SSRG International Journal of Electronics and Communication Engineering
ISSN: 2348-8549/ https://doi.org/10.14445/23488549/IJECE-V13I6P110

Volume 13 Issue 6, 124-133, June 2026

Original Article

A Delay-Aware Congestion Control and Flow Aggregation Method for Improving Performance of FANET

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Received: 11 March 2026 Revised: 10 April 2026 Accepted: 09 May 2026 Published: 27 June 2026

Abstract - *Increases in the use of UAVs for communication have led to the widespread emergence of Flying Ad hoc Networks (FANET). Conversely, UAV's mobility and environmental obstacles affect communication links, resulting in link unreliability and inefficient routing. To combat these challenges, an Energy and Mobility-Aware Stable and Safe clustering (EMASS) protocol has been developed, which prevents obstacles in the routing path and minimizes the influence of high mobility on data transfer. However, it does not address the congestion issue in FANET routing, which degrades the data transfer in delay-constrained applications. Hence, this manuscript proposes a new Enhanced Intelligent-based Energy and Mobility, and Obstacle-aware Clustering (EIEMOC) protocol to control the network congestion while meeting End-to-End Delay (E2D) constraints in delay-constrained FANET applications. The main optimization objectives of this protocol are the cumulative rates over the connections and various factors that influence the E2D for 1-hop communication. First, a dispersed delay-aware congestion control scheme is developed that integrates a 1-hop delay constraint to obtain the best solution. Then, a delay support factor is introduced for every connection, and the 1-hop delay constraint is updated by conjointly merging the cumulative arriving flow and the probability of data being rejected at a specific connection. Thus, this protocol maximizes the system reliability and reduces the E2D in a dispersed manner. Finally, extensive simulations establish that the EIEMOC achieves higher network performance compared to the classical protocols in FANETs.*

Keywords - *FANET, Clustering, EMASS, Congestion, Delay-constrained network, Flow aggregation*.

1. Introduction

Drones are widely used in various sectors, with FANETs being a unique type of network consisting of multiple UAVs flying together. These networks have enhanced flexibility, squad-based execution, and frequent topological changes, which affect UAV robustness and routing protocol design [1, 2]. However, UAVs' functional limitations limit their processing power and energy capacity, affecting network longevity and dependability [3]. To enable reliable interactions, energy-efficient clustering methods should be used [4]. The emergence of UAV swarms makes data transfer and coordination challenging because UAVs have typically short ranges to broadcast and receive, and have poor communication between UAVs [5, 6].

Resolving these issues is crucial to adapting UAV topologies for various applications and tasks. UAV clustering techniques aim to improve data transfer and inter-UAV cooperation by boosting throughput, reducing latency, and power [7]. All clusters have several Cluster Members (CMs) and an elected Cluster Head (CH), which exchanges information between them. Because of UAVs' varied structure and movement, sophisticated routing techniques are crucial for stable connectivity. Failure can occur at links produced by a traditional clustering approach, and this can influence the reliability of the routing protocol, along with changes occurring in crucial frequencies, worsening the system performance [8-12].

Among many cluster-based routing protocols, the Energy and Mobility-Aware Stable and Safe clustering (EMASS) protocol was developed in [13], which utilizes Energy-Aware Link-based Clustering (EALC) and Bio-Inspired Clustering Scheme for FANETs (BICSF) methods to minimize impacts and compute the average distance among UAVs. A robust structure was used to form groups, with UAVs in similar transmission ranges engaging in electing CHs. On the other hand, legacy schemes often send Hello messages, increasing the power and bandwidth consumption in high mobility applications involving UAVs. To resolve this problem, an Intelligent-based Energy and Mobility-aware Clustering (IEMC) protocol was developed to mitigate the unnecessary dissemination of Hello packets. It adopted the Battle Royale Optimization (BRO) scheme to form a cluster and elect the optimal CH according to all UAVs' utility factor.

In route maintenance, the Hello packet duration was modified utilizing the Deep Q-Learning (DQL) approach that takes into account authorized flying areas, the number of UAVs, and velocity. Besides, training variables were adapted in response to the UAV surroundings so they could promptly react to topological changes. This approach uses a few hello packets to find neighbor routes, reducing unnecessary overhead, energy, and bandwidth consumption. Typically, FANETs use air-to-air and air-to-ground wireless links to communicate in order to achieve high consistency and low delay communications. However, the atmosphere may have some obstacles such as structures, terrain, and weather conditions. Along with the constant movement of UAVs, there are challenges in maintaining stable connections between these means and the energy, safety, and mobility awareness for resilient FANET connectivity. To address these issues, an Intelligent-based Energy, Mobility, and Obstacle-aware Clustering (IEMOC) protocol has been designed, which applies an advanced Bezier path choice to navigate barriers hindering UAVs and a velocity-based mobility estimation strategy to mitigate the effects of mobility in communication. In the event of link failure caused by an obstruction in the network, the best alternate route was identified through nearby UAVs, using mobility features, connection period, system connectivity, and path availability, thereby re-establishing the broken path without commencing the path formation procedure.

On the other hand, it does not address the congestion problem, which can degrade data transmission, specifically in E2D-restricted applications. Congestion might cause data loss and retransmissions at the MAC or top layers. Implementing a congestion control scheme is difficult as it requires consideration of various parameters. In the current congestion control strategies, the multi-hop routing in FANETs might not be effectively handled. The unreliable wireless channel leads to a varying rate of E2D and loss, which is very difficult to overcome for delay-sensitive congestion control in FANETs. Additionally, constraining the overall E2D within a certain threshold value is difficult because of the volatile connection conditions triggered by the UAV’s mobility. So, there is a need for a delay-conscious congestion control strategy, which adapts to changing connection conditions and meets E2D demands.

This article presents the EIEMOC protocol to address the congestion issue in delay-constrained FANET applications. By satisfying E2D requirements, this protocol primarily aims to control network congestion. It adopts a dispersed delay-conscious congestion control scheme, which integrates a 1-hop delay constraint to find the ideal solution. To boost the system reliability and lessen E2D in a dispersed manner, a delay support factor is introduced for every connection, and a 1-hop delay constraint is updated by conjointly merging the cumulative arriving flow and the probability of data being rejected at a specific connection.

Here is the outline of the article: Section 2 provides a summary of the prior literature. The EIEMOC protocol is discussed in Section 3. Its performance is validated in Section 4. This work is summarised in Section 5.

2. Literature Survey

Recent research on FANET routing is covered in this section. Joint Topology Control and Routing (JTCR) is a FANET protocol that Alam and Moh [14] created. To control the movement of UAVs and make sure they have stable bi-connectivity, it has a Virtual Force-based Mobility Control system. Then, an energy and mobility-aware fuzzy clustering method was used to group UAVs and aggregate sensed data to CHs using UAV mobility. Additionally, a topology-aware Q-routing algorithm was used to transfer aggregated data from CHs to the BS along the best route chosen based on the delay, route stability, and energy usage. However, energy usage and routing overhead were high because of the existence of hindrances.

Kaur et al. [15] stated the traffic congestion control scheme as a system reliability optimization dilemma in FANET. They developed a load-balancing technique based on the Geographical Position Mobility Oriented Routing (GPMOR) scheme and the Firefly method to determine the likely locations of unknown nodes inside FANETs. However, delay and energy utilization were high. Khan et al. [16] developed a fuzzy logic-based Ant Colony Optimisation (ACO) method called Ant-Hocnet for finding the best possible connection for data transfer by considering the accessible bandwidth, mobility, and connection quality. However, the average E2D was high due to high congestion in FANETs.

Liu et al. [17] formulated the optimization problem as minimizing state error with a quadratic cost function and introduced a delay-knowledgeable Markov decision process to improve performance by incorporating previous actions. They used an extended delay-knowledgeable deep deterministic policy gradient scheme, but did not address cooperative communication. Kumar et al. [18] developed a Link-optimized Cone-assisted Location (LoCaL) routing technique to increase UAV connection time. They selected a forwarding UAV according to the residual energy, connection period, and safety parameters. Also, a utility function was used to improve route stability by choosing forwarding UAVs. However, Packet Delivery Ratio (PDR) and throughput were low.

Ali et al. [19] presented a path priority UAV selection in a Link Stability and Transmission Delay-Aware (LSTDA) routing protocol that ensures dependable transmission.

However, PDR and network lifetime were low. Also, it focused only on link stability, neglecting other network parameters. Yang et al. [20] developed the Inter-Cluster Routing Protocol (ICRP) using a hybrid ACO to select the best relay node. Inspired by Physarum polycephalum's foraging conduct, it considered hop count, node load, and pheromone weight parameters. It also used prophetic restoration and reduction to handle paths for high mobility UAVs. However, packet loss occurred due to network link instability.

Hussain and Ahmad [21] presented a Delay and Energy Aware Routing (DEAR) protocol to simultaneously reduce energy usage and E2D while making routing decisions. The path selection was modified according to the energy levels of UAVs and the required delay thresholds to offer efficient data transmission and extend the network's operational life. However, PDR remained low. The Ad-hoc On-demand Distance Vector (AODV) method, known as AODV-EM, was presented by Dong et al. [22] to maximize the energy usage and mobility of UAVs. However, the PDR and network throughput were low. A hybrid protocol called Hyd-AODV was developed by Garg et al. [23] for decentralized UAV networks. However, the E2D and overhead were still high due to interferences like wind or obstacles.

From the above studies, it can be observed that current routing protocols in FANETs struggle to effectively manage congestion due to a lack of consideration of network factors. This results in poor network performance. To solve this issue, a new routing protocol is proposed in this study, which ensures fair communication and enhances network performance.

3. Proposed Methodology

The results and discussion may be presented separately, or in one combined section, and may optionally be divided into headed subsections. This part elucidates the EIEMOC protocol in detail. The UAV topology, seen in Figure 1, is characterized as an undirected Euclidean graph $G = (V, E)$, $\forall v \in V$ denotes the collection of UAVs and $\forall e \in E$ signifies the group of connections. The communication range between two UAVs is represented as r, presumed to be uniform across all UAVs. Two UAVs are considered nearby if their distance is less than r, and this distance defines the relationships in E. Consider s is a session assigned by the source UAV, and S is a collection of each implementing session. The route $E(s)$ represents the group of connections covered by s, and a group having each source that utilizes e is denoted as $S(e) = \{s \in S | e \in E(s)\}$.

The 1-hop delay over e (d_e), and the E2D of the route $E(s)$, represented as $\sum_{e \in E(s)} d_e$, must be lower than the delay threshold ζ_s. Consider that each session has an equal delay threshold, and each UAV has an equal energy level. The capacity of e, denoted as c_e, is considered invariant at a particular time Δt. All connections are defined as an M/G/1 queue, and each packet has an exponentially dispersed size with an average of K bits. Then, an estimated 1-hop delay for e at Δt is as follows:

$$d_e = \frac{K}{c_e - \sum_{s \in S(e)} r_s} \tag{1}$$

In Equation (1), $\sum_{s \in S(e)} r_s$ denotes the cumulative rate of each session over e.

The BRO-assisted clustering scheme is employed to partition the topology and identify the appropriate CH for all clusters. The residual energy, mean safety degree, and mean mobility-awareness factor for all UAVs in the specified communication range are taken into account to formulate the fitness function in the CH process. Additionally, the DQL is applied to modify the hello packet durations. The DQL uses a Deep Neural Network (DNN) with Q-learning. It generates greeting messages by selecting the optimal policy value, instead of using a distribution-based decision. And optimizes hello and timeout time for each UAV adaptively. In highly mobile FANETs, it establishes small hello intervals, closely related to frequent changes in the network architecture. This results in a higher number of connection changes in dense networks. In low mobility FANETs, it lengthens the hello interval. In low-density networks, this helps to have a reduced number of connections being changed and very few hello intervals.

Moreover, the optimal route is determined according to the node’s residual energy, degree, and distance. If any obstacle occurs in the selected route, an intelligent Bezier path selection approach is adopted to choose a different path based on the mobility awareness factor, link duration, path availability, and system connectivity. Moreover, this study prevents congestion and aggregates data flow during data transfer within delay constraints.

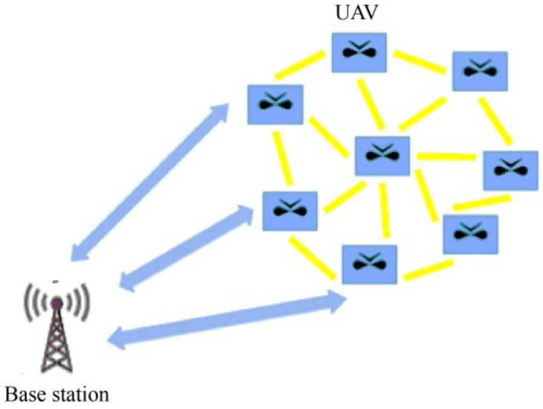

Fig. 1 Network model

3.1. Problem Formation

Consider that all source nodes can obtain a utility function $U(r_s)$ by creating a packet flow at the rate of r_s, where $U(r_s) = \omega_s \log(r_s)$ and ω_s are fixed. It is observed that $U(r_s)$ is even, rigorously concave, monotonically non-reducing, and 1-rank serially differentiable variable of r_s. This study plans to maximize the overall utility of each source node under the connection capacity and E2D constraints.

Therefore, the challenge is modeled as a utility maximization dilemma. P_1 as follows:

$$P_1: \max \sum_{s\in S} U(r_s) \tag{2}$$

$$\text{Subject to } \sum_{s\in S} r_s \le c_e, \forall e \in E \tag{3}$$

$$\sum_{e\in E(s)} d_e \le T_s, \forall s \in S \tag{4}$$

Based on the concavity of $U(r_s)$The cumulative function in Equation (2) is too concave. Because of the linear associations of the constraints (3) and (4), P_1 It is similarly a concave optimization.

3.2. Dispersed Delay-Conscious Congestion Control Scheme

It is observed that the constraint (4) is endwise strongly combined, which enables P_1 formation is highly difficult. So, to decompose the association of (4), it is viable to convert the primary difficult dilemma into a local soluble dilemma. To attain the objective, a support factor $(\bar{d}_e)$ is adopted as the 1-hop delay constraint for all e. Therefore, the following inequality holds $\sum_{e\in E(s)} \bar{d}_e \le T_s$. So, constraint (4) is defined as $d_e \le \bar{d}_e$ and $\sum_{e\in E(s)} \bar{d}_e \le T_s$. To substitute d_e With the right side of Equation (1), the 1-hop delay constraint over e is represented by ${K}\big/{\left(c_e - \sum_{s\in S(e)} r_s\right)}$ $\left(\le \bar{d}_e\right)$, and to reschedule the disparity, it will acquire the rank as:

$$\sum_{s\in S(e)} r_s \le c_e - \frac{K}{\bar{d}_e} \tag{5}$$

Since the value of $\frac{K}{\bar{d}_e}$ is higher than 0, the association $\left(c_e - \frac{K}{\bar{d}_e}\right) \le c_e$ is preserved. Examining the pattern of Equations (3) and (5), the earlier one is a highly compact constraint compared to the final one. So, Equation (5) is utilized rather than constraint (3) in P_1 formation, which are represented as:

$$P_2: \max \sum_{s\in S} U(r_s) \tag{6}$$

$$\text{Subject to } \sum_{s\in S(e)} r_s \le c_e - \frac{K}{\bar{d}_e} \tag{7}$$

$$\sum_{(i,j)\in E(s)} \bar{d}_e \le T_s \tag{8}$$

3.2.1. Lagrangian Solution

The decentralized architecture of FANETs complicates addressing congestion issues with connection capacity and delay constraints in a centralized manner. However, the Lagrangian dual approach may solve this challenge by including Lagrange multiplier vectors for constraint (6) to accelerate the optimization task, referred to as γ. The Lagrangian representation of P_2 is defined by

$$D = \max\left(\sum_{s\in S} U(r_s) + \sum_{e\in E} \gamma_e \times \left(c_e - \left(\frac{K}{\bar{d}_e} + \sum_{s\in S(e)} r_s\right)\right)\right) \tag{9}$$

By restructuring Equation (8), the following novel form is obtained:

$$D = \max\left(\sum_{s\in S}\left(U(r_s) - r_s \times \sum_{e\in E} \gamma_e\right) - \sum_{e\in E}\left(\gamma_e \times \frac{K}{\bar{d}_e}\right)\right) \tag{10}$$

It can be observed that the expressions $-max$ and min are equivalent. So, Equation (10) is split into 2 optimization problems as:

$$D_1 = \max \sum_{s\in S}\left(U(r_s) - r_s \times \sum_{e\in E} \gamma_e\right) \tag{11}$$

$$D_2 = \min \sum_{e\in E}\left(\gamma_e \times \frac{K}{\bar{d}_e}\right) \tag{12}$$

$$\text{Subject to } \sum_{e\in E(s)} \bar{d}_e \le T_s, \forall s \in S \tag{13}$$

Based on the feature of $U(r_s)$, D_1 It is considered an unconstrained concave optimization. This is resolved by the gradient descent approach. The ideal value of r_s is determined by

$$r_s^* = \operatorname{argmax}\left(U(r_s) - r_s \times \sum_{e\in E} \gamma_e\right) \tag{14}$$

The notation $\gamma_e(n)$ is the value of the Lagrange multiplier γ_e at n^{th} step.

$$\gamma_e(n+1) = \left[\gamma_e(n) - \beta \frac{\partial D}{\partial \gamma_e}\right]^+ \tag{15}$$

In Equation (15), β refers to the step size variable, the operation $[\cdot]^+$ represents $x = \max\{0, x\}$, and

$$\frac{\partial D}{\partial \gamma_e} = c_e - \left(\frac{K}{\bar{d}_e} + \sum_{s\in S(e)} r_s\right) \tag{16}$$

In dynamic situations, network topology often varies, leading to unstable channel states. So, choosing a constant step size is crucial to ensure convergence and speed up the computations.

It is noticed that r_s^* solely associated with the cumulative step size $\sum_{e\in E(s)} \gamma_e$ from Equation (14). On the other hand, the update of γ_e is related to r_s and $\bar{d}_e$ defined with Equation (15).

According to this, it is essential to determine $\bar{d}_e$. For the sake of D_2, considering the regularity for the ideal value of (4) is necessary, hence the endwise data must be used in the form of $\bar{d}_e$. Such a local solution should be found in order to avoid any delay that is due to the information present on the channels on the route, and which may affect the efficiency of the solution.

The probability of a data being rejected at e because of the extreme 1-hop delay threshold is derived by

$$P_{th} = P_r\{d_e > \bar{d}_e\} = e^{\{-(c_e - \sum_{s\in S(e)} r_s)\times \bar{d}_e\}} \tag{17}$$

From Equation (17), it is observed that P_{th} is proportional to the cumulative rate $\sum_{s\in S(e)} r_s$, however, an inverse case of the c_e and $\bar{d}_e$. The association in Equation (17) achieves the objective of this study, which is to develop a technique to compute $\bar{d}_e$ by constraining the proportions of P_{th}.

Consider that constant $0 < \varepsilon < 1$ is the maximum margin of P_{th} permitted by the transmission scheme for each link, and substitute P_{th} With ε, Equation (17) is transformed into

$$\varepsilon = e^{\{-(c_e - \sum_{s\in S(e)} r_s)\times \bar{d}_e\}} \tag{18}$$

Then, $\bar{d}_e$ is determined as follows:

$$\bar{d}_e = \frac{-1n\varepsilon}{c_e - \sum_{s\in S(e)} r_s} + \varepsilon_e \tag{19}$$

In Equation (19), ε_e represents the cumulative delay errors on the connections traversed by the data before reaching e. The initial 1-hop delay constraint is defined as $\bar{d}_e^{int} = {}^{T}/_{|E(s)|}$, and the primary ε is determined via substituting $\bar{d}_e$ with $\bar{d}_e^{int}$. The 1-hop error $\bar{\varepsilon}_e$ is defined by $\bar{\varepsilon}_e = \bar{d}_e - \bar{d}_e^{int}$. Consider $|H_e|$ is the sum of hops traversed by the data between source s and e, apart from the connection e. Therefore, $\varepsilon_e = \left(\sum_{e=s}^{|H_e|} \bar{\varepsilon}_e\right) \Big/ {}_{|H_e|}$. For the network to reach a steady mode within a specific duration, consider $\sum_{e=s}^{|H_e|} \bar{\varepsilon}_e \leq 0$ should be satisfied for each session because of the existence of a delay threshold ζ_s.

Once this condition is met, Equation (19) can be substituted into the objective of Equation (12), leading to the optimization of D_2 towards an optimal solution as $\sum_{s\in S(e)} r_s$ increases. The solution obtained from Equation (19) is then utilized to adjust the iterations given in Equation (15).

Consequently, when the rates r_s of all sources and the Lagrange multiplier vector γ reach optimality, $\bar{d}_e$ also achieves an optimal solution for all e. This study proposes an efficient technique to solve the optimization problem.

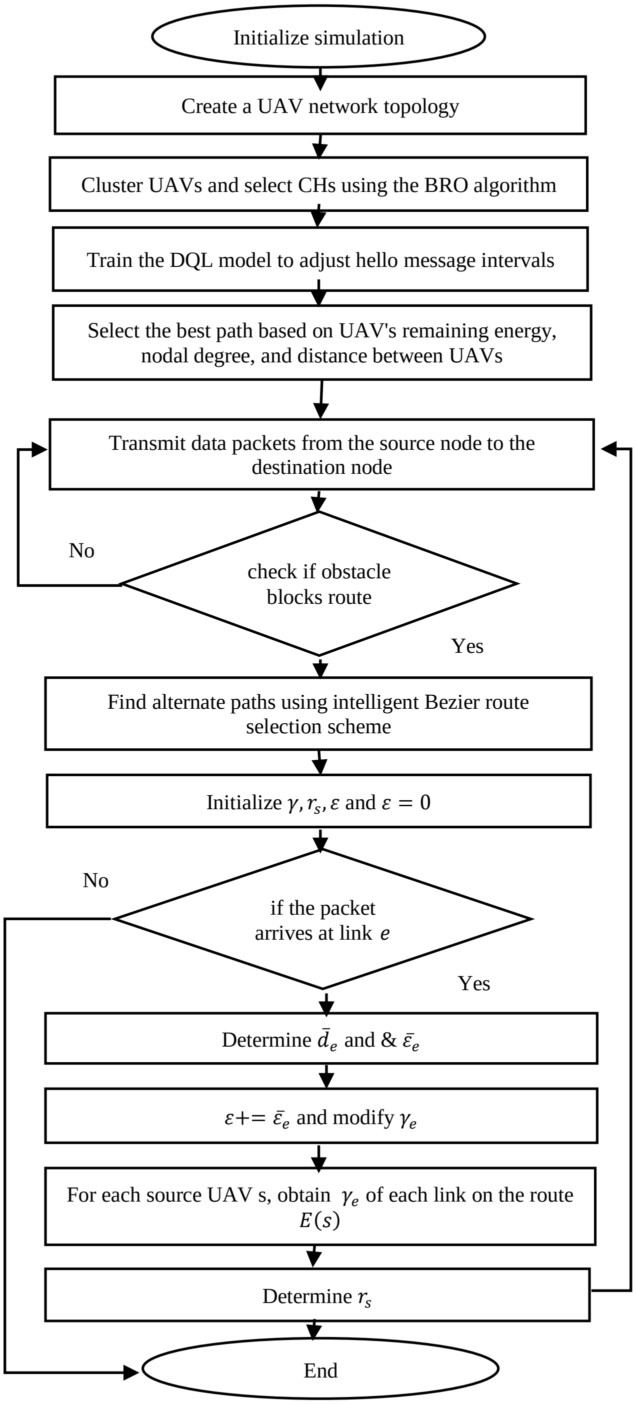

Fig. 2 **Flow diagram of EIEMOC protocol for FANETs**

P_2 by updating parameters based on local information. However, the constraint in Equation (12) may lead to the total 1-hop delays on the route exceeding. ζ_s. It is evident that the problem is solved by updating ε. When a large amount of data is rejected because of ζ_s, a higher ε is needed. Algorithm 1 summarises the completion of this congestion control scheme's execution with the IEMOC protocol, and Figure 2 shows a flow diagram of the EIEMOC protocol for FANETs.

Algorithm 1: Dispersed Delay-Conscious Congestion Control Scheme in IEMOC Protocol

```
Input: N UAVs
Result: Congestion-free best alternate paths
Start
Construct the UAV system and group UAVs;
Use the BRO scheme to pick CHs and DQL to fine-tune the hello packet duration.
Pick the route among UAVs according to the route identification factor [9];
while(data transmission is ongoing)
  if(an obstacle presents on a route)
    Choose alternate paths utilizing an intelligent Bezier route selection scheme;
  end if
  Initialize the parameters $\gamma, r_s, \varepsilon$ and $\varepsilon = 0$;
  while(vector $\gamma$ remains unchanged)
    if(the packet arrive at link e)
      Determine $\bar{d}_e$ using Equation (19);
      Determine $\bar{\varepsilon}_e$;
      $\varepsilon += \bar{\varepsilon}_e$;
      Modify $\gamma_e$ with $\sum_{s \in S(e)} r_s$ and $\bar{d}_e$;
      for(each source UAV s)
        Obtain $\gamma_e$ of each link on the route $E(s)$;
        Determine $r_s$ using Equation (14);
      end for
    end if
  end while
  Transfer data between the source and target UAVs through the chosen path;
end while
End
```

4. Simulation Results and Discussion

The EIEMOC protocol's performance is assessed and compared to that of other protocols in this section: EMASS [7], GPMOR [15], LSTDA [19], ICRP [20], DEAR [21], and AODV-EM [22]. The simulations are executed with NS2.35 on a machine equipped with an i5-4210 CPU @ 2.80 GHz, 4 GB RAM, Windows 10 64-bit OS. The parameters used for simulation are listed in Table 1. The DQL parameters are given in [12]. The assessment is based on PDR, E2D, overhead, energy use, and cluster longevity across different numbers of UAVs.

4.1. PDR

It counts the number of packets sent and received by the two UAVs as:

$$PDR = \frac{\sum received\ data\ packets\ at\ the\ destination}{\sum transmitted\ data\ packets\ from\ the\ source} \quad (20)$$

Table 1. Parameters settings

Parameters	**Values**
No. of UAVs	200
Mobility type	Reference point mobility model
Velocity of UAVs	20-60 m/s
MAC protocol	IEEE 802.11a
Data rate	100 kbps
Communication rate	2.4 GHz
Propagation type	Free space
Transmission range	100 m
Message size	250 bytes
Starting energy for UAVs	85 W/h
Simulation duration	200 s
Simulation zone	1500×1500 m^2

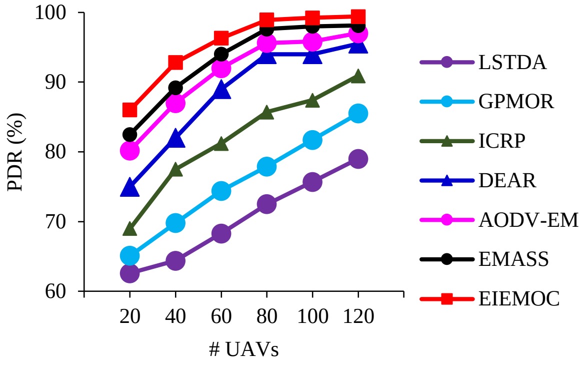

Fig. 3 PDR vs. UAV Counts

Figure 3 shows the PDR of several FANET routing protocols as the number of UAVs in the network increases, with a mobility speed of 20 m/s. It can be found that the PDR of the EIEMOC is relatively greater than the others. For 120 UAVs, EIEMOC increases the PDR by 25.82%, 16.26%, 9.35%, 4.08%, 2.47%, and 1.33% compared to the LSTDA, GPMOR, ICRP, DEAR, AODV-EM, and EMASS protocols, respectively.

4.2. E2D

It determines the average duration for the packets to reach destination UAVs as:

$$E2D = \frac{\sum_{p_i \in L} T_A(p_i) - T_D(p_i)}{Total\ number\ of\ data\ packets\ (L)} \quad (21)$$

In Equation (21), p_i indicates the accepted packet, $T_A(p_i)$ denotes the acceptance period of p_i, and $T_D(p_i)$ indicates the transferring interval of p_i. Figure 4 illustrates the average E2D results for various routing schemes under varying UAV counts at 20 m/s mobility. It can be observed that the average E2D of the EIEMOC is comparatively lower than the others. With 120 UAVs, the E2D of EIEMOC is decreased by 40.4%, 37.93%, 36.4%, 34.55%, 27.42%, and 16.28% compared to the

LSTDA, GPMOR, ICRP, DEAR, AODV-EM, and EMASS, respectively.

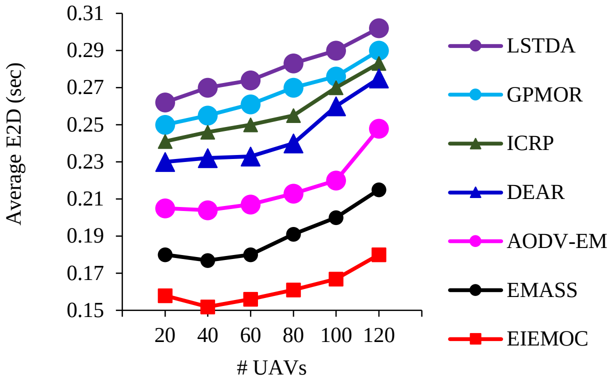

Fig. 4 E2D vs. UAV Counts

4.3. Energy Usage

It determines the absolute energy utilized by every UAV per second as:

$$E_{total} = E_z \times T_z \tag{22}$$

In Equation (22), p_z indicates the energy dissipated in state z, and T_z indicates the interval taken in z, where z is data observing, transfer, reception, and inactive.

Figure 5 displays the overall energy consumed by various routing protocols for varying UAV quantities at 20 m/s mobility. It can be observed that the energy consumed by the EIEMOC is less than that of the others. With 120 UAVs, the energy consumed by EIEMOC is reduced by 59.23%, 57.37%, 54.57%, 50.31%, 41.11%, and 29.65% compared to the LSTDA, GPMOR, ICRP, DEAR, AODV-EM, and EMASS protocols, respectively.

4.4. Routing Overhead

It determines the proportion of all messages generated at the source UAVs to messages accepted by the destination UAV. Figure 6 displays the routing overhead for various protocols under different UAV quantities at 20 m/s mobility. It can be observed that the overhead of the EIEMOC is less than that of the others. With 120 UAVs, the routing overhead of EIEMOC is reduced by 53.05%, 50%, 44.44%, 39.58%, 33.33%, and 13.04% compared to the LSTDA, GPMOR, ICRP, DEAR, AODV-EM, and EMASS protocols, respectively.

4.5. Cluster Lifespan

It determines the duration taken to form clusters and elect CHs until a fresh CH is re-elected. Figure 7 portrays the cluster lifespan for various protocols with an increasing number of UAVs at 20 m/s mobility. It is observed that the cluster lifespan of the EIEMOC is higher than that of the others. With 120 UAVs, the cluster lifespan of EIEMOC is 63s, which is higher than the cluster lifespan values of LSTDA, GPMOR, ICRP, DEAR, AODV-EM, and EMASS protocols, such as 21s, 26s, 32s, 38s, 46s, and 55s, respectively.

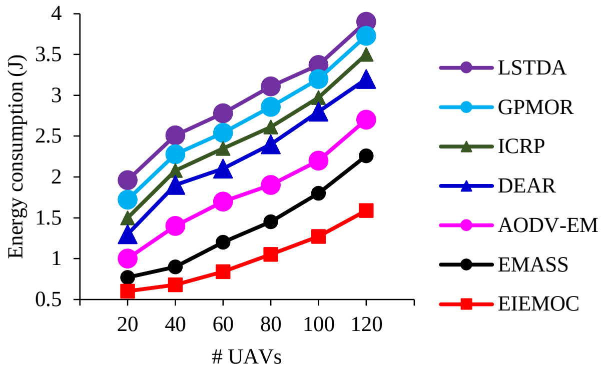

Fig. 5 Energy usage vs. UAV Counts

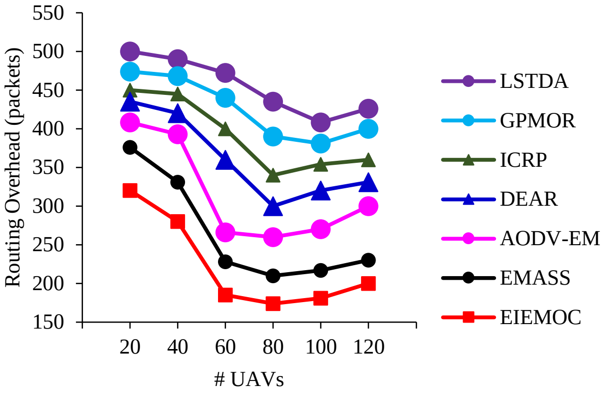

Fig. 6 Routing overhead vs. UAV Counts

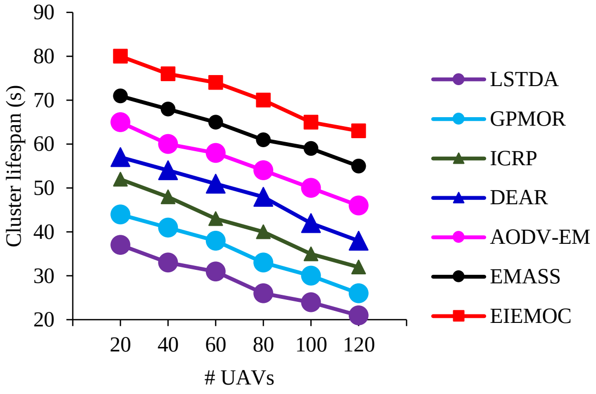

Fig. 7 Cluster lifespan vs. UAV Counts

4.6. Ablation Study

This section presents the results obtained from the ablation experiments for 120 UAVs, which considers two different scenarios: (i) EIEMOC without the delay-conscious congestion control scheme and (ii) EIEMOC without the flow aggregation method. Table 2 presents the results of the ablation study.

Table 2. Results for ablation study

Metrics	Without delay-conscious congestion control	Without flow aggregation	EIEMOC (both delay-conscious congestion control + flow aggregation
PDR (%)	98.2	97.4	99.4
E2D (s)	0.32	0.48	0.18
Energy usage (J)	1.68	1.85	1.59
Routing overhead (packets)	211	234	200
Cluster lifespan (s)	53	45	63

Table 3. Comparison between existing protocols and proposed EIEMOC for varying UAV mobility (No. of nodes = 120)

UAV velocity	LSTDA	GPMOR	ICRP	DEAR	AODV-EM	EMASS	EIEMOC
	PDR (%)						
20	79	85.5	90.9	95.5	97	98.1	99.4
30	77.3	83.9	89.2	94.0	95.5	96.7	98.8
40	76.0	82.3	87.7	92.5	93.8	95.2	96.9
50	73.5	80.6	84.4	90.2	91.4	92.9	94.3
60	69.8	77.4	81.5	87.6	89.4	90.3	92.8
UAV velocity	**E2D (ms)**						
20	0.262	0.250	0.241	0.230	0.205	0.180	0.158
30	0.271	0.258	0.247	0.238	0.215	0.187	0.166
40	0.284	0.267	0.253	0.247	0.222	0.199	0.176
50	0.295	0.280	0.262	0.255	0.231	0.210	0.184
60	0.310	0.289	0.275	0.267	0.240	0.221	0.196
UAV velocity	**Energy Consumption (J)**						
20	1.96	1.72	1.50	1.30	1.00	0.77	0.60
30	2.14	1.91	1.63	1.38	1.14	0.91	0.72
40	2.20	2.04	1.75	1.51	1.23	1.08	0.85
50	2.35	2.13	1.90	1.63	1.35	1.19	0.98
60	2.47	2.25	1.99	1.76	1.50	1.31	1.10
UAV velocity	**Routing Overhead (packets)**						
20	500	474	450	435	408	376	320
30	512	490	465	451	423	394	338
40	528	503	482	468	449	410	356
50	540	518	499	487	466	425	371
60	556	530	513	501	480	439	388
UAV velocity	**Cluster Lifespan (s)**						
20	37	44	52	57	65	71	80
30	34	41	48	53	62	67	75
40	31	38	45	49	58	64	70
50	28	34	40	45	53	59	66
60	25	30	36	40	49	52	61

It is observed that the proposed EIEMOC, which incorporates both delay-conscious congestion control and flow aggregation, increases the PDR by 1.22% and 2.05% compared to the case without delay-conscious congestion control and flow aggregation, respectively. The E2D is 43.75% and 62.5% lower than in the same scenarios. Energy usage is reduced by 5.36% and 14.05% compared to the same cases. The overhead for routing is also decreased by 5.21% and 14.53%, respectively (compared to the same cases). The cluster lifespan is increased by 18.95% and 40% compared to similar situations. The results of these analyses indicate that the proposed EIEMOC, which combines delay-aware congestion control and a flow aggregation approach, has substantial benefits in terms of network performance and efficiency.

Table 3 gives a comparison of the performance of the existing protocols and the suggested EIEMOC on varying vehicles of UAVs (20–60 m/s) with a constant network size of 120 nodes. Due to the high mobility of UAVs, there is an enhanced dynamicity of the network, which influences the stability of routing and communication performance. The results showed that with the increase of UAV velocity, the number of breaks in the links reduces, thus causing a decrease in PDR. However, the PDR of EIEMOC is higher than that of other protocols, which means that its data transmission is more reliable. With more movement from the UAV's in the E2D scenario, there is a corresponding delay as more route discoveries/retransmissions are needed. However, EIEMOC has the lowest delay among all levels of mobility compared to the others. In the same manner, the use of energy also increases as UAV speed increases because of an increase in control operations and maintaining the routes. Despite these circumstances, EIEMOC reduces the energy usage compared to the existing protocols, which indicates it is the most energy-efficient communication method.

The overhead routing grows over the speed of the UAV because, as the speed increases, more control packets are needed for the path discovery and maintenance. By regulating congestion, EIEMOC can reduce the overhead of the other protocols. Similarly, cluster lifespan decreases with increasing UAV velocities as clusters tend to be unstable.

However, EIEMOC maintains the highest cluster lifespan. Overall, the findings show that EIEMOC offers greater reliability, lower delay and energy usage, and better network stability even when UAV mobility is high.

5. Conclusion

This study developed the EIEMOC protocol for congestion management in delay-constrained FANETs. This protocol considered the cumulative flow rates over the connections and distinct factors that influence the total E2D for 1-hop communication as the objective functions. The dispersed delay-conscious congestion control scheme was developed by integrating a 1-hop delay constraint to discover the ideal solution. Also, a delay support factor was adopted for all connections in the selected route. Then, the 1-hop delay constraint was updated by relating the cumulative arriving flow and probability of data being rejected at a specific connection to reduce E2D and boost system reliability. Finally, simulation findings revealed that the EIEMOC for 120 nodes attained a 99.4% PDR, 0.18s mean E2D, 1.59J consumed energy, 200 packets overhead, and 63s cluster lifespan in contrast with the LSTDA, GPMOR, ICRP, DEAR, AODV-EM, and EMASS protocols.

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