copies to improper forwarding UAVs can increase energy depletion and degrade the PDR. As a result, adaptive copy routing is crucial to cope with the high mobility of UAVs and dynamic topology of FANETs.

Hence in this article, an EPFL-CLCT-RP is proposed for effective data transmission in FANETs. In this protocol, the real-time fluctuations in network connection are initially calculated by data received from the number of adjacent UAVs during the data transmission procedure. After that, the CLCT process is introduced to choose suitable forwarding UAVs based on historical data and the transitivity of UAV interactions. Besides, the TPV is used as a criterion to limit the transmission of multiple data packet copies. Thus, this protocol can increase the reliability of information exchange and reduce the system resources in FANETs by deciding appropriate forwarding decisions.

The following sections are arranged as: Section II studies the recent works related to the RPs for FANETs. Section III explains the EPFL-CLCT-RP and Section IV displays its simulation findings. Section V summarizes the whole work and offers future research directions.

II. LITERATURE SURVEY

Royer & Perkins [19] investigated the Adhoc On-demand Distance Vector (AODV)-RP, which performs the route discovery process only if a route request was received. But, it was extremely problematic to utilize AODV protocol in FANETs since it was not well-suited to the unique characteristics of these networks like regular breakage of transmission links, high-speed flying nodes, etc.

Li & Yan [20] presented a Link stability Estimation-based Preemptive Routing (LEPR) scheme in FANETs. A new link stability measure was adopted depending on the position data of drones, which includes link excellence, security level and movement estimation. The path discovery in the AODV was modified and the paths were determined by the link stability measure. But, other factors like delay, power, node stability and hop count were not considered.

Oubbati et al. [21] developed an Energy-efficient Connectivity-aware Data delivery (ECaD) in FANETs. But, when the energy of each adjacent node was lower than the fixed threshold, this node can’t create paths with another node. So, a fixed threshold was not appropriate in the network. Also, the link quality and node stability factors were not considered in the path discovery process, which results in the creation of low-quality routes.

Darabkh et al. [22] developed a Multi Data Rate Mobility Aware (MDRMA) protocol in FANETs. In this protocol, an optimal data transfer rate was computed by each node. Then, the MAC sub-layer of the target was analyzed by delivering the RREQ to decide whether it can engage in data transfer by choosing whether it was positioned within the communication range of that advertised data transfer rate. Also, the mobility direction and velocity of the nodes were considered to find stable paths. But, the chance of collisions and congestion was increased while increasing the packet rate with a predetermined number of nodes.

Sang et al. [23] developed an Energy-Efficient Opportunistic Routing depending on Trajectory Prediction (EORB-TP). Initially, the node's location was estimated in 3D space and the issue of uncertainty of node interaction in opportunistic transmission was solved. Then, the node's trajectory metric was defined to determine the node's trajectory aspects and prevent the extra usage of edge nodes. Also, a power-efficient data transfer method was developed to cope with the restricted power resources and memory space of UAVs while selecting relay nodes. But, it was not suitable for high-speed UAVs scenario while estimating the UAV's position. Also, the number of copies of data packets was high, which increases the network overhead.

Hong et al. [24] developed a proactive topology-aware method for routing strategy according to the swarm creation control policies for monitoring network topology alterations. A method was utilized to predict the path lifetime depending on the construction status and topology relevant data. Also, the Hello interval and path holding timer were adjusted adaptively for the path lifetime. But, it has a high overhead while the adjacent modifies rapidly.

Hou et al. [25] designed a novel protocol called the T-Optimized Link State Routing (OLSR) protocol, which considers the trajectory of UAVs as a known factor. In T-OLSR, Q-learning was employed to discover the optimal route. Also, a data transfer configuration was defined, which solves the issue of deteriorating image quality frequently experienced by UAVs. But, the overhead was not reduced since the use of a simple trajectory transfer scheme, which was not adequate in real-time applications.

Khan et al. [26] aimed for a power-efficient RP for FANET depending on the Ant Colony Optimization (ACO) scheme. An energy stabilization threshold was introduced to preserve the nodes' energy and enhance the total lifespan, QoS by constraining the data transmission. But, its efficiency was less in terms of PDR and it needs advanced optimization algorithms for selecting the optimal paths.

Hameed et al. [27] designed the Gray Wolf algorithm with the Cooperative diversity method (GW-COOP)-based RP for FANETs. First, the UAV requirements were managed by properly configuring the gray wolves. Afterward, an idea of cooperative diversity was adopted by 2 relays to sustain the source-to-target paths. Also, the optimal possible paths were discovered depending on power, relay location and distance to the destination node. But, the link latency and transmission loss were not reduced.

Arafat & Moh [28] developed a new Q-learning-based Topology-Aware Routing (QTAR) scheme in FANET to make consistent arrangements between the origin node and target. In this protocol, the network topology was controlled by 2-hop adjacent data of UAV nodes. The optimum route between the origin node and target was chosen by taking the best 2-hop adjacent connection based on the different metrics associated with the adjacent location, latency, speed and energy. Also, a dynamic Q-learning method was applied to adapt to rapid alterations in topology by fine-tuning the Q-learning variables dynamically according to the network conditions. But, the routing time was high in the case of local minimum, which exists if each adjacent node was farther away from the target.

Usman et al. [29] developed a Reliable Link-adaptive Position-based Routing (RLPR) scheme in FANET. In this RLPR protocol, a relative velocity, signal strength, node's power and the geographic distance towards the target using a forwarding angle were considered. This angle was utilized to compute the transmission area, which reduces the unwanted control packets to find the path. Also, the next hop with a high energy range in the transmission area was chosen and a high connectivity level was achieved based on the node's signal strength and relative velocity. However, undesirable and unreliable routes between the origin node and the target were not reduced. Also, the energy consumption was high because of the high mobility of nodes.

Bhardwaj & Kaur [30] designed a Secure Energy-Efficient Dynamic RP (SEEDRP) for reliable and secure communication in FANETs. Initially, a unique adaptive routing scheme was executed, which discovers a cost-efficient route between the origin node and the target. After that, a distinct dynamic key formation method was applied to secure the forwarded data. But, it needs to analyze power usage and system longevity to ensure the network QoS.

Ali et al. [31] developed a performance-aware RP named G-OLSR for effective transmission and collaboration among the UAVs in a FANET setting based on the greedy forwarding method. In this protocol, a self-adaptation of the network was considered in case of any topological modifications. Also, the distribution loops were avoided for reliable data transmission among UAVs to enhance the QoS. But, it did not consider high mobility nodes, which impact the overall network efficiency.

III. PROPOSED METHODOLOGY

In this section, the presented EPFL-CLCT-RP is described in brief. First, the FANET design used in this presented protocol is discussed. Next, an overview of EPFL is provided to comprehend the basic stages of the routing process. Then, the CLCT mechanism is explained, which controls the real-time changes in the network connectivity of the FANET due to their high mobility.

3.1 Network Design

In this study, a homogeneous FANET is built as illustrated in Figure 1, which comprises many UAVs deployed in a 3D region.

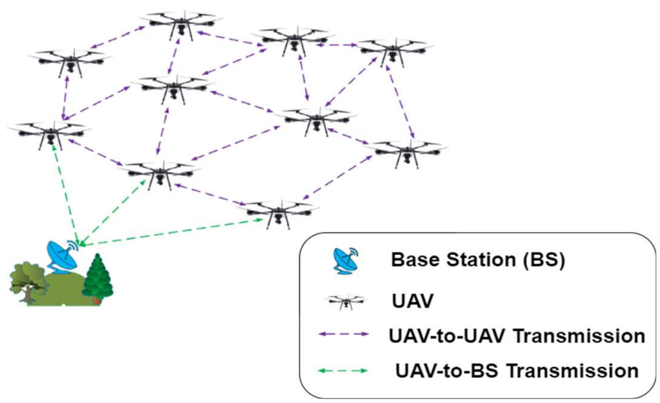

Figure 1. FANET Design

All UAVs use the IEEE 802.11a wireless link at the MAC layer since it effectively supports extremely flexible structures and offers broad connectivity for data transmissions. In this FANET, UAVs are traveling and the space among them varies over a period [18]. All UAVs have a unique identifier. Also, it is considered that UAVs are implemented with the GPS so each UAV is alert of its location (x_a, y_a, z_a) and speed $\left(v_{x,a}, v_{y,a}, v_{z,a}\right)$ at each instant. Consider that the UAV speed is restricted to $[0, V_{max}]$, where $V_{max} > 0$ refers to the fixed value. Additionally, this EPFL-CLCT-RP facilitates 2 kinds of transmission in the FANET.

1. UAV-to-UAV (U2U) transmission: UAVs interact with one another in this sort of transmission to execute typical processes like routing or destination discovery. This kind of transmission can be either 1-hop or multi-hop. Also, it can be either short- or long-range to enhance FANET efficiency regarding data rate and transmission region.
2. UAV-to-BS (U2B) transmission: In this sort of transmission, the UAV interacts with the BS to analyze the received data. In this study, each UAV is not immediately linked to the BS. Only UAVs, which are near the BS, will be immediately linked to it.

Additionally, Air-to-Air (A2A) channel system is utilized, which is described by the free-space transmission strategy since the packet dropping is greater at lower fading. So, the path loss in the A2A system is defined as:

$$Path\ loss(d_{ab}) = \beta 10 \log_{10} d_{ab} + \alpha \tag{1}$$

In Eq. (1), β is the path loss exponent, which is equal to 2 in the free-space transmission, α denotes the path loss at the reference spot. In the free-space transmission, α is defined as:

$$\alpha = 10 \log_{10}\left(\frac{4\pi}{l}\right) \tag{2}$$

In Eq. (2), w denotes the carrier frequency and l defines the light velocity, i.e. $l = 3 \times 10^8$m/s. As well, d_{ab} denotes the distance between 2 UAVs a and b, which is determined by

$$d_{ab} = \sqrt{(x_a - x_b)^2 + (y_a - y_b)^2 + (z_a - z_b)^2} \tag{3}$$

In Eq. (3), (x_a, y_a, z_a) and (x_b, y_b, z_b) are spatial coordinates of a and b, correspondingly.

3.2 Different Kinds of Packets in the EPFL-CLCT Routing Protocol

In this study, the structure of RREQ and RREP in the AODV are modified [18]. These packets are used to create a path, whereas the data packet is a small piece of a large message, i.e. a bit of information that the source UAV desires to transmit to the target UAV.

- *RREQ packet*: Its structure is illustrated in Figure 2 and utilized in the path discovery phase.

Message category	Hop count	Path fitness	Path delay
RREQ packet ID			
Destination IP address			
Destination sequence number			
Source IP address			
Source sequence number			

Figure 2. RREQ Packet Structure

- *RREP packet*: Once the RREQ is received by the target UAV, it creates an RREP message as illustrated in Figure 3 and transmits it to the origin UAV. Observe that the message category field should be equivalent to two in an RREP packet.

Message category	Hop count
RREP packet ID	
Destination IP address	
Destination sequence number	
Source IP address	
Lifetime	

Figure 3. Format of RREP Packet

- *Data packets*: These comprise the information that the origin UAV requests to transmit to the target UAV via a path. The format of data packet is shown in Figure 4.

Packet ID	Destination IP address	Source IP address
Data packet information		

Figure 4. Format of Data Packet

3.2 Overview of EPFL Mechanism

The EPFL mechanism is adopted to enhance the AODV protocol [18]. In this mechanism, different factors like link quality, node stability and energy are determined during the transmission task; therefore reliable paths are formed and the PDR is increased. As well, the network lifespan is increased by optimizing the energy utilization of the UAVs. This mechanism involves 2 distinct stages: (i) path creation and (ii) path maintenance stages.

1. Path creation stage: This procedure begins when the origin UAV desires to transmit data packets to the target UAV yet lacks a path to it in its routing table. In these scenarios, the origin UAV forwards the RREQ packet to its nearby UAVs. Once this packet is received, the nearby UAVs compute their scores according to the different factors like traveling direction, residual energy, link quality and node stability. Such factors are standardized in [0,1] to have an equal impact on the score.

   Determination of Score for All UAVs:

   During the path creation procedure, it is essential for all UAVs to determine its score (SC_{UAV_a}) associated with the previous-hop UAV (UAV_{prev}). Here, SC_{UAV_a} is determined as follows:

- Traveling direction: It is used to choose the next hop UAV (UAV_{next}) from the UAVs that accepted the RREQ packet, therefore the chosen UAV travels in equal direction since UAV_{prev} may interact with every other for longer time. So, they establish highly robust paths. It is determined as:

$$\lambda_{UAV_a} = \begin{cases} 1, & \theta = 0 \\ \frac{\pi-\theta}{\pi}, & \theta < \theta < \pi \\ 0, & \theta = \pi \end{cases} \tag{4}$$

In Eq. (4), θ is the angle between the velocity of UAV_a $\left(\vec{V}_{UAV_a}\right)$ and the speed of UAV_{prev} $\left(\vec{V}_{UAV_{prev}}\right)$.

- Remaining energy: It is determined as follows:

$$E_{UAV_{a-s}} = \frac{E_{UAV_a} - E_{min}}{E_{max} - E_{min}} \tag{5}$$

In Eq. (5), E_{UAV_a} is the energy of UAV_a at any interval, $E_{min} \geq 0$ denotes the least energy and $E_{max} > 0$ denotes the primary energy of UAVs.

- Link quality: It is used to choose UAVs, which possess a greater link quality compared to the other UAVs during the path creation procedure. The Received Signal Strength Indication (RSSI) data is utilized to determine the link quality. UAVs will get RSSI data while accepting the RREQ packet from their adjacent UAVs. The link quality $\left(Q_{std-link_{UAV_{a-prev}}}\right)$ between 2 UAVs such as UAV_a and UAV_{prev} is determined by the averaging scheme on RSSI values. The link quality value is standardized as:

$$Q_{std-link_{UAV_{a-prev}}} = \frac{Q_{link_{UAV_{a-prev}}} - Q_{min}}{Q_{max} - Q_{min}} \tag{6}$$

In Eq. (6), $Q_{min} \geq 0$ and $Q_{max} > 0$ are the lowest and highest quality of transmission connection between 2 UAVs, respectively. The RSSI values differs from 0 to R_{max}. When $RSSI = 87$dBm, the PDR is nearly 99%, and if $RSSI = 0$, then the PDR is 0. So, such values are considered as Q_{max} and Q_{min}, correspondingly.

- Node stability: It is used to choose UAVs, which are at an appropriate distance from UAV_{prev} to engage in the path creation procedure. Such distance is known as the trust distance (D_{trust}), which is described in $[d_{min}, d_{max}]$, where $0 \leq d_{min} < d_{max}$, $d_{min} < d_{max} \leq R$ and R is the transmission range of the UAVs. The node stability δ_{UAV_a} is determined as:

$$\delta_{UAV_a} = \begin{cases} 1 - \frac{\left|d_{min} - d_{UAV_{a-prev}}\right|}{d_{min}}, & 0 \leq d_{UAV_{a-p}} < d_{min} \\ 1, & d_{min} \leq d_{a-pre} \leq d_{max} \\ 1 - \frac{\left|d_{UAV_{a-pre}} - d_{max}\right|}{R - d_{max}}, & d_{max} < d_{UAV_{a-prev}} \leq R \end{cases} \tag{7}$$

In Eq. (7), $d_{UAV_{a-prev}}$ denotes the Euclidean distance between UAV_a and UAV_{prev} at interval while the RREQ packet is accepted by UAV_a.

Once all the factors are determined, SC_{UAV_a} is determined by

$$SC_{UAV_a} = w_1(\lambda_{UAV_a}) + w_2(E_{UAV_{a-std}}) + w_3\left(Q_{std-link_{UAV_{a-prev}}}\right) + w_4(\delta_{UAV_a}) \quad (8)$$

In Eq. (8), w_1, w_2, w_3, and w_4 are the weight coefficients, thus $w_1 + w_2 + w_3 + w_4 = 1$. When the desired score is achieved, each nearby UAV will retransmit the RREQ packet to the origin UAV [18]. This procedure may increase the efficiency of this EPFL mechanism and alleviate the broadcast storm issue. Further, a fuzzy logic system is applied in the path selection process to pick paths with greater fitness, minimum delay and less hops for information exchange. The fuzzy logic known as fuzzy sets is a statistical method that nearly defines intellectual knowledge.

The membership function characterizes a fuzzy set. Triangular, trapezoidal and Gaussian functions are the well-known membership functions in defining fuzzy sets. Fuzzification, defuzzification, a fuzzy rule base and a fuzzy inference engine are the four major processes in fuzzy logic system. By assigning a single membership value to all fuzzy sets, the fuzzification process translates the inputs to the related fuzzy sets, which are then processed by the fuzzy inference engine using the fuzzy rules stated as IF-THEN rules. Its results called fuzzy variables are transformed to crisp values by the defuzzification process. Table 1 presents some examples of fuzzy rule base in the EPFL mechanism.

Table 1. Some Examples of Fuzzy Rule Base

Fuzzy rules	**Inputs**			**Result**
	Path fitness	Hop count	Path delay	Optimal path
1	L	L	L	H
2	L	M	H	VL
3	M	H	L	M
4	M	L	M	H
5	H	H	L	H
6	H	H	H	L
7	H	L	M	VH

*Note: L-Low; M-Medium; H-High; VL-Very Low; VH-Very High

2. Path maintenance stage: This stage involves (a) path failure prevention, and (b) failed path reconstruction. The initial process is used to identify and rectify paths that are at the failure threshold. It prevents disturbances in the data forwarding task in the FANET. When the energy of UAV_a in a path is smaller than the threshold, i.e., $E_{UAV_a} < E_{threshold}$, then this UAV is at the failure threshold. When the data traffic of UAV_a in a path is greater than the threshold value, i.e. $Traffic_{UAV_a} < Traffic_{threshol}$, then the buffer capacity of this UAV is at a failure threshold. Also, when the link quality

between UAV_a and UAV_b in a specific path is less than the threshold value, i.e., $Q_{link_{a-b}} < Q_{threshold}$, then the link between these 2 UAVs is at a failure threshold. So, the route should be altered. If one of these conditions exist, UAV_a transmits the warning message to its previous-hop UAVs in such path to alter that path by establishing a new valid path for data transmission.

The second process is utilized to identify and restore the unsuccessful paths rapidly to avoid disturbances in the data forwarding procedure. So, the source UAV regularly transmits the path validation message to the destination UAV via the path in its routing table. If this message is received by the destination UAV properly, then it defines that the route is valid and transmits the acknowledgment message to the source UAV. Or else, the path is congested and the route error message is sent to the source UAV. So, the source UAV should continue the path discovery procedure to establish the new path to the destination for data transfer.

But, data transmission in FANETs is experienced problems like unsteady transmission links and restricted resources in the network due to the high-speed UAVs and the dynamic network topology. To combat this problem, data transmission has been performed by opportunistic transmission, which uses a “store-carry-forward” strategy for information exchange.

According to this strategy, when the UAV accumulates the data packets from the adjacent UAVs and transmits duplicated data packets (copies) to the next hop UAVs during transmission. Conversely, when the UAV transmits multiple data copies to the inappropriate relay UAVs can increase the energy utilization and reduce the PDR. This problem during data transmission can be solved by adopting the CLCT strategy, which determines the TPV as transmission utility value to regulate the transmission of multiple copies and predict the network connectivity to find the appropriate relay UAVs for better data transmission. Algorithm 1 presents pseudocode associated with the CLCT-enhanced EPFL protocol.

Algorithm 1 CLCT-enhanced EPFL Protocol

Input: UAV_i, $i = 1, \dots, N$ where N denotes the total UAVs, data expiry time $(Exp.T_{Data})$

Output: Effective path between source UAV_S and destination UAV_D

Begin

Step 1: UAV_S generates an RREQ packets, inserts all fields of the RREQ packet and transmits them to the adjacent UAVs;

Step 2: $\boldsymbol{if}(UAV_i\ receives\ the\ RREQ\ message\ from\ one\ node)$

$\boldsymbol{if}(the\ RREQ\ message\ is\ not\ duplicated)$

UAV_i calculates SC_{UAV_i} using Eq. (8), updates a few fields of the RREQ packet (i.e., hop count, path fitness, path delay) and retransmits them to the adjacent UAVs;

$\boldsymbol{end\ if}$

Step 3: $\boldsymbol{else}$

UAV_i calculates SC_{UAV_i} 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;

$\boldsymbol{end\ if}$

Step 4: $\boldsymbol{if}(UAV_D\ receives\ the\ RREQ\ message)$

UAV_D calculates SC_{UAV_D} using Eq. (8), updates a few fields of the RREQ messages, and chooses the optimal path using the fuzzy scheme;

Step 5: $\boldsymbol{else}$

Go to Step 2;

$\boldsymbol{end\ if}$

Step 6: UAV_D generates an RREP packets, unicasts them to the former hop UAV UAV_i via the chosen path;

$\boldsymbol{while}(ID\ of\ UAV_i \neq Source\ IP\ Address\ field\ of\ the\ RREP\ message)$

UAV_i assigns the successive hop in its routing table and unicasts the RREP to the former hop UAV via the chosen path;

$\boldsymbol{end\ while}$

Step 7: UAV_S transfers data packets to UAV_D via the selected path;

Step 8: $\boldsymbol{for}(i = 1{:}N)$

$\boldsymbol{if}\left(E_{UAV_i} < E_{threshold}\ or\ Traffic_{UAV_i} < Traffic_{threshold}\ or\ Q_{link_{i-j}} < Q_{threshold}\right)$

a. UAV_i transmits a warning information to the former hop UAV (UAV_j);
b. UAV_j sends a path recovery data to its adjacent UAVs $(UAV_{adjacent})$;
c. $UAV_{adjacent}$ transmits its spatial coordinates to UAV_j;
d. UAV_j chooses the adjacent UAV nearest (that has not yet been chosen) to UAV_i as $UAV_{alternative}$;
e. $\boldsymbol{if}(UAV_{alternative}\ cannot\ create\ a\ valid\ path)$

Go to Line d;

$\boldsymbol{end\ if}$

If ($UAV_{alternative}\ created\ a\ valid\ path\ \&\&\ Exp.T_{Data} == flase$)

Add $UAV_{alternative}$ as its next hop UAV in the routing table;

Transmit the data packets through the new path;

Else$\boldsymbol{if}(Exp.T_{Data}True\&\&UAV_{alternative}\ cannot\ create\ a\ valid\ path)$

Call Algorithm 2;

Go to Line a;

end if

Check $UAV_{alternative}$ is selected as optimal UAV or potential UAV is ID.

Transmit the data packets through the new path;

Otherwise

Forward copied packets to $UAV_{alternative}$ from optimal UAV or potential UAV

Transmit the data packets through the new path;

$\boldsymbol{end\ if}$

$\boldsymbol{end\ for}$

Step 9: UAV_S transmits a route validation message to UAV_D;

$\boldsymbol{if}(path\ is\ valid)$

UAV_D transmits an ACK message to UAV_S;

$\boldsymbol{else}$

UAV_S receives a route error (RRER) message from the intermediate UAV;

Go to Step 1;

$\boldsymbol{end\ if}$

End

Figure 5 presents the overall flow diagram of the CLCT-enhanced EPFL protocol.

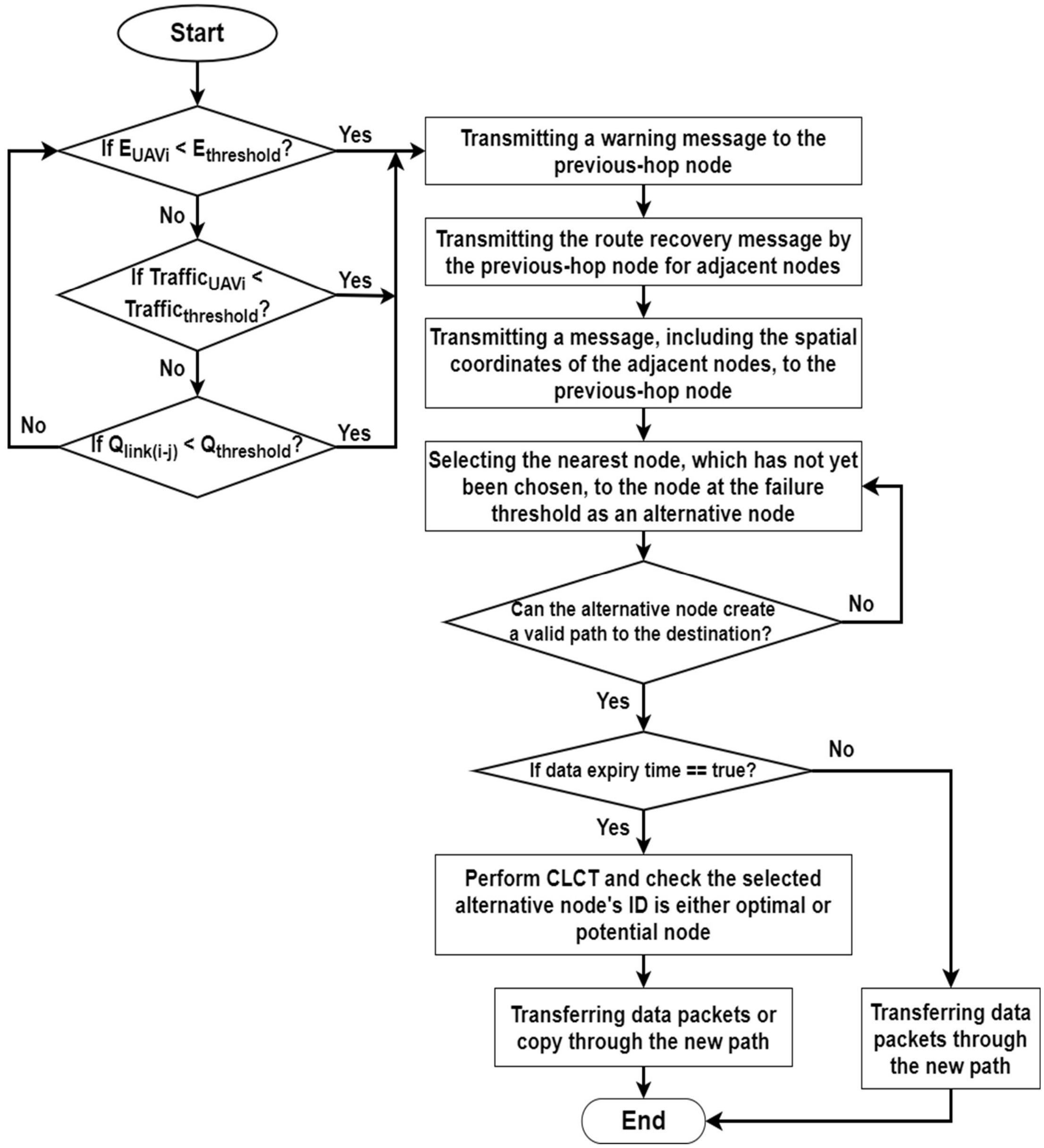

Figure 5. Overall Flow Diagram of CLCT-enhanced EPFL Protocol

In the following subsections, the CLCT strategy during the data transmission is described briefly.

3.3 CLCT for Data Transmission

This CLCT strategy introduces the dynamic copy transmission according to the network connectivity. The processes in this CLCT strategy for data communication in FANET are explained below.

A. Prediction of Network Connectivity

To handle the FANETs' unreliable transmission connections, this CLCT strategy predicts the network connectivity before creating the data transmission decisions. The network connectivity is determined based on the cluster size. The cluster size is defined as the number of transmissible adjacent UAVs, which comprises the neighbor UAVs and UAVs that may be reached by the multihop transmission. Consider N UAVs in the FANET and n_i UAVs that the UAVs will interact with, then the cluster size C is defined by

$$C = \frac{\sum_{i\in N} n_i}{N} \quad (9)$$

Also, the standardized cluster size is utilized to estimate the connectivity independent of network size. The range of the standardized cluster size of the FANET is defined as follows:

$$C_{std} = \frac{C}{N-1} \quad (10)$$

From Eqns. (9) and (10), observe that the properties of the standardized network cluster size are: when N remains unaltered, the higher the transmission area of UAVs is, the greater the standardized network cluster size can be. If the transmission range of UAVs is predetermined, the more UAVs in the FANET, the greater the size of the standardized cluster. A high number of adjacent UAVs that the UAV will interact with define a better network connectivity condition.

If the network is in a linked condition, every UAV in the FANET will interact with each other via single or multiple hops, as well as, the range of the highest standardized cluster size of the network is 1. Hence, the principles to estimate network connectivity are the following:

- $C_{std} = 1$ defines that the FANET is in a linked condition and each UAV will interact with every other.
- $C_{std} < 1$ defines that the FANET is in a condition of irregular connectivity and few UAVs are isolated from other UAVs.

If the network is in linked condition, then the data transmission is achieved by the route decided by the EPFL algorithm. Or else, each UAV determines and keeps the TPV for proper relay UAV selection, which supports path maintenance process.

B. Computation of Transmit Prediction Value

The TPV is the probability of data forwarding from a certain UAV to the interacted UAV. It is utilized to determine the UAV delivery probability. The larger the TPV is the greater the delivery probability of the UAV pair.

The computation of TPV encompasses 3 different units: renewal, decay, and transitivity. If 2 UAVs j and i encounter, all can update their TPV as:

$$TPV = TPV_{(j,i)old} + \left(1 - TPV_{(j,i)old}\right) \times TPV_{int} \quad (11)$$

In Eq. (11), TPV_{int} denotes the initialization constant and satisfies $TPV \in (0,1)$ and $TPV_{(j,i)old}$ denotes the previously estimated PDR. According to this, it is observed that when a pair of UAVs (j,i) do not meet each other in a specified interval, their TPVs can decay by

$$TPV_{(j,i)} = TPV_{(j,i)old} \times y^{l} \tag{12}$$

In Eq. (12), y refers to the discount variable and satisfies $y \in (0,1)$ and l denotes the interval experienced by the 2 UAVs as the final encounter. Also, assuming the transitivity of UAVs, when j and i regularly encounter and UAV i regularly encounter UAV k; then,

$$TPV_{(j,k)} = TPV_{(j,k)old} + \left(1 - TPV_{(j,k)old}\right) \times TPV_{(j,i)} \times TPV_{(i,k)} \times \epsilon \tag{13}$$

In Eq. (13), ϵ defines the transfer variable. Because the encounter scenario between UAVs in FANETs is arbitrary, it is hard to accurately identify which UAVs are highly probable to encounter the destination UAV and achieve data transfer; thus, the encounter probability between UAVs may be predicted by the historical encounter data of UAVs. A large TPV indicates that the UAV pair meets often and the delivery probability is high. In contrast, a lower TPV signifies a low encounter incidence of the UAV pair, which defines that the distance between the 2 UAVs is large and they can be linked via numerous relay UAVs, or one of the UAVs is separated from the network without an entire route.

By estimating the delivery probability of UAVs, this protocol will predict which UAVs are highly probable to encounter the destination UAVs; hence, if the candidate UAV is chosen to transfer the data packet, the encounter UAV with a greater TPV with the destination UAV is chosen for data transmission. It not only prevents the transmission of unwanted data packet copies and decreases the buffer's traffic load. Also, it improves the PDR and lowers data communication costs in the FANET.

From this perspective, the optimal UAV of j is defined as the UAV with the maximum TPV among its adjacent and is lower than its individual TPV. Also, the potential UAVs of j are each UAV in its adjacent UAVs whose TPV is higher than its own. UAVs often find their adjacent through transmitting regular beacons that signify their present state information (such as position, velocity, power and so on) to adjacent UAVs. This CLCT strategy utilizes beacons to keep the UAV's TPV, which belongs to the UAV’s state information. During the data transmission procedure, when j predicts that the network is linked, it can transmit the data to the optimal UAV; or else, j transmits data to each potential UAV. Thus, this CLCT decides and controls the transmission of data packet copies according to the TPV.

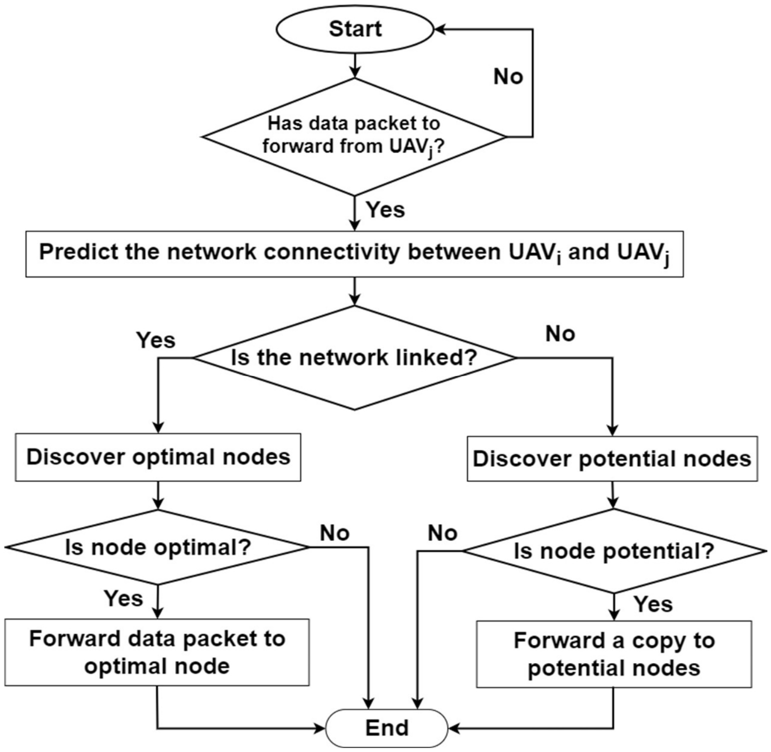

Figure 6. CLCT-based Packet Transmission Strategy during Path Maintenance

As illustrated in Figure 6, when the network is predicted to be linked, the UAV will transfer the data packet to the optimal UAV, i.e. the UAV with the highest delivery probability between the UAV and the target UAV. Or else, the UAV transmits a data packet replica to all potential UAVs, i.e. to every adjacent UAV whose delivery probability value is higher than that of the UAV. When neither the optimal UAV nor the potential UAV is available, the UAV can keep the data packet, since transmitting the data packet to those UAVs with a poor delivery probability can squander energy and network resources. Because of the UAV mobility, their predicted delivery probability values are regularly modified and transmission decisions are created by the UAVs according to the re-predicted connectivity. This algorithm reacts adaptively to the variation of the number of UAVs in the FANET. Algorithm 2 presents the pseudocode for the CLCT-assisted data transmission mechanism.

Algorithm 2: CLCT-assisted data transmission

$\boldsymbol{for}(each\ data\ packet\ in\ UAV_j)$

$\boldsymbol{if}(UAV_j\ predicts\ the\ network\ is\ linked)$

Optimal UAV = UAV_j;

$\boldsymbol{for}(every\ UAV_i\ in\ UAV_j's\ neighborhood)$

$\boldsymbol{if}(TPV_i > TPV_{optimal\ node})$

Optimal UAV = UAV_i;

$\boldsymbol{end\ if}$

$\boldsymbol{end\ for}$

$\boldsymbol{if}(optimal\ node \neq UAV_j)$

Transmit the data to the optimal UAV;

$\boldsymbol{end\ if}$

$\boldsymbol{else}$

$\boldsymbol{for}(each\ UAV_i\ in\ UAV_j's\ neighborhood)$

$\boldsymbol{if}(TPV_i > TPV_j)$

Transmit a copy of the data packet to UAV_i;

$\boldsymbol{end\ if}$

$\boldsymbol{end\ for}$

$\boldsymbol{end\ if}$

$\boldsymbol{end\ for}$

IV. SIMULATION RESULTS

This section analyzes the efficiency of the EPFL-CLCT protocol by simulating it in Network Simulator version 2.35 (NS2.35). Also, the results achieved from this simulation are compared with the existing RPs including EPFL [18], AODV [19], LEPR [20], ECaD [21], T-OLSR [25], RLPR [29], SEEDRP [30] and G-OLSR [31]. The random waypoint mobility paradigm is utilized to configure the mobility of UAVs. In this test-bed, consider that the dimension of the FANET configuration is equivalent to 1500×1500×1000m^3. Also, 120 UAVs are evenly and arbitrarily circulated in the FANET setting. The simulation is conducted for 350s. The considered simulation environment is presented in Table 2. Moreover, the efficiency of this EPFL-CLCT protocol is examined based on the different network metrics: End-to-End Delay (E2D), PDR, routing overhead, path stability, hop count and energy utilization.

Table 2. Simulation Parameters

Parameter	Range
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 mean interval needed from creating the data packet by the origin UAV to reach the target UAV.

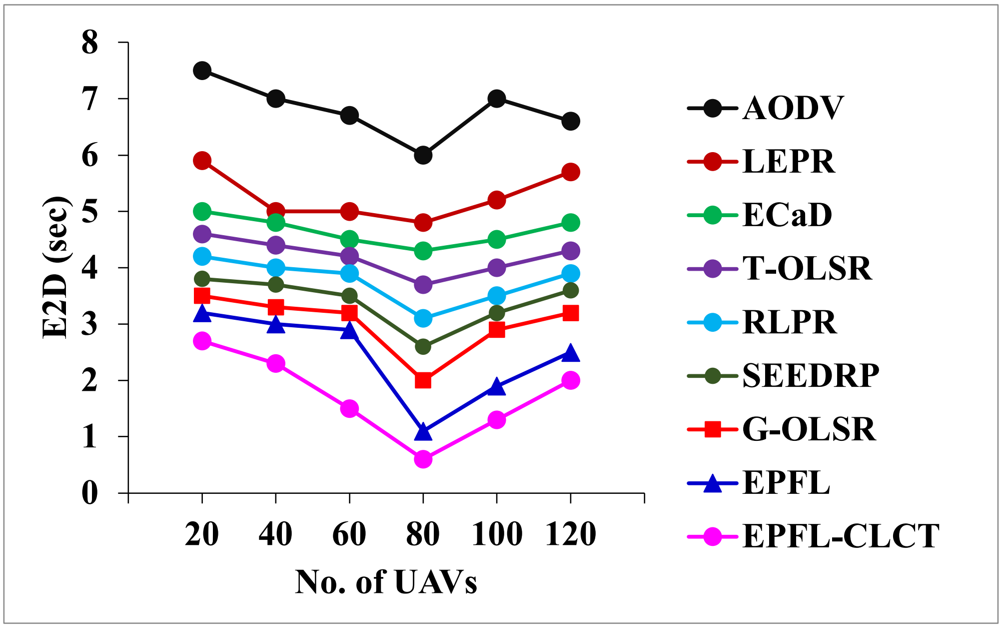

Figure 7. E2D vs. No. of UAVs

Figure 7 evaluates E2D in various RPs for the different number of UAVs in the FANET. In this scenario, it must be observed that the velocity of UAVs is a fixed range, i.e. 30m/s. As illustrated in Figure 3, the presented EPFL-CLCT protocol attains the minimum E2D compared to the other protocols. On average, the EPFL-CLCT protocol can decrease E2D by 74.51%, 67.09%, 62.72%, 58.73%, 53.98%, 49.02%, 42.54%, and 28.77% compared to the AODV [19], LEPR [20], ECaD [21], T-OLSR [25], RLPR [29], SEEDRP [30], G-OLSR [31], and EPFL [18], correspondingly. This is due to the consideration of path latency in the path creation task to choose the paths with the minimum E2D for packet forwarding. Also, it considers the network connectivity and TP rate for choosing the optimal adjacent UAVs, which controls the path or link failure during path maintenance tasks. So, this EPFL-CLCT protocol can choose the high-quality links in a routing path and reduce the E2D significantly in the packet forwarding task.

4.2 PDR

It is the proportion of the overall received data packets at the target UAV to the overall data packets created.

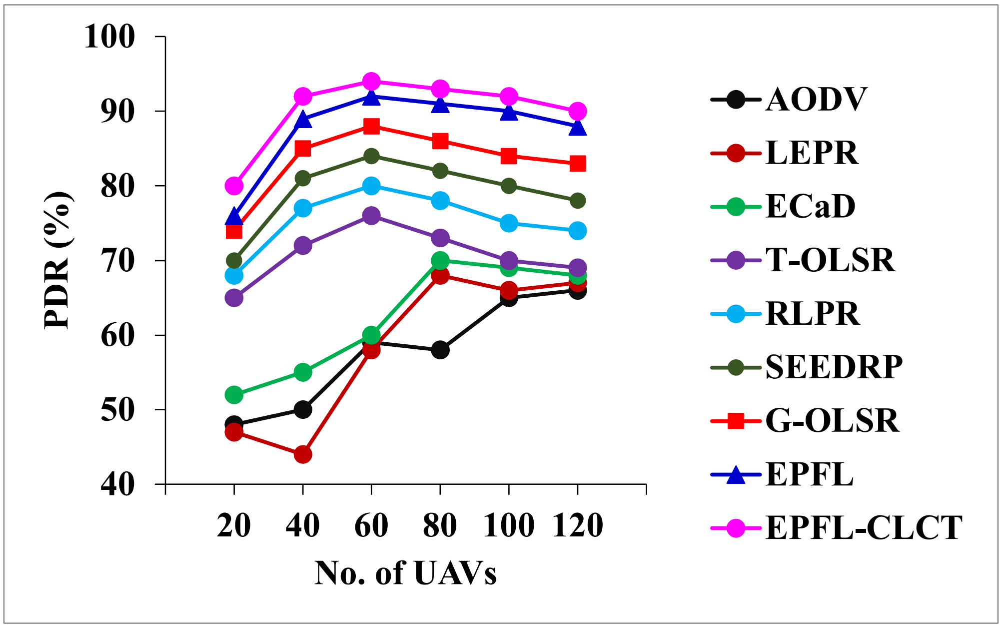

Figure 8. PDR vs. No. of UAVs

Figure 8 portrays the PDR in various RPs for the different number of UAVs in the FANET. In this scenario, it must be observed that the velocity of UAVs is 30m/s. As illustrated in Figure 4, the EPFL-CLCT protocol achieves the maximum PDR compared to the other protocols. On average, the EPFL-CLCT protocol increases the PDR by 56.36%, 54.57%, 44.65%, 27.29%, 19.69%, 13.89%, 8.2% and 2.85% compared to the AODV [19], LEPR [20], ECaD [21], T-OLSR [25], RLPR [29], SEEDRP [30], G-OLSR [31], and EPFL [18], correspondingly. Thus, the PDR is nearly stable in the EPFL-CLCT protocol while increasing the number of UAVs in the FANET.

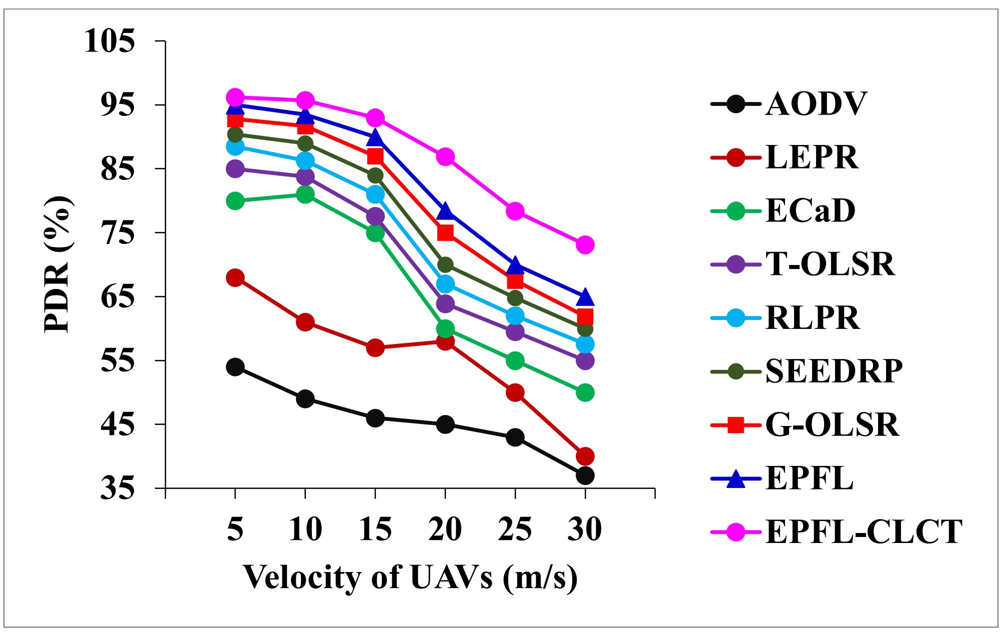

Figure 9. PDR vs. Velocity of UAVs

Figure 9 evaluates the PDR in various RPs for varying the velocity of 50 UAVs in the FANET. As depicted in Figure 5, the efficiency of different RPs is degraded and the PDR is decreased while increasing the velocity of UAVs in the FANET. If the velocity of UAVs is increased, the paths built among UAVs can be less reliable. So, the path loss change and packet failure are increased. In terms of PDR, the EPFL-CLCT protocol is the most effective. On average, the EPFL-CLCT protocol increases the PDR by 90.99%, 56.68%, 30.5%, 23.19%, 18.29%, 14.21%, 9.96% and 6.36% compared to the AODV [19], LEPR [20], ECaD [21], T-OLSR [25], RLPR [29], SEEDRP [30], G-OLSR [31], and EPFL [18], correspondingly. This is because of the adaptation of the CLCT strategy, which chooses the optimal adjacent UAVs and minimizes the transmission of redundant data replicas. Also, it minimizes the packet dropping since it prevents more unsuccessful or broken paths because of poor network connectivity.

4.3 Routing Overhead

It is the fraction of each message created in the packet forwarding task to messages delivered in the target UAV. Figure 10 illustrates the routing overhead in various RPs for the different number of UAVs in the FANET. In this scenario, it must be observed that the velocity of UAVs is a fixed range, i.e. 30m/s.

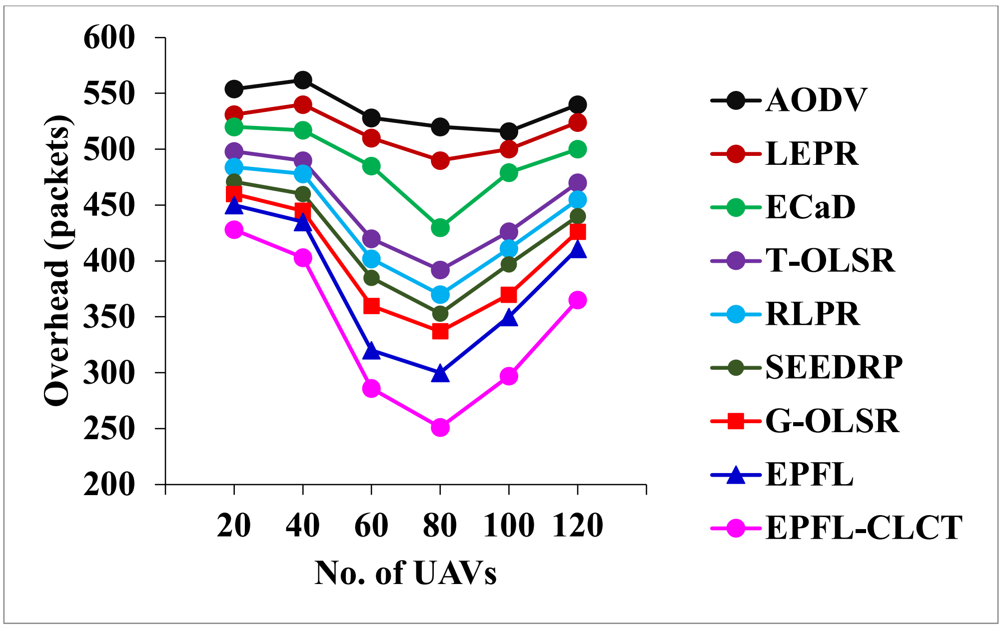

Figure 10. Overhead vs. No. of UAVs

As displayed in Figure 10, the routing overhead of the presented EPFL-CLCT protocol is less than the other protocols. It decreases the routing overhead by 36.96%, 34.41%, 30.74%, 24.7%, 21.92%, 18.99%, 15.35% and 10.41% compared to the AODV [19], LEPR [20], ECaD [21], T-OLSR [25], RLPR [29], SEEDRP [30], G-OLSR [31], and EPFL [18], respectively. This is because the CLCT strategy alleviates the redundant packet replica transmission according to the network connectivity and TP rate.

4.4 Path Stability

It is measured according to the sum of unsuccessful routes. When the RP lessens the sum of unsuccessful paths, it will create more robust paths.

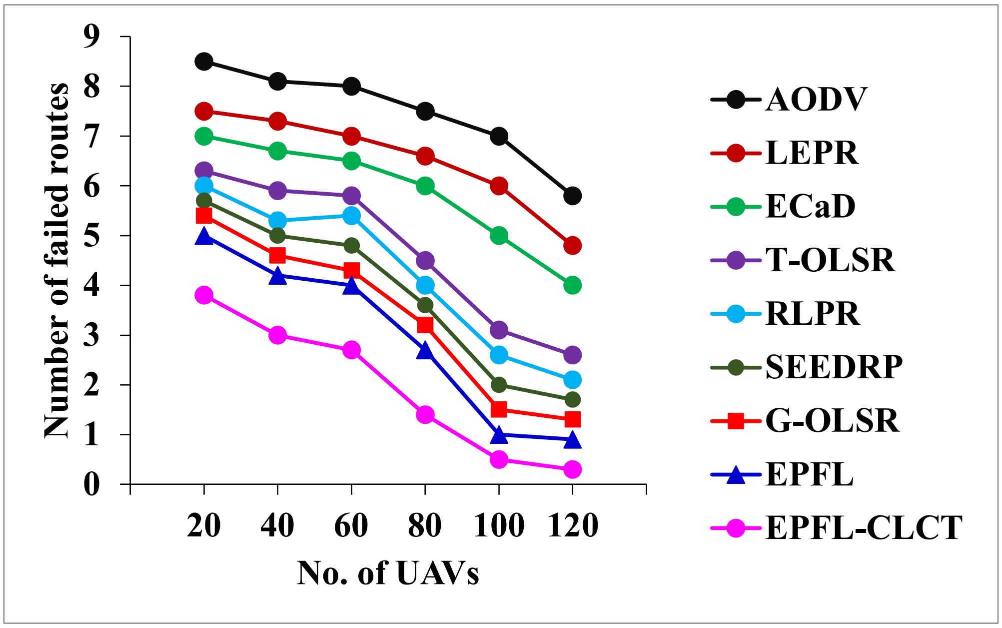

Figure 11. Path Stability (No. of Failed Routes) vs. No. of UAVs

Figure 11 depicts the number of failed routes in various RPs for the different number of UAVs in the FANET. In this scenario, it must be observed that the velocity of UAVs is a fixed range, i.e. 30m/s. Observe that the number of UAVs in the FANET and the number of failed routes are inversely correlated with each other, i.e. the more UAVs and lesser the broken paths. As depicted in Figure 11, the presented EPFL-CLCT protocol will construct more robust paths compared to the other protocols. On average, the EPFL-CLCT protocol can decrease the number of failed routes by 73.94%, 70.15%, 66.76%, 58.51%, 53.94%, 48.68%, 42.36% and 34.27% compared to the AODV [19], LEPR [20], ECaD [21], T-OLSR [25], RLPR [29], SEEDRP [30], G-OLSR [31], and EPFL [18], correspondingly.

Figure 12 illustrates the path stability of various RPs for varying the velocity of 50 UAVs in the FANET. Observe that the path stability and velocity of UAVs in the FANET are inversely correlated with each other. As a result, if the UAV's velocity increases, then the number of failed paths can be reduced. In FANET, the UAV's velocity is high, thus the RP should be effective while the UAV's velocity is high.

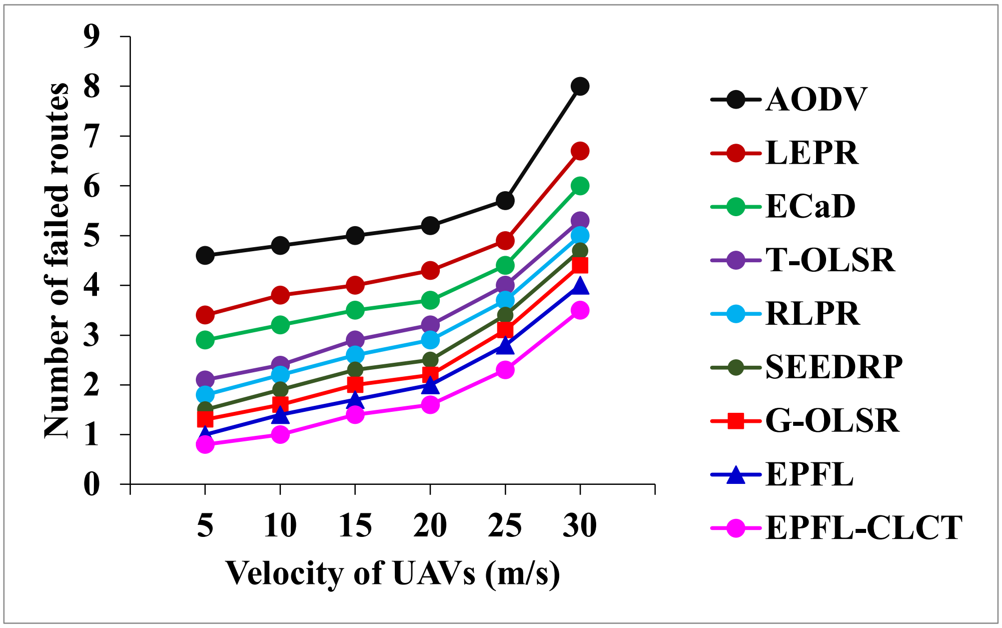

Figure 12. Path Stability (No. of Failed Routes) vs. Velocity of UAVs

As portrayed in Figure 12, the presented EPFL-CLCT protocol achieves a minimum path failure compared to the other protocols. On average, the EPFL-CLCT protocol decreases the number of failed routes by 68.17%, 60.89%, 55.27%, 46.73%, 41.76%, 34.97%, 27.4% and 17.83% compared to the AODV [19], LEPR [20], ECaD [21], T-OLSR [25], RLPR [29], SEEDRP [30], G-OLSR [31], and EPFL [18], correspondingly. This is because of using fuzzy logic and the CLCT strategy, which chooses the proper relay UAVs, and prevents the transmission link failures during packet forwarding. It considers various parameters such as network connectivity, TP rate, latency and hop count, which help to enhance the path stability by minimizing the number of broken paths because of poor network connectivity.

4.5 Hop Count

It defines the mean amount of hops exists in the route during data forwarding.

Figure 13 analyzes the number of hops in various RPs for varying transmission ranges. In this scenario, it must be observed that the number of UAVs and their velocity are fixed, i.e. 50 UAVs and 30m/s, respectively. As demonstrated in Figure 13, the EPFL-CLCT achieves the minimum number of hops compared to the other RPs. If the UAV’s transmission range is high, the number of hops is decreased since the maintenance of network connectivity is simpler in the scenario of a long transmission range.

On average, the EPFL-CLCT protocol reduces the number of hops by 63.68%, 56.74%, 50.64%, 45.39%, 40.77%, 35.83%, 28.7% and 19.79% compared to the AODV [19], LEPR [20], ECaD [21], T-OLSR [25], RLPR [29], SEEDRP [30], G-OLSR [31], and EPFL [18], correspondingly.

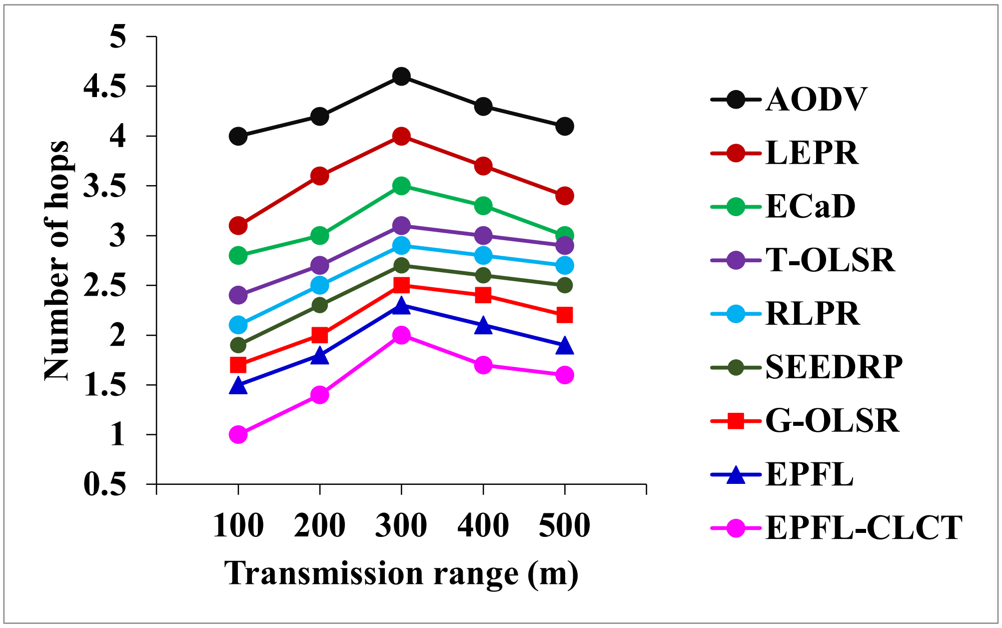

Figure 13. Hop Count vs. Velocity of UAVs

4.6 Energy Consumption

It is the sum energy dissipated by all UAVs during path creation and packet forwarding stages. Figure 14 exhibits the energy utilization in various RPs for varying simulation periods. In this scenario, it must be observed that the number of UAVs and their velocity are fixed, i.e. 50 UAVs and 30m/s, respectively. As depicted in Figure 10, the EPFL-CLCT achieves the minimum energy utilization compared to the other RPs. On average, the EPFL-CLCT protocol reduces the energy utilization by 31.26%, 23.14%, 20.38%, 16.3%, 14.17%, 11.87%, 9.86% and 6.88% compared to the AODV [19], LEPR [20], ECaD [21], T-OLSR [25], RLPR [29], SEEDRP [30], G-OLSR [31], and EPFL [18], correspondingly.

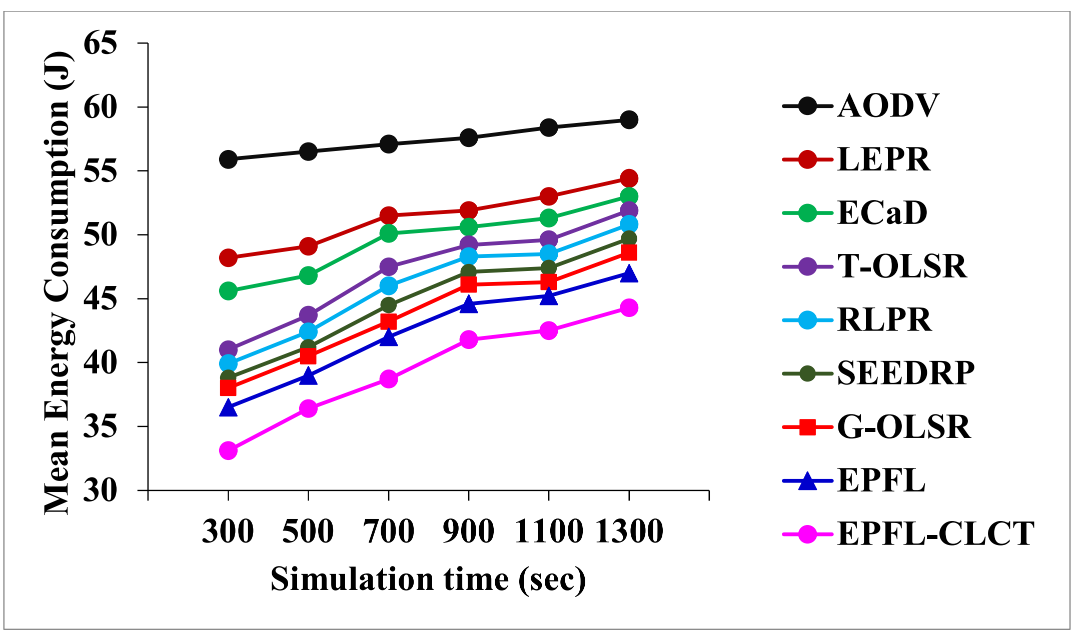

Figure 14. Energy Consumption vs. Simulation Time

This is because of determining multiple parameters like traveling direction, remaining energy of UAVs, path stability, hop count, E2D, network connectivity and TP rate to create the robust paths with the optimal adjacent UAVs in the FANET. Transmitting the redundant data replicas is alleviated, which also results in less energy utilization of UAVs in the data forwarding.

V. CONCLUSION

This article developed the EPFL-CLCT-RP in FANETs. First, the EPFL was applied to choose the best path according to the fuzzy fitness determined using various network parameters during the path creation stage. After that, the CLCT was adopted in the data transmission and path maintenance stage to avoid unstable transmission links and lessen energy usage. In this CLCT strategy, the network connectivity and the TPV were computed to choose the proper relay UAVs and prevent the transmission of multiple data packet copies. So, the PDR was increased efficiently and the energy usage during data transmission was reduced. At last, this EPFL-CLCT protocol was analyzed based on the different network metrics and contrasted with the existing RPs. On average, such outcomes prove that the EPFL-CLCT protocol has an E2D of 1.73sec, a PDR of 90.17%, an overhead of 338.33, path stability of 1.95, a hop count of 1.5 and mean energy utilization of 39.47J compared to the other RPs.

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