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ARTICLE

Integrated Energy-Efficient Distributed Link Stability Algorithm for UAV Networks

Altaf Hussain[1], Shuaiyong Li[2], Tariq Hussain[3], Razaz Waheeb Attar[4], Farman Ali[5,*], Ahmed Alhomoud[6] and Babar Shah[7]

[1]School of Computer Science and Technology, Chongqing University of Posts and Telecommunications, Chongqing, 400065, China

[2]Key Laboratory of Industrial Internet of Things and Networked Control, Ministry of Education, Chongqing University of Posts and Telecommunications, Chongqing, 400065, China

[3]School of Computer Science and Information Engineering, Zhejiang Gongshang University, Hangzhou, 310018, China

[4]Management Department, College of Business Administration, Princess Nourah bint Abdulrahman University, Riyadh, 11671, Saudi Arabia

[5]Department of Applied AI, School of Convergence, College of Computing and Informatics, Sungkyunkwan University, Seoul, 03063, Republic of Korea

[6]Department of Computer Science, College of Science, Northern Border University, Arar, 91431, Saudi Arabia

[7]College of Technological Innovation, Zayed University, Dubai, 19282, United Arab Emirates

*Corresponding Author: Farman Ali. Email: farmankanju@gmail.com

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ABSTRACT

Ad hoc networks offer promising applications due to their ease of use, installation, and deployment, as they do not require a centralized control entity. In these networks, nodes function as senders, receivers, and routers. One such network is the Flying Ad hoc Network (FANET), where nodes operate in three dimensions (3D) using Unmanned Aerial Vehicles (UAVs) that are remotely controlled. With the integration of the Internet of Things (IoT), these nodes form an IoT-enabled network called the Internet of UAVs (IoU). However, the airborne nodes in FANET consume high energy due to their payloads and low-power batteries. An optimal routing approach for communication is essential to address the problem of energy consumption and ensure energy-efficient data transmission in FANET. This paper proposes a novel energy-efficient routing protocol named the Integrated Energy-Efficient Distributed Link Stability Algorithm (IEE-DLSA), featuring a relay mechanism to provide optimal routing with energy efficiency in FANET. The energy efficiency of IEE-DLSA is enhanced using the Red-Black (R-B) tree to ensure the fairness of advanced energy-efficient nodes. Maintaining link stability, transmission loss avoidance, delay awareness with defined threshold metrics, and improving the overall performance of the proposed protocol are the core functionalities of IEE-DLSA. The simulations demonstrate that the proposed protocol performs well compared to traditional FANET routing protocols. The evaluation metrics considered in this study include network delay, packet delivery ratio, network throughput, transmission loss, network stability, and energy consumption.

KEYWORDS

FANET; UAV; internet of UAVs; relay mechanism; energy consumption; routing; IEE-DLSA

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1 Introduction

With the advancement of network technology, Unmanned Aerial Vehicles (UAVs) have been used as flying nodes to monitor the environment remotely [1–3]. These UAVs are part of an ad hoc network called the Flying Ad hoc Network (FANET) [4,5]. There are two types of communication in FANET: UAV-to-UAV communication [6] and nd station [6]. UAVs can be deployed anywhere without any human personnel. Therefore, FANET is mainly deployed where a human approach is impossible or in places that are a danger zone for humans [7]. With the Internet of UAVs (IoU-enabled) technology, the FANET is more useful in flying communication. The IoU-enabled FANET has been applicable for multiple purposes, including remote sensing [8,9], the smart delivery of drones [10,11], transportation [12], military communication [13,14], and so on. Although this technology has tremendous potential, many energy and routing issues with the IoU of drones can impact the network's performance. UAVs have limited power and computational capabilities. Thus, the energy in this network is a major concern. The group of flying UAVs is known as a "swarm of UAVs," in which each UAV is connected to another [8–10]. In this regard, the UAVs perform router and sender/receiver functionalities. Some have fixed wings, and some have rotors or propellers that can hover in the air for a specific time to observe and remotely sense the target area effectively. Recent research has focused on FANET energy consumption models and efficiency [11–15]. The Integrated Energy-Efficient Distributed Link Stability Algorithm (IEE-DLSA) routing protocol has been proposed in this paper for energy consumption to consume less energy and effectively communicate during the communication process.

As stated earlier, the flying nodes UAVs of FANET will be the eyes of the humans in the sky [16,17]. To be effectively functionalized and operated long-term in the sky, these UAVs are equipped with computational power and limited batteries to speed up the process [18,19]. Thus, it is important to enhance the communication skills of these UAVs by enhancing their energy level [20]. It is important to efficiently organize in a fashion that can consume less energy and reduce packet and transmission loss during transmission. To be deployed on the network layer, these UAVs have to overcome the problems they are facing regarding energy and routing [21]. The core contribution and focus of the proposed work are to design an energy-efficient routing protocol for FANET and to evaluate it with the existing approaches to FANET. To avoid any disruption and packet and transmission loss, the network must deal with the theme of the relay in which the advanced relay energy nodes have been utilized. To introduce the smart concept of drones, the IoU-enabled FANET will be able to work, perform, and adapt to the environment. As the UAVs travel far from one another and the distance increases, the transmission loss models can deal with this aspect to calculate the best routing path for data transmission and amplify the signal [20–22].

Routing with an energy-efficient approach is crucial in scenarios where nodes are equipped with limited power batteries. This consideration is particularly important in the context of FANETs, where the energy constraints of UAVs can significantly impact network performance [23,24]. This paper proposes a novel energy-efficient routing protocol for FANET called IEE-DLSA. The IEE-DLSA protocol aims to effectively transfer data by utilizing advanced nodes to measure energy efficiency through a relay approach. This relay mechanism optimizes routing paths, ensuring that data transmission is energy-efficient and reliable.

Additionally, the protocol incorporates the R-B tree data structure to manage and balance the energy load among network nodes. This ensures that energy-efficient nodes are used fairly, preventing overuse and promoting balanced energy consumption across the network. By combining the relay approach with the R-B tree method, IEE-DLSA maintains optimal performance in energy-constrained environments, such as FANETs. The proposed protocol not only improves network stability and reduces energy consumption but also enhances the overall efficiency and longevity of the network. Through this innovative approach, IEE-DLSA ensures that FANETs can be effectively utilized, providing a reliable and energy-efficient solution for data transmission in UAV networks. The key contributions of the proposed IEE-DLSA are given below:

- The proposed IEE-DLSA routing protocol introduces a novel approach to enhance energy efficiency in FANETs. This innovative protocol, IEE-DLSA, is specifically designed to address these networks' energy consumption challenges. The key feature of this protocol is its relay mechanism, which optimizes routing paths to select the most energy-efficient routes for data transmission. This mechanism not only helps reduce energy consumption but also enhances the overall stability of the network, making it particularly suitable for applications on the IoU. By building upon and addressing the limitations of the existing DLSA routing scheme, IEE-DLSA offers significant improvements in network performance and energy management.
- A notable contribution of the IEE-DLSA protocol is utilizing the R-B tree method for managing and balancing the energy load among network nodes. The R-B tree is a self-balancing binary search tree that ensures efficient data organization and retrieval. In the context of IEE-DLSA, the energy load is distributed more evenly across the network. This method prevents the overuse of any single node by ensuring that energy-efficient nodes are used fairly, promoting balanced energy consumption. Consequently, this approach enhances the overall energy efficiency of the network, extending the operational lifetime of FANETs.
- The performance of the IEE-DLSA protocol is demonstrated through its higher Packet Delivery Ratio (PDR). The protocol achieves a PDR of 93.131%, which is significantly higher than that of existing routing methods such as EE-LEACH (Energy-Efficient Low-Energy Adaptive Clustering Hierarchy), AC-OLSR (Adaptive Clustering Optimized Link State Routing), and DLSA (Delay and Link Stability Aware). This high PDR indicates the protocol's effectiveness in maintaining stable connections and ensuring reliable data delivery. The ability to deliver a higher percentage of packets successfully is crucial for the performance of FANETs, especially in challenging environments where maintaining stable and reliable communication links is difficult.
- The contributions of the proposed IEE-DLSA routing protocol are manifold. First, it introduces a novel energy-efficient routing mechanism that significantly optimizes network performance and stability. Second, it leverages the R-B tree method to ensure fair and balanced use of energy-efficient nodes, enhancing overall network energy efficiency. Third, it achieves a higher PDR than existing routing protocols, demonstrating its effectiveness in maintaining reliable and stable network performance. These advancements collectively push the boundaries of energy-efficient routing for FANETs and IoU, offering substantial improvements in network stability, energy consumption, and reliability. Overall, the IEE-DLSA protocol represents a significant advancement in energy-efficient routing for FANETs. By addressing the limitations of existing protocols and introducing innovative mechanisms for energy management and routing optimization, the IEE-DLSA protocol provides a robust solution for enhancing the performance and longevity of FANETs. Its contributions to energy efficiency, network stability, and reliability make it a valuable addition to the state-of-the-art FANET and IoU technologies.

The structure of this article is as follows: In Section 2, the existing approaches are discussed. Section 3 discusses the proposed methodology with a mathematical model for IEE-DLSA. In Section 4, the results are analyzed. Finally, Section 5 presents the conclusion of this work.

2 Related Work

This section consists of the related work and the contrast of the proposed work. Different state-of-the-art solutions have been discussed in this section. Most state-of-the-art routing has been discussed in FANET because this research has focused on routing cooperatively.

De Rango et al. [1] suggested a novel routing protocol that has the ability and has been inspired by nature to operate like natural insects such as moths and ants, which act as a swarm. The moth can heave in the air, and ants can perform in a sward fashion. Thus, the proposed protocol has nature-inspired capabilities. Sharma et al. [6] proposed a problem of network partitioning, in which they divided this network into three layers, each named with different labels. The authors have proposed a routing scheme named the Distributed Priority Tree-based Routing (DPTR) protocol.

Using a tree named R-B, the concept of network partitioning was accomplished because the tree can balance the nodes in the network by giving them the highest priority. They have tested their proposed protocol based on the performance metrics overhead, delay, Packet Delivery Ratio (PDR), throughput, and channel utilization. They have witnessed that their work has shown outstanding performance compared with the state-of-the-art. da Costa et al. [25] proposed a routing approach for FANET, in which the quality and quartile of the FANET were addressed. For mobility purposes and scenarios, the authors have proposed their work to overcome the issue of network delay and network throughput. To minimize and keep the lowest possible network delay and maximize and enhance the network throughput performance. Zhao et al. [26] suggested a FANET routing protocol to overcome the issue of energy consumption and transmission loss.

The authors have focused on the lowest possible and enhanced energy consumption models. The core contribution is that the authors have proposed their work for FANET regarding energy consumption and proposed an energy-efficient protocol. In this regard, the protocol consumes less energy, has less delay, can gain high throughput, and gives a high network lifetime. The authors in this work have focused on energy consumption and use a path-finding route from one node to another with an efficient solution. Lin et al. [27] proposed a routing protocol to improve the routing approach in FANET. With a focus on the OSI layers, the authors have drawn attention to layered approach models for FANET. Nebbou et al. [28] proposed a routing approach on which the three major categories were introduced and focused. The three major aspects are information on road traffic, the forwarding, and the recovery strategy with the backward. With the utilization of the VANET, the authors have deployed their work of FANET into VANET to combine a strategy and form an ad hoc network of vehicles for road and flying. Darabkh et al. [29] introduced a threshold-based value in which one node does not go far away from another and where link instability and discontinuation occur. The terminology CTS/RTS was also introduced to monitor and avoid collision of the nodes. From the simulations, it has been revealed that the proposed Multi Data Rate Mobility Aware (MDRMA) has outperformed well in contrast with the other Mobility Aware and Dual Phase AODV Protocol with Adaptive Hello Messages (MA-DP-AODV-AHM). Bharany et al. [23] and Mah et al. [30] suggested an approach based on security in which the path of the flight and power of transmission of the UAV is based on the perspective of relay optimizations for improving security. In this regard, they have used an algorithm named Particle Swarm Optimization (PSO), in which the power and path of the UAV flight are jointly utilized as a single device to improve security and the energy level. Souza et al. [31] suggested a routing protocol in which the major concerns are the quality of energy and service. With the NS-2 implementation, they have derived the results and evaluated their work with state-of-the-art solutions.

Abualola et al. [32] have a concept called Multi-Point Relays (MPR), which the relay concept uses to boost the network and avoid delay. Along with that, they have also used a clustering mechanism to improve the network. Their simulations revealed that the contrast was based on PDR, delay, and throughput with state-of-the-art. Jain et al. [24,33] introduced a novel scheme in which the primary focus was based on energy to save energy by using the Energy Efficient Hello (EE-Hello) approach as a proposed work. In this work, the authors proposed a method in which if a node must send a message to other nodes, the distance was estimated before sending that message to predict the environment. The main task was to stop unnecessary messages and improve the network's quality. Anand et al. [34] said in their work that they focused on the Medium Access Control (MAC) layer in which the routing protocols utilize the measurement and calculations of stability and the network threshold of stability. Their major focus is to link stability with the MAC layer implementation. Tropea et al. [35] focused on accurately using FANET in multiple applications. The authors have thoroughly surveyed this to cover all the aspects of this network that can be considered an advanced tool in the future. Hussain et al. [22] introduced a routing protocol named DLSA for network improvement in FANET. The authors' major contribution was to focus on link stability effectively. The authors have proposed a threshold measuring values for link stability. With the introduction of link stability, the maximum threshold values are selected for FANET.

Aissa et al. [36] proposed an algorithm based on a clustering mechanism for providing the same distance and fast mobility of the UAV network and extending the network's lifetime and stable communication. Introducing a clustering algorithm, this work focused on the mechanism of clustering to segregate and classify the desired task. For evaluation purposes, the authors have compared the Energy, Safety, and Mobilit Aware Scheme (EMASS) with Bio-Inspired Clustering Scheme for FANET (BICSF) and Energy Aware Link based Clustering (EALC) based on guaranteed safety, high PDR, low delay, and improved energy saving. Zhao et al. [37] suggested an IoT-enabled routing protocol for FANET. The authors have focused in this work on enabling the Internet of Drones (IoD) technology in which the smart UAVs can perform well in a smart environment where the UAVs can automatically use a smart fashion to operate. Khan et al. [38] proposed an ant colony-inspired routing protocol that can perform in the fashion of the ants. The ants live in a colony and form a swart. So, the work they presented can operate ad hoc and use sword fashion. In this fashion, the UAVs operate and create a link with another UAV, and so on. All the UAVs perform in a sward fashion and maintain the best distance, in which transmission loss and other signal loss seldom occur. Namdev et al. [39] proposed a Whale Optimization Algorithm-Optimized Link State Routing (WOA-OLSR) scheme. A routing protocol, an existing approach of FANET with the combination of the WOA algorithm capabilities, is proposed. With the WOA, the OLSR can perform in the dynamic environment in which the dynamic topology is used. The OLSR uses the MPR to use the relay mechanism. Park et al. [40] presented an existing approach named AODV. This work performs the activity by demand, and each table entry is updated on demand. If an entry changes, the entire table's entries are also changed by the flooding, route request, and route reply mechanism. For security purposes, the authors have proposed this work. Radley et al. [41] resented the movement-aware routing protocol for FANET. Movement activities use mobility models such as random waypoints, indoor positioning technology [42–44].

Previous studies [1–3], despite significant strides in developing various routing protocols and addressing key issues in FANET, present several limitations. Firstly, many of these studies are constrained by the specific scenarios or simulation environments in which they were tested, leading to potential generalizability and real-world applicability limitations. For instance, although innovative, the routing protocols inspired by natural behaviors, such as those by De Rango et al. [1] and Khan et al. [38] may not fully account for the complexities and unpredictability of real-world network conditions. Moreover, works like those by Sharma et al. [6] and Aissa et al. [36], which proposed hierarchical or clustering-based approaches, might face scalability challenges when applied to larger, more dynamic networks. Additionally, some studies, such as those by Pasandideh et al. [8] and Abualola et al. [32], focus on specific performance metrics like delay, throughput, or energy consumption, potentially overlooking other critical factors like security, robustness, and adaptability in diverse environmental conditions. The reliance on simulations rather than real-world deployments also raises concerns about the accuracy and reliability of the results, as seen in the works of Souza et al. [31] and Tropea et al. [35]. Furthermore, while certain protocols like those proposed by Bharany et al. [23] and Mahmud et al. [33] aim to enhance security and energy efficiency, their approaches might introduce additional computational overhead, potentially affecting overall network performance. Finally, the use of specific algorithms, such as the Particle Swarm Optimization (PSO) in Bharany et al.'s work [23] and the WOA in Namdev et al.'s study [39], although effective in theory, may not fully translate into practical, scalable solutions, particularly in highly dynamic and unpredictable FANET environments.

Several research gaps are identified and addressed based on the literature review and the contributions of the proposed IEE-DLSA protocol.

- Energy Efficiency in Routing Protocols: Existing protocols often focus on specific aspects of energy efficiency but lack a comprehensive approach that integrates energy consumption with overall network stability. The IEE-DLSA protocol addresses this by incorporating a relay mechanism and R-B tree method to balance energy load among nodes, optimizing energy usage and network stability.
- Packet Delivery Ratio (PDR): Many existing protocols, such as EE-LEACH, AC-OLSR, and DLSA, struggle to maintain a high Packet Delivery Ratio (PDR) in challenging environments. IEE-DLSA improves upon these by achieving a significantly higher PDR, indicating better reliability in data transmission.
- Network Longevity: While protocols like MDRMA focus on reducing energy consumption, they often neglect the impact on network longevity and stability. The IEE-DLSA protocol contributes to extending the operational lifetime of FANETs by ensuring balanced energy consumption across the network.
- Mobility Handling: Existing works like da Costa et al. [8] and Nebbou et al. [28] address mobility scenarios but often with network stability and energy management limitations. The IEE-DLSA protocol enhances these aspects by introducing a more efficient routing mechanism better suited for the dynamic environments in which FANETs operate.
- Clustering Mechanisms: While some protocols incorporate clustering mechanisms for load balancing and network stability, they often do so without optimizing energy efficiency. The IEE-DLSA protocol leverages the R-B tree method to ensure a more energy-efficient and balanced use of network nodes, enhancing energy management and network stability.

Limitations & Issues with Existing Works.

- Limited Focus on Energy Balance: Many existing protocols, such as EE-LEACH and AC-OLSR, emphasize energy efficiency but do not effectively manage energy balance across the network, leading to potential overuse of certain nodes and reduced network longevity.
- Suboptimal Routing Paths: DLSA may not always select the most energy-efficient routing paths, leading to higher energy consumption and reduced network performance. The IEE-DLSA protocol addresses this by optimizing routing paths through its relay mechanism.
- Inadequate Handling of High Mobility: Protocols proposed by da Costa et al. [8] and Nebbou et al. [28] may not efficiently handle high-mobility scenarios, leading to increased

delays and reduced throughput. The IEE-DLSA protocol improves on this by maintaining stable and efficient communication links even in dynamic environments.

- Complexity in Implementation: Some state-of-the-art protocols, such as those using clustering mechanisms or multi-layer approaches, can be complex to implement and may require significant computational resources. The IEE-DLSA protocol aims to balance complexity and efficiency, offering a more streamlined approach to energy management and routing optimization.
- Security Concerns: Protocols focusing on energy efficiency or mobility, such as the one by Bharany et al. [23] may overlook security aspects, potentially making the network vulnerable to attacks. While IEE-DLSA focuses on energy efficiency and stability, additional security measures may still be needed to address potential vulnerabilities in FANETs. By identifying these gaps and issues, the IEE-DLSA protocol presents a significant advancement in addressing the challenges of energy efficiency, network stability, and reliability in FANETs.

3 IEE-DLSA: The Proposed Protocol

The FANET nodes monitor the environment remotely using photosensors embedded in UAVs that fly in the air. The data acquired by the UAVs must be reliable enough to be received by the destination nodes.

These nodes are UAVs that operate from a distance, and energy plays a vital role. These UAVs are equipped with limited energy, and the flying nodes consume more energy when operated from a long distance. To fully connect nodes and stabilize the communication of these nodes with the ground stations. The energy-efficient algorithm is introduced, in which the relay nodes work as threshold measuring nodes to boost the connection and optimize the energy in FANET. In this paper, a novel protocol, IEE-DLSA, has been proposed, with a major focus on its energy efficiency. As shown in Fig. 1, the proposed protocol comprises three existing FANET protocols: DLSA, EE-LEACH, and AC-OLSR. The existing works have focused on link stability, network partitioning, and network corridor selection for maximum channel optimization. In IEE-DLSA, the focus has been placed on optimizing and deploying an energy-efficient algorithm in the existing protocol.

3.1 System Model

Based on the contributions outlined, we can develop a system mathematical model with equations that incorporate the IEE-DLSA protocol's principles.

3.1.1 Proposing IEE-DLSA Routing Protocol

- Novel Energy-Efficient Routing Protocol

The routing protocol aims to minimize energy consumption while maintaining network stability. The energy consumption EC for transmitting a packet can be modeled as in Eq. (1):

$$E_{tx} = P_{tx} \,.\, T \tag{1}$$

where, E_{tx} is the energy required for transmission, T is the transmission time, and P_{tx} denotes the power of transmission.

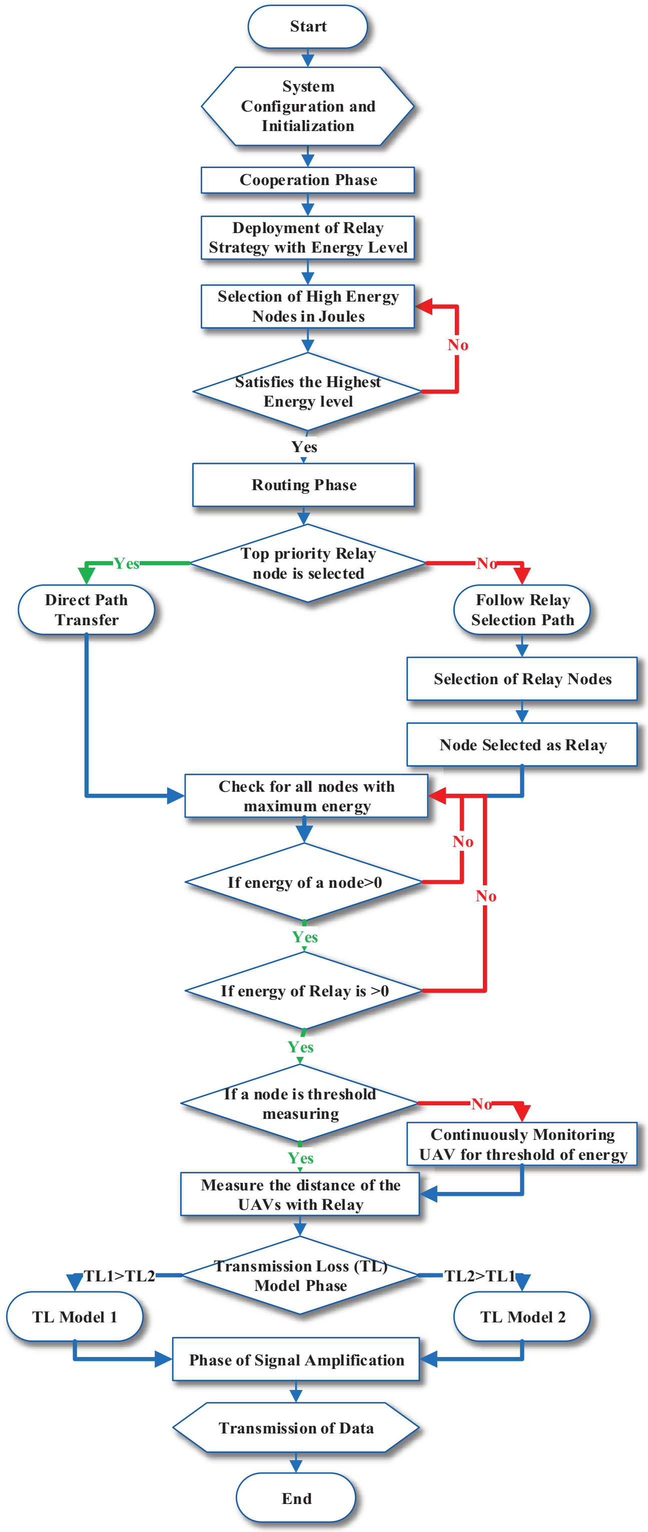

Figure 1: Operation and working of IEE-DLSA protocol

For IEE-DLSA, the energy consumption $E_{IEE\text{-}DLSA}$ can be formulated as in Eq. (2):

$$E_{IEE-DLSA} = P_{tx} \,.\, T . f_{relay} \left(d, N\right) \tag{2}$$

where, $f_{relay}\left(d, N\right)$ is a function representing the relay mechanism, considering distance d and the number of nodes N.

- Relay Mechanism

The relay mechanism optimizes routing paths to minimize energy usage can be given as in Eq. (3):

$$f_{relay}\left(d, N\right) = \min\left(\sum\nolimits_{i=1}^{N}\left(\frac{d_i}{p_{tx_i}}\right)\right) \tag{3}$$

where, d_i and p_{tx_i} are the distance and transmission power of the ith node in the relay path.

- Enhanced DLSA Scheme

To improve network stability, we define the stability function S as in Eq. (4):

$$S_{IEE-DLSA} = S_{DLSA} \,.\, g_{stability}(d, N) \tag{4}$$

where, $g_{stability}(d, N)$ enhances the existing DLSA stability by considering node mobility and link duration.

3.1.2 Utilization of R-B Tree Method for Energy Efficiency

- Efficient Use of the R-B Tree Method

The energy load balancing using the R-B tree can be expressed as in Eq. (5):

$$L_{RB}\left(t\right) = \frac{1}{N}\sum\nolimits_{i=1}^{N} E_i(t) \tag{5}$$

where, $E_i(t)$ is the energy level of the ith node at time t, and $L_{RB}\left(t\right)$ is the balanced load distribution over N nodes.

- Fairness for Advanced Energy-Efficient Nodes

Fair usage of nodes can be ensured by the fairness index F as in Eq. (6):

$$F = \frac{\left(\sum_{i=1}^{N} E_i\right)^2}{N.\sum_{i=1}^{N} E_i^2} \tag{6}$$

This index ensures that no single node is overburdened, thus balancing the energy consumption.

The energy and relay node implementations of IEE-DLSA have been performed in five phases. In 1st phase, the network initialization has been done in which the UAV's neighborhood support is utilized. In the 2nd phase, the stability period of the network is utilized, during which the expected transmission count and the estimated link time are introduced. In 3rd phase, the energy of UAVs has been utilized, for which the proposed energy metric is introduced for both the sending and the receiving UAVs. In 4th phase, the deployment of the keys for the UAVs has been introduced. Finally, in 5th phase, the proposed four parameters have been merged and assigned a weight criterion for each.

3.1.3 UAV's Neighborhood Support (Network Initialization Phase)

For evaluations of nearby support of each UAV, obtain the number of nearby nodes that lie in the range of UAVs in FANET. If a UAV contains a vast number of nearby nodes, then there are three factors for which it is selected: to neglect packet drop, to consume less energy, and to maximize packet transmission effectively. UAV's Neighborhood Support (UNS) is obtained by using Eqs. (7) and (8):

$$N\left(U_a\right) = \{U_b, \ni distance\left(U_a, U_b\right) < TRU_a\} \tag{7}$$

$$UNS\left(U_a\right) = |N(U_a)| \tag{8}$$

The terms U_a and U_b = ath nodes of FANET and the distance have been shown by distance (U_a, U_b), which is less than the range of transmission of the UAVs denoted by TRU_a. The U_a, $|N(U_a)|$ Denotes the number of UAVs in the U_a and the UNS (U_a), which denotes the value of the UAVs in the UNS and is expressed by U_a. The U shows the initials of the UAVs in the given equations and the upcoming equation, too. The U_a and U_b denote the sender and the receiver UAV and thus are illustrated by these terms.

UAV's Stability Period (Network Operational Time Phase)

The UAV's mobility is also linked to the UAVs Stability Period (USP). In FANET, the UAVs are linked with other UAVs, and the estimated time of the connected UAVs linked period is for obtaining the stability period of every UAV in IEE-DLSA routing by FANET. This indicates that many USPs have the potential to provide less mobility of UAVs in terms of an optimal routing technique. At the initial stage, the UAV's Estimated Time of the Link (ETL) is developed by using Eq. (9), and then the evaluation of USP is performed by using Eq. (10):

$$ETL\left(U_a, U_b\right) = \frac{-\left(pq + rs\right) + \sqrt{(p^2 + r^2)(TR)^2 - (ps - qr)^2}}{p^2 + r^2} \tag{9}$$

The expression ETL (U_a, U_b) illustrates the estimated time of the link from the ath and bth UAVs. The terms $p = SU_a\ cos\theta U_a - SU_b\ cos\theta U_b$, $q = U_{xa} - U_{xb}$, $r = SU_a\ sin\theta U_a - SU_b\ sin\theta U_b$, and $s = U_{yb}$ and the TR shows the transmission range. Sua and Sub represent the speed of the ath and bth UAVs with the proposed direction of $\theta U_a \& \theta U_b$, Ux_a, Ux_b, Uy_a, Uy_b = xth and yth components of ath and bth UAVs:

$$USP\left(U_a\right) = \frac{\sum_{U_b=1}^{UNB(U_a)} ETL(U_a, U_b)}{UNB\left(U_a\right)} \tag{10}$$

The term USP (U_a) denotes the ath USP of the UAVs in the proposed scenario.

UAV's Energy (Energy Efficiency Phase)

With the maximum energy level, the UAVs have been optimally deployed for IEE-DLSA in FANET. As a ratio of remaining energy, the UAV's Energy (UE) has been calculated to the value of UNS of a node with having a specific time in FANET in Eq. (11):

$$UE\left(U_a\right) = \frac{Residual\_Energy\ \left(U_a\right) - Residual\_Energy\left(U_b\right)}{UNS\ \ \left(U_a, U_b\right)} \tag{11}$$

In the meantime, Residual Energy (RE) (U_a) and RE (U_b) denote the remaining energy of the ath and bth UAVs, and UE denotes the energy of the UAV in the given equation.

UAV's Key Deployment (UAVs Deployments Phase)

For optimal routing in IEE-DLSA, a UAV possesses the maximum number of keys to utilize effectively. The proposed keys are utilized to encrypt the data packets. For one/single file encryption, a single key must be utilized in UAVs for FANET. Diverse keys encrypt diverse data packets in UAVs such as U_a *and* U_b. So, UAV's Key Deployment (UKD) is calculated by using Eqs. (12) and (13).

$$UKD\left(U_a\right) = \begin{cases} \sum_{k=1}^{k} UK_{U_a,k} & if\ \exists\ keys \in U_a \\ 0 & otherwise \end{cases} \tag{12}$$

where,

$$UK_{U_a,k} = \begin{cases} 1 & if\ K_k \in U_a \\ 0 & Otherwise \end{cases} \tag{13}$$

In the meantime, the $UKU_{a,k}$ is the relation of the UAVs with the ground nodes, which deploys the keys for relay optimizations and illustrates the relation between the ath UAVs and the kth keys. The K_k illustrates the Kth key from the group of key K's, and $UKD\ (U_a)$ illustrates the value of ath UAV.

UAV's Concluding Substantial Weight (Merging Strategy of UAVs)

This is the last and combining phase of the IEE-DLSA in which the UAV's Concluding Substantial Weight (UCSW) has been obtained for every UAV with the combination of the proposed parameters (UNS, USP, UE, and UKD) for the generation of multi-objectives feature by Eqs. (14) and (15).

$$Maximizing\ UCSW = (\omega_1 * UNS) + (\omega_2 * USP) + (\omega_3 * UE) + (\omega_4 * UKD) \tag{14}$$

where, the terms $\omega_1, \omega_2, \omega_3$, and ω_4 illustrate the weights of every parameter and their values are 0.25, 0.25, 0.25, and 0.25, respectively, thus

$$\omega_{1(0.25)} + \omega_{2(0.25)} + \omega_{3(0.25)} + \omega_{4(0.25)} = 1 \tag{15}$$

For optimal routing of IEE-DLSA in FANET, the R-B tree with UCSW was applied after obtaining the multi-objective feature of UCSW. This can maximize the value of UCSW by obtaining the best results. In the R-B tree, the UAVs are represented as red and black with a fair mechanism for energy efficiency. For FANET, the R-B tree has been concluded to satisfy a condition of concluding, and the best UAVs are found from the existing ones.

3.2 Procedures of IEE-DLSA

The working operations of IEE-DLSA consist of 6 steps, and each step represents the methodology used for it.

Step-1: For UAV evaluation, the UNS is evaluated in Eqs. (7) and (8).

Step-2: For the generation of ETL of the UAVs, Eq. (9) and UAVs USP calculation Eq. (10) are used.

Step-3: For the calculation of UE, Eq. (11) is used.

Step-4: For the calculation of UKD, Eqs. (12) and (13) are used.

Step-5: To obtain UCSW of the UAVs with the combination of UNS, USP, UE, and UKD for generation of the multi-objectives feature, Eqs. (14) and (15) are used.

***Step-6*:** To generate UCSW with a multi-objectives feature, Steps 1 to 5 are recurrently repeated for all UAVs in FANET. The proposed IEE-DLSA operates in Algorithms 1 and 2.

To develop an energy-efficient and relay mechanism system mathematical model for a drone system using the proposed IEE-DLSA, we must consider several aspects of the drone's operation, including energy consumption, relay mechanisms, and search efficiency.

3.3 Energy Consumption

Let's denote the following parameters;

P_h: Power consumption during hover (Watts).

P_f: Power consumption during flight (Watts).

$\mathcal{V}$: Velocity of the drone during flight (m/s).

t_h: Time spent hovering (seconds).

t_f: Time spent flying (seconds).

E_{total}: Total energy consumed (joules).

The total energy consumption E_{total}: can be expressed in Eq. (16) as:

$$E_{total} = P_h \, . \, t_h + P_f \, . \, t_f \tag{16}$$

Let's include a factor considering the IEE-DLSA mechanism, where energy efficiency is improved through optimized search patterns and relay mechanisms. $\eta_{IEE-DLSA}$ representing the efficiency improvement, which is given in Eq. (17) as:

$$E_{total} = \eta_{IEE-DLSA} \, . \, \left(P_h \, . \, t_h + P_f \, . \, t_f\right) \tag{17}$$

3.4 Relay Mechanism

We assume that drones relay information to a base station or between each other for the relay mechanism. Let's denote:

D: Distance between the drone and the base station or relay point (meters).

P_{tx}: Power consumption for transmission (Watts).

R: Data rate (bits per second).

d: Distance covered per relay (meters).

N_r: Number of relays.

The power consumption for transmission can be affected by the distance D and is given in Eq. (18) as:

$$P_{tx} = P_{tx,0} \, . \, \left(\frac{D}{d}\right)^{\alpha} \tag{18}$$

where, $P_{tx,0}$ is the base transmission power, and α is the path loss exponent (typically between 2 and 4 for free space).

The total energy for transmission E_{tx} can be expressed in Eq. (19) as:

$$E_{tx} = P_{tx} \, . \, \left(\frac{N_r \, . \, D}{\upsilon}\right) \tag{19}$$

Including the efficiency factor for IEE-DLSA, $\eta_{IEE-DLSA}$ and is given in Eq. (20) as:

$$E_{tx} = \eta_{IEE-DLSA} \cdot P_{tx,0} \cdot \left(\frac{D}{d}\right)^{\alpha} \cdot \left(\frac{N_r \cdot D}{\upsilon}\right) \tag{20}$$

3.5 Search Efficiency

The efficiency of the search algorithm affects the time the drone spends in the air and, thus, its energy consumption. Let's calculate as:

A: Area to be searched (square meters).

$\tau_{IEE-DLSA}$: Search efficiency factor for IEE-DLSA.

The time to search the area t_s can be approximated by Eq. (21) as:

$$t_s = \tau_{IEE-DLSA} \cdot \frac{A}{\upsilon} \tag{21}$$

3.6 Combined Scheme

Combining these aspects, the total energy consumption E_{total} for the drone system incorporating the IEE-DLSA can be expressed as:

$$E_{total} = \tau_{IEE-DLSA} \cdot \left(P_h \cdot t_h + P_f \cdot t_f + P_{tx,0} \cdot \left(\frac{D}{d}\right)^{\alpha} \cdot \left(\frac{N_r \cdot D}{\upsilon}\right)\right) \tag{22}$$

Eq. (22) encapsulates the impact of the IEE-DLSA on the drone's energy consumption through more efficient hover, flight, transmission, and search operations.

3.6.1 Considerations

Flight and Hover Time: t_h and t_f are derived based on mission parameters and search patterns.

Transmission: Efficient relay mechanisms reduce P_{tx}.

Search Efficiency: Optimized search algorithms reduce t_s.

By incorporating the IEE-DLSA efficiency factors into each component of the drone's operation, the overall energy efficiency can be significantly enhanced, leading to extended operational time and reduced energy consumption. Algorithm 1 illustrates the EE and Relay mechanism of the proposed IEE-DLSA protocol.

Algorithm 1: Energy efficient (EE) advanced relay algorithm

1. Inputs:
2. N–Number of nodes;
3. M–Number of messages or other relevant parameter;
4. K–Number of iterations or specific control parameters; % N, M, K are the parameter constraints that are used for Ground Nodes (N), Aerial Nodes (M), and their Mutual link (K) as relay nodes.
5. Energy Efficient Relay Nodes-Set of nodes designed for energy efficiency;
6. Output:
7. UAV's Energy Efficiency in IEE-DLSA;
8. Ensure there are 75 nodes and 25 EE (Energy Efficient) nodes;
9. Initialize a R-B tree for fairness with EE nodes;

(Continued)

Algorithm 1 (continued)

10. while the conditions that are terminated are not satisfied; % Continue until termination conditions are met;
11. do;
12. for each node UAV; % Loop through each UAV node
13. do;
14. if UAV(EE_n)<=UAV($EE_n{}^*$); % Check if the energy of node i is less than or equal to a threshold
15. then;
16. $EE_n{}^* \leftarrow$ (EE_n); % Assign EE_n as the current energy efficiency node
17. end;
18. end;
19. NMK Neural with Aerial and Ground UAVs, where 'EE_n' is the selected energy-efficient node and
'EE^*' is the updated energy efficiency for the current iteration
20. UAV($EE_n{}^*$) and $EE^* \leftarrow EE_{NMK}$;
21. UAV(EE_n); % Update the energy of the UAV nodes using a specific (Eq. (11))
22. $EE_n \leftarrow EE+$UAV(EE_n); % Update the energy efficiency node
23. end;

The EE advanced relay algorithm enhances UAV networks' energy efficiency through energy-efficient relay nodes. The algorithm takes three inputs: the total number of UAVs (N), the number of energy-efficient relay nodes (M), and the specific parameter K, which could represent a variable in the network. The goal is to ensure optimal energy efficiency across the UAV network, particularly within the IEE-DLSA framework. Initially, the algorithm sets up an R-B tree structure to ensure fairness in energy efficiency distribution among the nodes. This setup involves 75 UAVs, out of which 25 are designated as energy-efficient nodes.

The core loop of the algorithm runs until the termination conditions are met, iterating over each UAV node. For each node, it checks if a node's energy efficiency (EE_n) is less than or equal to a predefined threshold ($EE_n{}^*$). If this condition is met, the node's energy efficiency is updated (EE_n). *The process then involves using a neural approach that integrates both aerial and ground* UAVs, *updating their energy efficiencies* UAV(EE_n) and EE^*. This phase leverages Neural Network methodologies to optimize energy consumption patterns dynamically. The updated energy efficiency values for the UAVs are computed using a specific equation (denoted as Eq. (11) in the algorithm). Subsequently, the energy efficiency of each node is recalculated by combining the energy-efficient node's value with the current UAV's efficiency ($EE_n \leftarrow EE+$UAV(EE_n)). The loop continues, iteratively refining the energy efficiency of the network until the conditions are satisfied, thereby ensuring sustained energy efficiency across the UAV network. The Complete IEE-DLSA Algorithm 2 with the input parameters NU = Number of UAVs for the nodes' Energy Efficiency is below:

Algorithm 2: IEE-DLSA working algorithm

1. % Algorithm for IEE-DLSA Protocol
2. % Step 1: Network Initialization Phase
3. procedure InitializeNetwork (UAVs, TR);
4. for each UAV U_a in UAVs, do;
5. neighbors = getNeighbors (U_a, UAVs, TR);

(Continued)

Algorithm 2 (continued)

```
        U_a.UNS = count(neighbors);
    end for;
end procedure;
% Step 2: Network Operational Time Phase
procedure ComputeStability(UAVs);
    for each UAV U_a in UAVs, do;
        total_ETL = 0;
        for each neighbor U_b in U_a.neighbors do;
            ETL = computeETL (U_a, U_b);
            total_ETL += ETL;
        end for;
        U_a.USP = total_ETL/length (U_a.neighbors);
    end for;
end procedure;
% Step 3: Energy Efficiency Phase
procedure ComputeEnergy (UAVs);
    for each UAV U_a in UAVs, do;
        remaining_energy = U_a.initial_energy - U_a.consumed_energy;
        U_a.UE = remaining_energy/U_a.UNS;
    end for;
end procedure;
% Step 4: UAV Deployment Phase
procedure ComputeKeyDeployment (UAVs, keys);
    for each UAV U_a in UAVs, do;
        U_a.UKD = 0;
        for each key k in keys, do;
            if keyAssignedTo (Ua, k) then;
                U_a.UKD += 1;
            end if;
        end for;
    end for;
end procedure;
% Step 5: Merging Strategy of UAVs
procedure ComputeUCSW(UAVs, weights);
    for each UAV U_a in UAVs, do;
        U_a.UCSW = (weights.UNS * U_a.UNS) +;
                   (weights.USP * U_a.USP) +;
                   (weights.UE * U_a.UE) +;
                   (weights.UKD * U_a.UKD);
    end for;
end procedure;
% Step 6: Relay Mechanism Phase;
procedure OptimizeRelay(UAVs);
    for each UAV U_a in UAVs, do;
        bestRelay = selectBestRelay(U_a, UAVs);
```

(Continued)

Algorithm 2 (continued)

```
        Ua.relay = bestRelay;
        Ua.energy_consumed += computeEnergyConsumption(Ua, bestRelay);
  end for;
end procedure;
% Main Procedure
procedure Main(UAVs, TR, keys, weights);
   InitializeNetwork(UAVs, TR);
    ComputeStability(UAVs);
    ComputeEnergy(UAVs);
    ComputeKeyDeployment(UAVs, keys);
    ComputeUCSW(UAVs, weights);
    OptimizeRelay(UAVs);
end procedure;
```

The IEE-DLSA aims to optimize energy consumption while maintaining network stability in UAV networks. The algorithm encompasses multiple phases, each contributing to the overall objective of energy-efficient network operations. The first phase, Network Initialization, involves setting up the network by identifying the neighbors of each UAV within a given transmission range (TR) and counting the number of such neighbors (UNS). This step ensures that each UAV knows its immediate network environment, which is crucial for subsequent operations.

In the Network Operational Time Phase, the algorithm computes the stability of the network by evaluating the total Expected Transmission Loss (ETL) for each UAV. Each UAV calculates its stability parameter (USP) by averaging the ETL values of its neighbors. This phase ensures that the network's operational stability is assessed and maintained. The Energy Efficiency Phase follows, where the remaining energy of each UAV is calculated by subtracting the consumed energy from the initial energy. The energy efficiency (UE) of each UAV is then determined by dividing the remaining energy by the number of its neighbors (UNS).

The UAV Deployment Phase involves computing the key deployment metrics (UKD) for each UAV based on the keys assigned to them. This phase ensures that each UAV has an optimal key deployment strategy, enhancing overall network security and efficiency. The algorithm then proceeds to the Merging Strategy Phase, where a composite stability weight (UCSW) is calculated for each UAV. This weight is a weighted sum of various parameters, including the number of neighbors (UNS), stability parameter (USP), energy efficiency (UE), and key deployment (UKD). This phase ensures that the UAVs are merged optimally based on their composite stability weights.

Finally, the Relay Mechanism Phase focuses on optimizing the relay selection for each UAV. The best relay for each UAV is selected based on specific criteria, and the energy consumed in communicating with the selected relay is computed. This phase ensures the UAVs select the most energy-efficient relay nodes, optimizing overall network energy consumption. The main procedure of the algorithm integrates all these phases, ensuring that the UAV network is initialized, its stability and energy efficiency are computed, key deployment is optimized, composite stability weights are calculated, and the relay mechanism is optimized, resulting in a highly energy-efficient and stable UAV network.

3.7 The Working Principle of IEE-DLSA

IEE-DLSA protocol for Enhancing Energy Efficiency: The proposed IEE-DLSA routing protocol introduces a novel approach to improve energy efficiency in FANETs. This protocol is specifically designed to address the energy consumption challenges inherent in these networks by implementing a relay mechanism that optimizes routing paths. The relay mechanism dynamically selects the most energy-efficient routes based on node energy levels, transmission distance, and link stability. By continuously monitoring these parameters, the relay mechanism ensures that only optimal paths are used, thereby reducing overall energy consumption and enhancing network stability. This makes the IEE-DLSA protocol particularly suitable for applications in the IoU. Utilization of the R-B Tree for Energy Load Management: A significant contribution of the IEE-DLSA protocol is integrating the R-B tree data structure to manage and balance the energy load among network nodes. The R-B tree is a self-balancing binary search tree that organizes data efficiently, ensuring quick retrieval and update operations. In the context of IEE-DLSA, the R-B tree tracks each node's energy levels and prioritizes nodes with higher energy levels for data transmission tasks. This load balancing prevents any single node from being overburdened, promoting fair usage of resources and extending the overall operational lifetime of the network. The R-B tree's balancing mechanism ensures that the energy consumption across the network remains as uniform as possible, thereby enhancing overall network energy efficiency.

High Packet Delivery Ratio (PDR) Achieved by the IEE-DLSA Protocol: The performance of the IEE-DLSA protocol is evidenced by its impressive Packet Delivery Ratio (PDR) of 93.131%, which is considerably higher than that achieved by existing routing protocols such as EE-LEACH, AC-OLSR, and DLSA. This high PDR directly results from the protocol's ability to maintain stable and reliable communication links even in challenging environments. The protocol achieves this by implementing threshold-based link stability measures, where nodes periodically evaluate the quality of their links based on signal strength, transmission error rates, and node mobility. Links that fall below a certain threshold are preemptively avoided or rerouted, reducing transmission losses and latency and ensuring more successful data delivery. Technical Enhancements and Detailed Implementation of IEE-DLSA: The IEE-DLSA protocol introduces several technical innovations that significantly enhance network performance.

Firstly, the relay mechanism optimizes routing paths by dynamically selecting routes based on real-time energy and link stability metrics. Secondly, integrating the R-B tree method ensures a balanced distribution of energy consumption, preventing node depletion and maintaining network performance over extended periods. Thirdly, the protocol's high PDR is achieved through the defined threshold ($\omega_{1(0.25)}$, $\omega_{2(0.25)}$, $\omega_{3(0.25)}$, and $\omega_{4(0.25)}$) measures that maintain link stability and reduce transmission losses, thereby lowering latency. Collectively, these innovations contribute to the protocol's effectiveness in energy management, network stability, and reliable data delivery, pushing the boundaries of energy-efficient routing in FANETs and IoU. The IEE-DLSA protocol significantly advances energy-efficient routing for FANETs. By addressing the limitations of existing protocols and introducing innovative mechanisms for energy management and routing optimization, the IEE-DLSA protocol offers a robust solution for enhancing the performance and longevity of FANETs. Its contributions to energy efficiency, network stability, and reliability make it a valuable addition to state-of-the-art FANET and IoU technologies.

4 Results

The performance of the proposed IEE-DLSA has been evaluated in contrast with the present routing protocols in which each scenario has been discussed. Tabular and graphical demonstrations have been performed for each aspect of the evaluation metrics. The proposed performance evaluation metrics are defined below which are proposed for analysis and evaluation of the IEE-DLSA routing protocol. The simulation setup for the proposed IEE-DLSA protocol was meticulously designed to evaluate its performance comprehensively. MATLAB was chosen as the simulation environment due to its robust computational capabilities and suitability for network simulations. The network size was set to cover a significant area of 800 by 700 by 500 m, providing a realistic scenario for FANET operations. The total number of nodes in the network was 100, including a combination of 75 aerial and ground nodes, with an additional 25 relay nodes designated as energy-efficient to optimize data transmission pathways. Each node had an initial energy of 15.0 joules, simulating realistic energy constraints in network operations. The transmission range for each node was set to 350 m, ensuring sufficient coverage for communication while maintaining network connectivity. Omni-directional antennas were used, which allowed for uniform signal distribution in all directions. The mobility models differed between ground and aerial nodes to reflect realistic movement patterns; ground nodes followed a Random Way Point mobility model, while aerial nodes adhered to a Fixed Way Point model. The maximum speed of aerial nodes was varied randomly between 10–50 m per second and ground nodes between 10–25 m per second, simulating dynamic movement in the network environment. Propagation models were selected to represent signal behavior in different scenarios accurately: the Two Ray Ground model for ground nodes and the Free Space model for aerial nodes. These models are crucial for evaluating signal attenuation and ensuring accurate simulation of real-world conditions. A pause time of 2.0 s was incorporated to account for periods when nodes remain stationary, adding to the realism of the simulation.

Data transmission was set to occur at two packets per second, with a mix of Variable Bit Rate (VBR) and Constant Bit Rate (CBR) traffic types to evaluate the protocol's performance under varying traffic conditions. The evaluation metrics included network delay (in milliseconds), network throughput (in bits per second), packet delivery ratio (percentage), transmission loss (in dBm), network stability period (measured by the number of dead nodes), and energy consumption (in joules). These metrics were chosen to provide a holistic assessment of the network's performance and the effectiveness of the IEE-DLSA protocol. Wireless 802.11a was utilized for the communication channel, reflecting a common standard for wireless communication. The existing protocols, DLSA, EE-LEACH, and AC-OLSR, were included in the comparative evaluation to benchmark the performance of the proposed IEE-DLSA protocol. Each packet size was fixed at 512 bytes, and the total simulation time was set to 10 intervals of 100 s each, providing ample time to observe and measure the protocol's performance under various conditions. This comprehensive simulation setup ensured that the proposed IEE-DLSA protocol was rigorously evaluated, highlighting its efficiency and effectiveness in improving network performance in FANET environments.

The chosen performance metrics for evaluating the proposed work are given as follows:

- **Transmission Loss**
  The term Transmission Loss of RL can be defined as the transmission loss during the propagation of a signal from sender to receiver. Transmission Loss can be measured in decibels mill-watt (dBm).
- **Network Delay**
  Delay or latency in a network can be measured in seconds or milliseconds. The delay occurs during the transmission when a packet takes more time than expected; then, it is called the delay of the network. The network delay should be maintained at a minimum of as much as possible. The network delay or network latency can be measured in milliseconds (ms).
- **Packet Delivery Ratio**
  The PDR is the ratio of packets successfully delivered from sender to receiver.

- **Network Throughput**
  The throughput of a network can be defined as the total number of successful packets sent from sender to receiver. In other words, network throughput refers to the efficiency of a network in terms of how many packets can be sent over medium from source to destination in a finite amount of time. It can be measured in either %age or total sent and received packets.
- **Energy Consumption**
  It also indicates the energy cost in which the energy consumption is calculated and how much energy is consumed in joules.
- **Network Stability**
  Network stability can be defined by the number of dead nodes in a network or the number of disconnected nodes in a network that are no longer a part of the communication scenario. Here, the network stability is measured by the total dead nodes of a network; when the death of the initial nodes occurs, that is the actual network stability.

4.1 Analysis and Evaluation of Transmission Loss (TL)

Loss in the data occurs for many reasons, such as the loss of path from one node to another or the loss of signal that cannot reach the destination due to some power or obstacles during transmission. In this regard, transmission loss means signal loss due to dead or disconnected nodes. As shown in Fig. 2, the loss of all the protocols evaluated in the proposed work has given the lowest value in the loss. It is to be noted that the lowest value in the loss is considered the best in which the loss has occurred minimum and low. The simulations were performed for 1000 s, and each 100 s was divided into different slots for clear understanding and evaluation perspectives, with a pause time of 2 s for each simulation scenario. From the initial stage, at 100 s, the TL of EE-LEACH is 180 in decibels mill watt (dBm), AC-OLSR has 431, DLSA has 380, and the proposed work has a TL of 160.

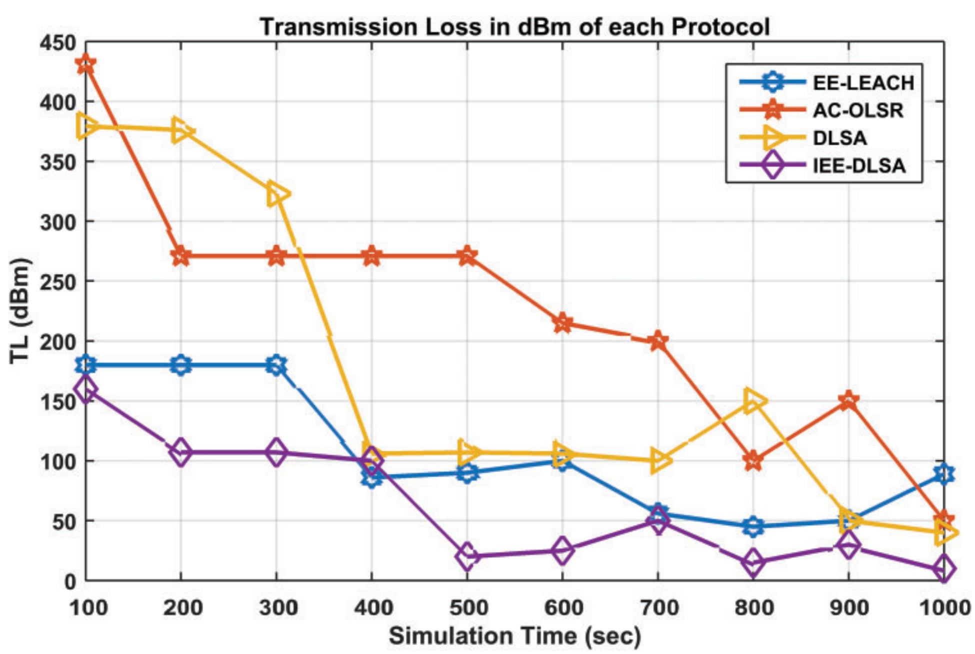

Figure 2: Simulated transmission loss of IEE-DLSA *vs.* other protocols

Similarly, at 200 simulation times, the TL of EE-LEACH is 180, AC-OLSR is 271, and DLSA is 376, whereas the proposed protocol has a TL of 107. The total simulations for TL are executed for up to 1000 s, and it has been witnessed that the proposed protocol has achieved the best performance compared with all the other routing protocols. Not only in each simulation 100 s slot, but on overall average, the proposed protocol has achieved the best performance of 62.4 TL in dBm, EE-LEACH has the average TL of 105.6, AC-OLSR has 223, and DLSA has TL recorded 173.8. The proposed IEE-DLSA protocol has achieved the best performance compared to all the protocols. The key factor is the utilization of the advanced relay nodes, which use the R-B tree concept to maintain a fair mechanism among the nodes. This procedure used a stability method in which each node is utilized based on the highest priority to measure the distance from each other.

It also utilizes the energy nodes with a relay mechanism and considers those nodes with the highest energy level. The TL decreases because of the transmission distance, which decreases as well. This distance directly relates to TL, which comes to the lowest value, and the nodes operate in an advanced manner because of the advanced relay and energy-efficient node deployment. The proposed protocol has assumed the lowest loss due to those advanced UAVs and the fair deployment of the R-B tree, which works to partition the network during the functional time.

4.2 Analysis and Evaluation of Network Delay

The network delay can be measured in seconds or milliseconds, which denotes the latency at the transmission time. When a node sends a packet to another, reaching after the desired time, it indicates a delay has occurred. The delay of a network needs to be minimized as much as possible to impact the throughput and PDR of a network that affects it. Fig. 3 illustrates the network delay analysis of the four routing protocols concerning the simulation time in seconds. The simulations were executed for 1000 s and divided into 100 s each for evaluation and analysis. With an initial time of simulations at 100 s, EE-LEACH has a network delay of 50, AC-OLSR has 45, DLSA has 50, and the proposed protocol has 52 network delays in milliseconds. With the passage of simulation time, each protocol has assumed the best performance in network delay, but the proposed IEE-DLSA has achieved outstanding functionality in all scenarios.

EE-LEACH's average network delay is 35.5, AC-OLSR is 26.7, DLSA has 27.6, and the proposed IEE-DLSA has recorded a network delay 19.3. The minimum network delay is to be considered the best among all in which the IEE-DLSA has achieved the best and minimum not only in each slot of simulations but also in the average. This average value denotes that the proposed protocol has a 19.3 delay in each scenario when considering the average calculations. IEE-DLSA has achieved the lowest and minimum delay in all scenarios because of the advanced nodes deployed for network improvement. A total of 100 nodes were deployed, of which 25 were utilized as advanced nodes, which focused on the delay to keep this value lowest and maximize the network PDR and the throughput in bps.

The remaining nodes are normal. The network has been improved with the proper utilization of these energy-efficient nodes. This is the key factor for all the proposed scenarios where the IEE-DLSA has achieved the best functionality and performance. With its hybrid nature, the proposed protocol assumes its methods, but the positive features of the existing protocols are also included. With time, the network delay decreases because of the primary focus on keeping and minimizing the delay of the network and delivering the data packets effectively in the desired time frame. The mobility of the UAVs, which fly in the air with the collaboration of the ground nodes, can keep the network delay low. At the initial stage, the network delay is witnessed as high, but gradually, it has been minimized effectively. When nodes come to the range of communication, the advanced nodes utilize these within the network to minimize distance and network delay.

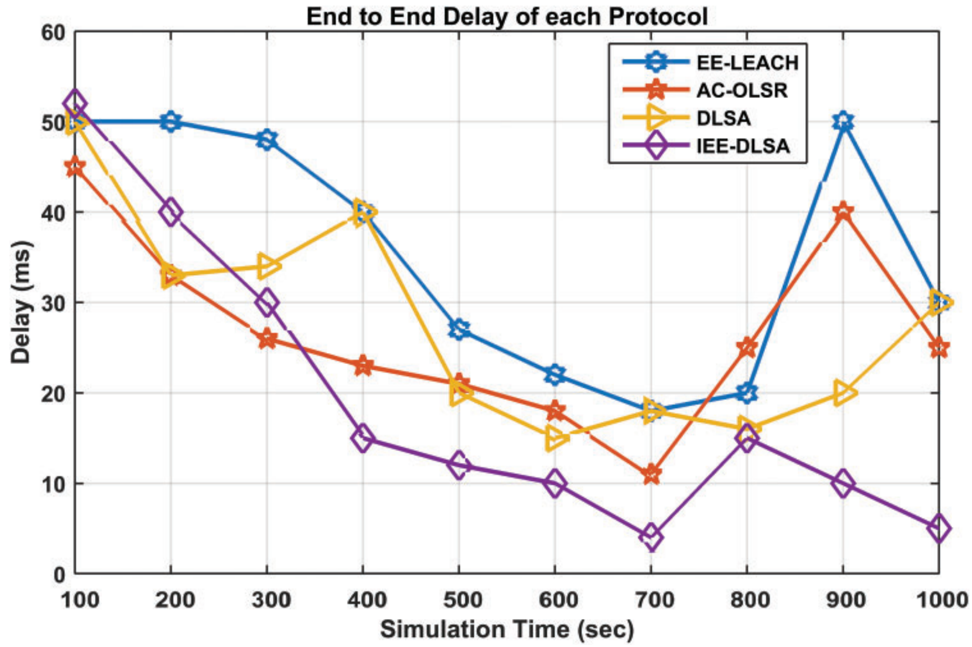

Figure 3: Simulated network delay of the proposed work *vs.* simulation time

4.3 Analysis and Evaluation of Packet Delivery Ratio (PDR)

PDR of a network illustrates the ratio of packets in which the sent and received packets are counted. A network with PDR is effective in which the sent and received packets at the destination are equal. This means that no loss occurred during the communication of the data packets. The PDR of a network can be measured in percentage in which the overall ratio can be witnessed respectively. Fig. 4 shows the PDR of four routing protocols, and the ratio of each protocol concerning the time of simulations is demonstrated. The simulations were executed for 1000 s; every 100 s, they were divided into clusters for clear understanding and effective evaluations. The PDR of a network can be maximized as much as possible, up to 100%. With the illustration of PDR values for each protocol, it has been shown that the proposed IEE-DLSA has achieved the best PDR values in all simulation scenarios. The total 100 simulation slots, each up to 10 slots of these values, make 1000 s for the proposed network to be evaluated differently with every 100 s.

It is admitted that the PDR value is not equal in each slot of simulation time because of the mobility nature of UAVs, and the PDR value increases and decreases with time. The PDR shown in this scenario is decreasing gradually because the mobile nodes come closer and then go far from each other during the flying and mobility of the ground nodes. At 100 initial times of simulations, the PDR value of EE-LEACH is 96.39, AC-OLSR is 93.57, DLSA is 99.32, and the proposed IEE-DLSA has achieved the PDR of 99.90, which shows an improved performance regarding the ratio of successfully delivered packets from sender to destination. This metric depends on and deals with the countdown of the packets in a network to be sent from the source node to the target node. With the overall average calculation of the PDR, EE-LEACH has secured 79.227, AC-OLSR has secured 73.464, DLSA has secured 85.82, and the proposed IEE-DLSA has secured 93.131 which it considered the best PDR in all scenarios of the simulations. The key factor is showing the best functionality with advanced nodes for relay to boost the network performance and calculate the nodes' energy efficiency level. As the PDR decreases gradually with the passage of simulation time, it is because the nodes are moving, and their transmission distance is increasing. Delivering the PDR with 100% in all scenarios is impossible because the node's mobility impacts the proposed random waypoint and fixed waypoint mobility models. With these, the ratio slowly decreases but delivers the best results.

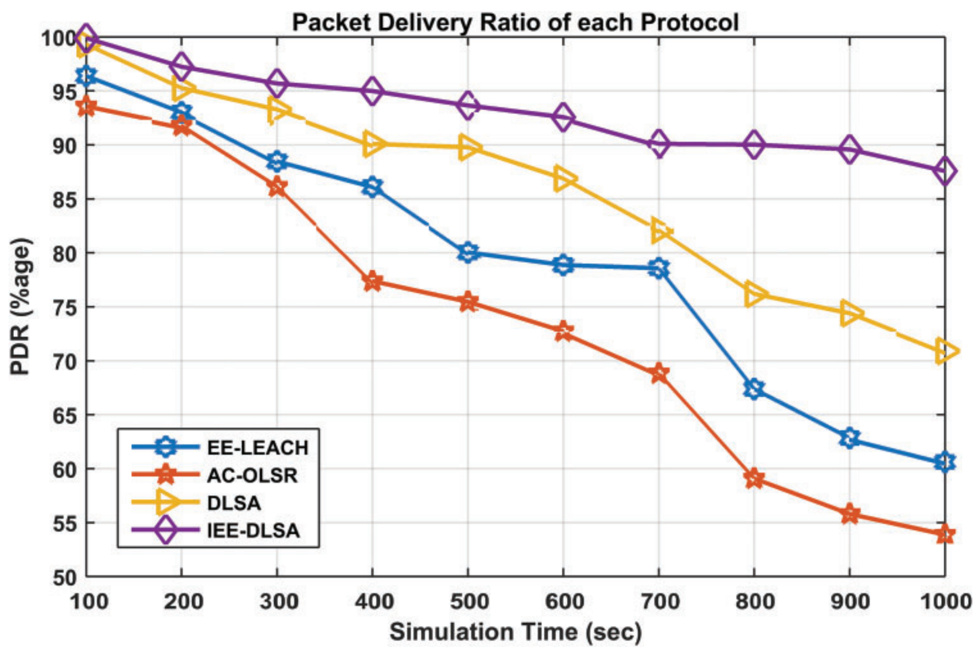

Figure 4: Simulated packet delivery ratio *vs.* simulation time of IEE-DLSA

4.4 Analysis and Evaluation of Network Throughput

The network throughput is the size of the bits, which can be measured in Mbps or bps, which means megabits per second or bits per second. It also can be defined as the actual frequency of passing via a medium in a finite amount of time. The PDR is the total amount of the packets, but the throughput is the actual size of the packets, like 256, 512, or 1028 bytes. It depends on the proposed packet size, and here in the proposed IEE-DLSA, the packet size is 512. Fig. 5 represents the network's throughput in bits per second for all four routing protocols. The given graph represents the throughput of a network, the amount of which varies from one protocol to another. Each protocol gives the throughput value, sending thousands of bits per second. The simulations were executed for 1000 s for network throughput, as shown in Fig. 5. The simulations were divided into ten slots, each consisting of 100 s.

For clear evaluation and analysis, it has been divided into different slots. Considering the simulation time, at 100 s, the network throughput of EE-LEACH has secured 94884.8, AC-OLSR has secured 98170.5, DLSA has secured 110956.5, and the proposed IEE-DLSA has secured 115678.4. This has been considered the best throughput among all the protocols because of the non-continuous transmission, and only the best priority nodes have been utilized for normal and relay with energy-efficient nodes. The network throughput gradually decreases as the distance increases during the simulation time because long distances deliver fewer data bits than those near each other. EE-LEACH's average calculated network throughput is 76376.21, AC-OLSR has 82218.19, DLSA has 87083.76, and the proposed IEE-DLSA has secured 93615.14. This average value shows that each protocol can be sent that number of bits per second from the source node to the destination node. The movable nature of the UAVs has a huge impact on the network throughput, increasing and decreasing by increasing the number of nodes and the communication distance. With the proposed 350 m range of communication for simulation purposes, some nodes may cover long distances, like from 100 up to 350 m range. With the increasing distance, the network throughput gradually decreases, but the proposed IEE-DLSA still performs best in the initial and final stages of simulations.

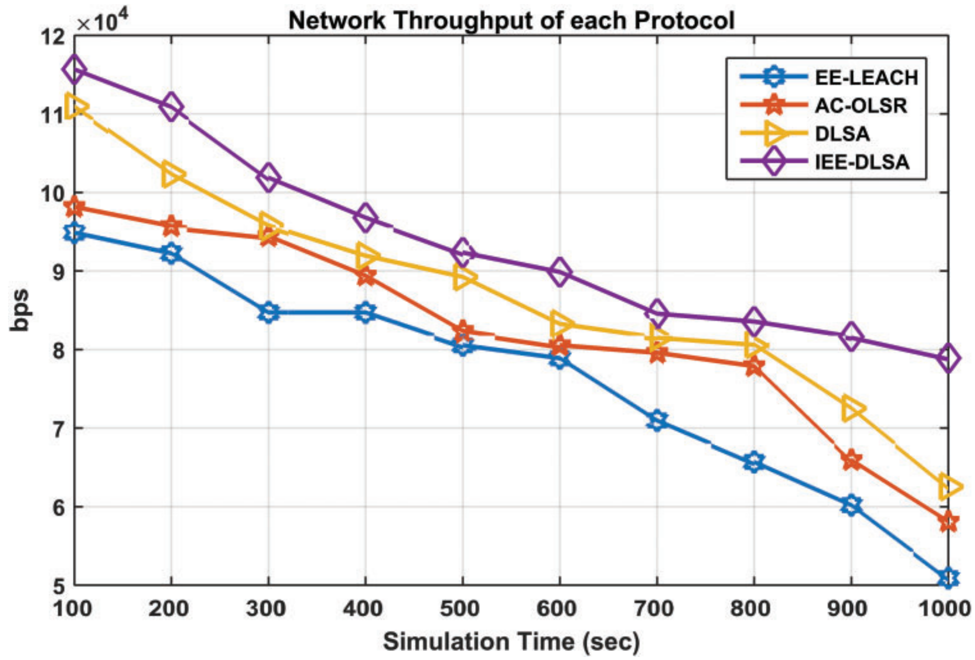

Figure 5: Calculated network throughput of IEE-DLSA *vs.* simulation time

4.5 Analysis and Evaluation of Energy Consumption

The network's energy in which the nodes are linked and operated via a wireless medium is vital for the nodes within a network. Energy plays a vital role in FANET because of the flying nodes, which are very crucial to making these nodes energy efficient and avoiding any danger and other dangerous tasks. The UAVs may fall and cause damage to the network and the environment. The lowest energy consumption in FANET is considered the best performance from the energy efficiency perspective. An energy-efficient protocol can consume less energy in joules (j) or megawatt hours (joules). These are the units where energy can be measured in a network. Fig. 6 demonstrates the energy consumption of the four routing protocols concerning simulation time. The total range of energy for normal nodes is proposed to be 15 joules, as shown in Table 1.

The simulations were executed for up to 1000 s and were divided into ten slots, each consisting of 100 s. This procedure has been applied to all scenarios for clear understanding, evaluation, and analysis. At the initial time of simulation, which was 100 s, the energy consumption of EE-LEACH was 9.19, AC-OLSR was 9.17, DLSA was 8.63, and the proposed IEE-DLSA was 7.98. The proposed IEE-DLSA has performed well in all energy consumption scenarios because of the energy-efficient nodes with advanced features. Similarly, with the remaining time of simulations, the proposed IEE-DLSA has performed well compared to the other protocols. This is the key and main metric for which the system model has been designed, and the UAV's Energy (UE) has been properly utilized. The remaining metrics depend on the energy efficiency of the nodes via which each metric has gained the best results. With the average calculation, the EE-LEACH has consumed energy at 10.759, AC-OLSR at 8.694, DLSA at 8.309, and the proposed IEE-DLSA at 7.644. The simulation analysis showed that the proposed protocol performed best in all scenarios. The advanced energy-efficient nodes have the ability and duty to operate all the nodes fairly and use the best routes during the simulations. In simulations, the proposed protocol's energy consumption has been decreased effectively.

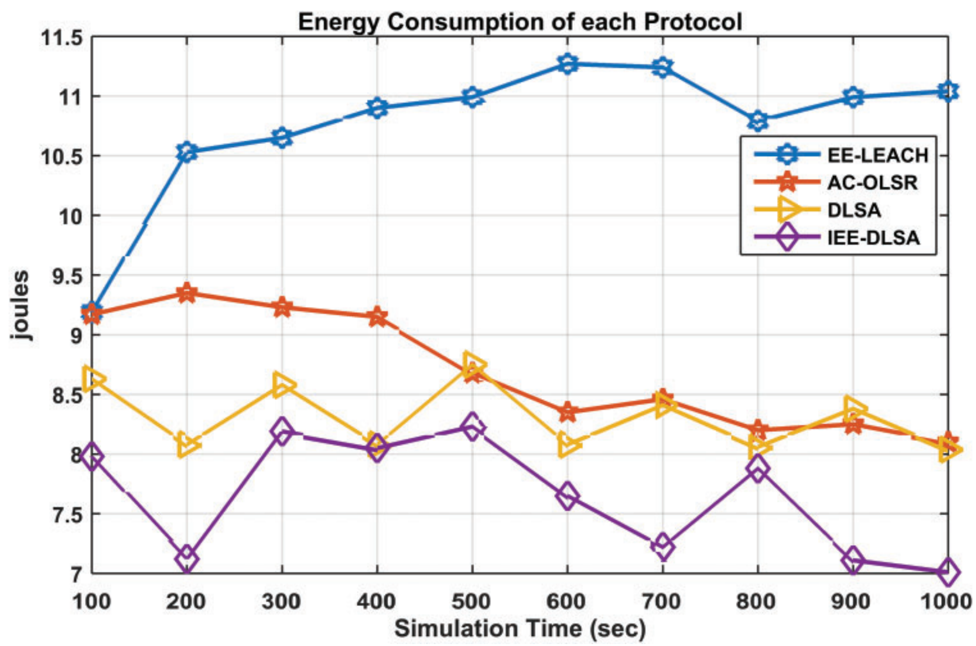

Figure 6: Total calculated energy consumption of four protocols *vs.* time

Table 1: Simulation setup for proposed IEE-DLSA protocol

Parameter	Value
Simulator	MATLAB R2015a
Network size	800 m × 700 m × 500 m
Total number of nodes	100
Aerial and ground nodes	75
Relay (energy efficient) nodes	25
Transmission range	350 m
Antenna type	Omni directional
Nodes with initial energy	15.0 joules
The maximum speed of aerial nodes randomly	10–50 m/s
The maximum speed of ground nodes randomly	10–25 m/s
Mobility model for ground	Random way point
Mobility model for aerial	Fixed way point

(Continued)

Table 1 (continued)

Parameter	Value
Propagation model for ground	Two ray ground
Propagation model for aerial	Free space
Pause time	2.0 s
Time of interval to send	2 p/s
Traffic type	VBR/CBR
Evaluation metrics	Network delay (ms), network throughput (bps), Packet delivery ratio (%), transmission loss (dBm), network stability period (dead nodes/death of first node), energy consumption (joules)
Channel	Wireless 802.11a
Existing protocols for comparative evaluation	DLSA, EE-LEACH, AC-OLSR
Proposed energy-efficient protocol	IEE-DLSA
Packet size	512 bytes
Simulation time	10×100 s

4.6 Analysis and Evaluation of Network Stability

Network stability tells the network stable time for how long the network is/was stable. It occurs when the first node in a network dies, and then the death of that node is the time calculated, called the stability of a network. It can be measured in dead nodes or both dead and alive nodes. If a network starts working from 0 s up to 5 or 10 min, and when the first node dies, then the stability of the network can be calculated. Fig. 7 shows the network stability period of the four routing protocols concerning the simulation time of 1000 s. With the proposed simulation time, it can be illustrated from the given Figure that the death of the first node of EE-LEACH occurred at 300 s but not just 1; five nodes are assumed dead at that time. Similarly, the death of the first node of AC-OLSR occurred at 200 s in which the first node died.

Likewise, the death of the first node of DLSA occurred at 400 s, which illustrates that the two nodes died at that time along with the first node. At the same time, the death of the first node of the proposed IEE-DLSA occurred at 500 s, which illustrated that one node had died. Each protocol was performed with the passage of the simulation time, and the nodes' deaths occurred, respectively. It is calculated from the average of the network stability that the average dead nodes of EE-LEACH are 5.1, AC-OLSR has 5.6, DLSA has 4, and the proposed IEE-DLSA has 2.1 nodes dead in perspective of the average calculation. So, it has been illustrated and witnessed that the network stability of the IEE-DLSA was calculated to be up to 500 s, which means that this protocol was stable until the first nodes died at 500 s. Likewise, EE-LEACH stability was calculated to be up to 300 s, AC-OLSR was 200 s, and DLSA was 400 s. The best performance has been demonstrated by IEE-DLSA, which has the lowest dead nodes and the highest network stability period.

From the above graphical illustrations and discussions, it has been concluded that the proposed IEE-DLSA routing scheme has aced all the concerned scenarios compared to the other FANET routing protocols. The proposed protocol has dramatically performed in considered settings by introducing the transmission loss models and energy consumption approach.

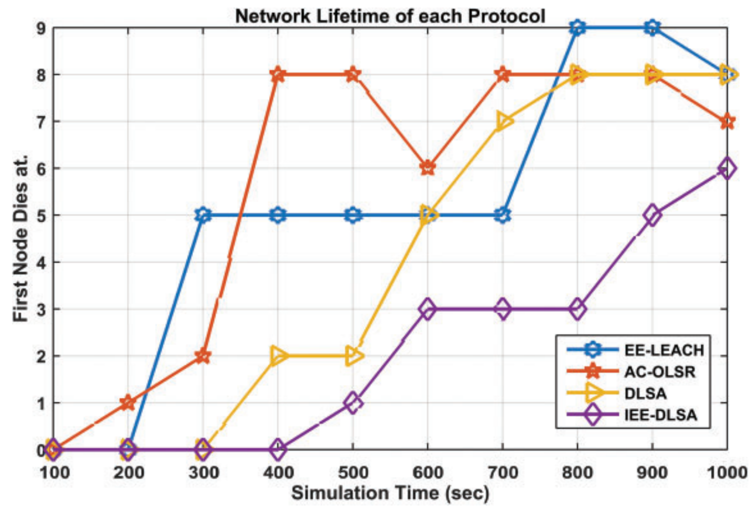

Figure 7: Overall network stability of AC-OLSR, EE-LEACH, and DLSA *vs.* IEE-DLSA

The positive feature of the existing DLSA deployment is that IEE-DLSA has also been considered the best for effectively obtaining the best results and declaring the best routing protocol for FANET. The comparison of the proposed work IEE-DLSA with the existing approaches has been shown in Table 2, while the overall cumulative and average performance and evaluation are illustrated in Figs. 8–10.

Table 2: Summarized results of the simulations and evaluations of DLSA, EE-LEACH, and AC-OLSR with IEE-DLSA

Name of protocol	Average transmission loss (dBm)	Average network delay (ms)	Average PDR (%)	Average network throughput (bps)	Average energy consumption (joules)	Average network stability (dead nodes)
EE-LEACH	105.6	35.5	79.227	76,376.21	10.759	5.1 ≅ 5
AC-OLSR	223	26.7	73.464	82,218.19	8.694	5.6 ≅ 6
DLSA	173.8	27.6	85.82	87,083.76	8.309	4
IEE-DLSA	**62.4**	**19.3**	**93.131**	**93,615.14**	**7.644**	**2.1 ≅ 2**

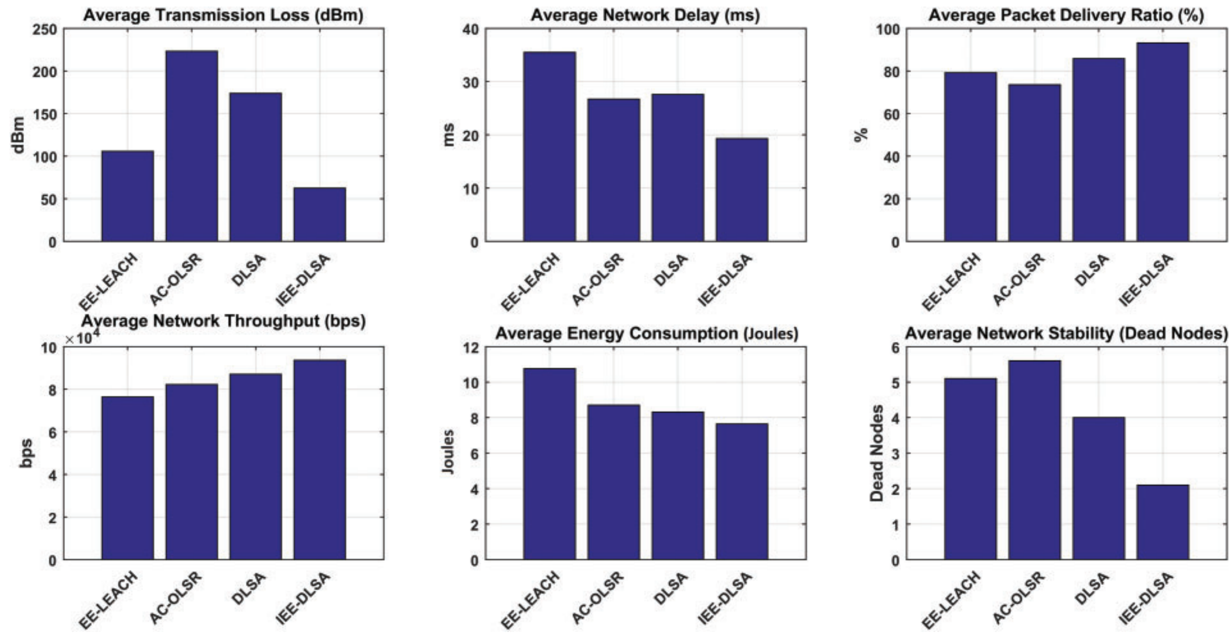

Figure 8: Graphical illustration of average evaluation of all protocols with their respective parameters

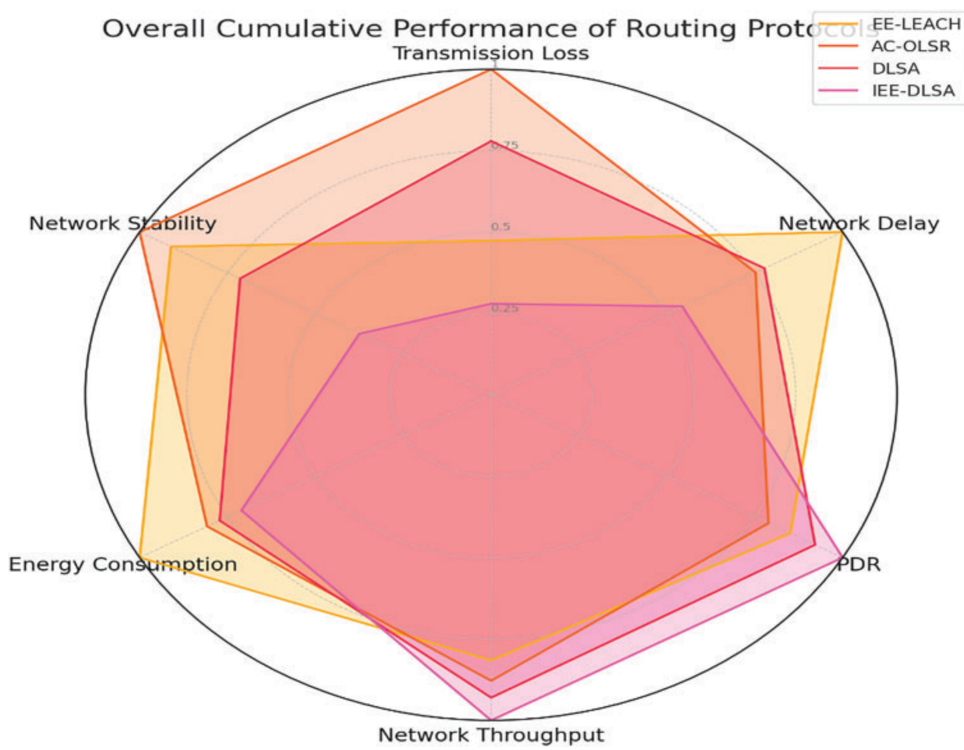

Figure 9: Cumulative performance radar plots of all protocols in terms of each parameter

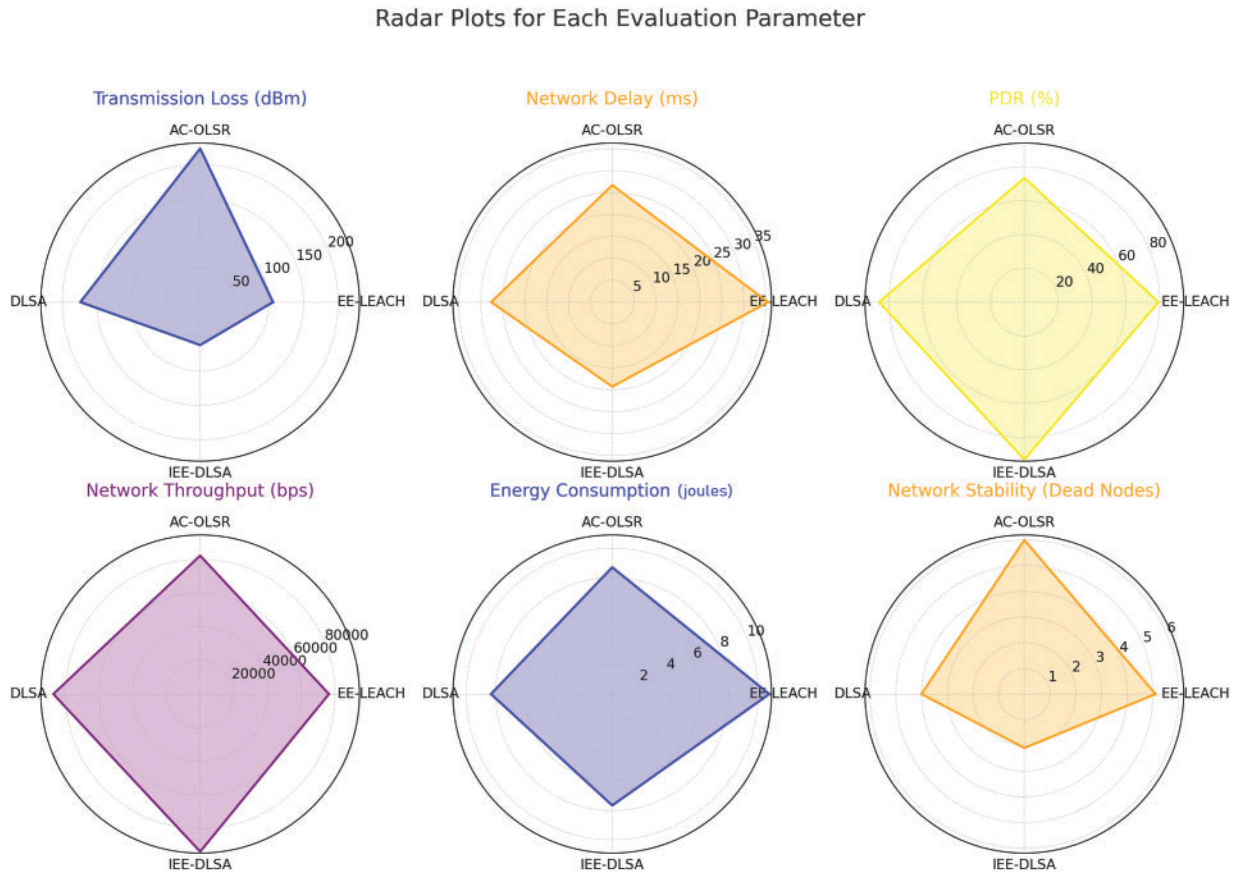

Figure 10: Individual radar plots for cumulative performance of all protocols in terms of each parameter

Based on the summarized results of the simulations and evaluations for EE-LEACH, AC-OLSR, DLSA, and IEE-DLSA, the following is the summary for each evaluation parameter:

- **Transmission Loss (dBm)**

IEE-DLSA demonstrates significantly lower average transmission loss at 62.4 dBm compared to the other protocols: EE-LEACH at 105.6 dBm, AC-OLSR at 223 dBm, and DLSA at 173.8 dBm. This substantial reduction in transmission loss implies that IEE-DLSA can maintain better signal strength and coverage, which is crucial for maintaining robust connectivity in FANETs. The lower transmission loss indicates that signals can travel longer distances without significant degradation, ensuring that node communication remains stable and reliable. This feature is particularly important in dynamic and challenging environments where UAVs operate, as it helps maintain a consistent connection, thus enhancing the overall network performance and effectiveness.

- **Network Delay (milliseconds)**

Regarding network delay, IEE-DLSA also excels by showing the lowest average delay at 19.3 ms. This is substantially better than the delays observed with EE-LEACH at 35.5 ms, AC-OLSR at 26.7 ms, and DLSA at 27.6 ms. Lower network delay indicates faster data transmission and reduced latency in communication, which is vital for real-time applications and timely decision-making processes in

FANETs. The minimal delay ensures that data packets are transmitted and received quickly, facilitating smooth and efficient communication between UAVs. This improvement in network delay directly contributes to enhanced user experience and operational efficiency, particularly in scenarios that require immediate data exchange and response.

- **Packet Delivery Ratio (%age)**

IEE-DLSA achieves the highest average Packet Delivery Ratio (PDR) at 93.131%, indicating superior reliability in delivering packets compared to EE-LEACH at 79.227%, AC-OLSR at 73.464%, and DLSA at 85.82%. A higher PDR reflects better network performance with fewer packet losses, ensuring that most transmitted data reaches its intended destination. This reliability is critical in applications where data integrity and consistency are paramount. The high PDR of IEE-DLSA means that the protocol can be trusted to maintain effective communication channels, reduce retransmissions, conserve network resources, and enhance overall efficiency.

- **Network Throughput (bps)**

IEE-DLSA demonstrates competitive average network throughput at 93,615.14 bps, which is comparable to AC-OLSR at 82,218.19 bps and DLSA at 87,083.76 bps and slightly higher than EE-LEACH at 76,376.21 bps. Higher throughput signifies better data transfer rates within the network, allowing more information to be exchanged in a given period. This capability is crucial for handling large volumes of data, especially in environments where numerous UAVs communicate simultaneously. The high throughput of IEE-DLSA indicates its effectiveness in managing substantial network traffic, supporting the seamless operation of multiple applications and services that depend on continuous and high-speed data exchange.

- **Energy Consumption (joules)**

In terms of energy consumption, IEE-DLSA shows the lowest average consumption at 7.644 joules, indicating efficient utilization of energy resources compared to EE-LEACH at 10.759 joules, AC-OLSR at 8.694 joules, and DLSA at 8.309 joules. Lower energy consumption is crucial for prolonging network operation and enhancing sustainability, particularly in battery-operated UAVs. Efficient energy use ensures that the UAVs can remain operational longer, reducing the frequency of battery replacements or recharges. The energy efficiency of IEE-DLSA contributes to the overall sustainability and cost-effectiveness of the network, making it an ideal choice for long-duration missions and operations.

- **Network Stability (Dead Nodes)**

IEE-DLSA exhibits the lowest average number of dead nodes at approximately 2.1, suggesting better network stability and reduced node failures compared to EE-LEACH at approximately 5, AC-OLSR at approximately 6, and DLSA at 4. Higher network stability indicates improved reliability and continuity of service, as a lower number of dead nodes means that more UAVs remain functional and capable of participating in the network. This reliability is essential for maintaining consistent network performance and avoiding disruptions in communication. The enhanced stability of IEE-DLSA ensures that the network can sustain prolonged and uninterrupted operation, which is critical for mission-critical applications and scenarios where network reliability is non-negotiable.

4.7 Discussion

EE-LEACH is a protocol designed to enhance energy efficiency in wireless sensor networks using a hierarchical clustering method. It performs reasonably well in transmission loss, which means it can maintain a relatively strong signal strength during data transmission. The PDR of EE-LEACH is also decent, indicating that a fair proportion of data packets successfully reach their intended destinations. However, EE-LEACH has higher energy consumption than some other protocols. This is due to the periodic reformation of clusters and the energy-intensive communication between cluster heads and their member nodes. Additionally, EE-LEACH exhibits moderate network stability, as indicated by the average number of dead nodes. The higher energy consumption can lead to quicker depletion of node batteries, reducing the overall lifespan of the network.

AC-OLSR offers a balanced performance with moderate energy consumption and throughput. It uses an optimized link state routing mechanism to adjust the network's topology to enhance efficiency dynamically. The energy consumption of AC-OLSR is lower than that of EE-LEACH, making it a more energy-efficient option in certain scenarios. Despite this, AC-OLSR suffers from higher transmission loss, which indicates weaker signal strength and potential challenges in maintaining strong communication links. Its PDR is also lower than other protocols, suggesting less reliable data delivery. These drawbacks highlight a trade-off in AC-OLSR between energy efficiency and reliable data transmission. DLSA excels in PDR and network throughput, indicating that it can reliably deliver high data packets and handle substantial traffic. This makes DLSA suitable for applications that require high data reliability and network capacity. However, DLSA has the highest transmission loss and network delay among the protocols considered. High transmission loss suggests significant signal attenuation, possibly due to longer transmission ranges or obstacles in the network environment. The high network delay indicates slower responsiveness, which could affect time-sensitive applications. These issues illustrate a trade-off in DLSA between achieving high reliability and throughput at the expense of responsiveness and signal strength. IEE-DLSA stands out as the most efficient protocol overall. It has the lowest transmission loss, indicating strong signal strength and efficient data transmission. The protocol also achieves the lowest network delay, ensuring quick responsiveness, which is crucial for real-time applications. IEE-DLSA boasts the highest PDR, meaning it has the most reliable data delivery system among the protocols. It also has the highest network throughput, demonstrating its capability to handle large volumes of data efficiently.

Moreover, IEE-DLSA consumes the least amount of energy, extending the operational life of network nodes and enhancing network stability, as evidenced by the lowest number of dead nodes. Each protocol has distinct strengths and weaknesses, making the protocol choice highly dependent on the network's specific requirements. For example, EE-LEACH is suitable for networks where transmission loss and PDR are critical, but energy consumption is less of a concern. AC-OLSR is appropriate for scenarios where a balance between energy consumption and throughput is needed despite its higher transmission loss and lower PDR. DLSA is ideal for applications demanding high PDR and throughput, where some delay and transmission loss can be tolerated. IEE-DLSA is the best choice for overall efficiency scenarios, including low energy consumption, minimal delay, high PDR, and strong network stability. Selecting a routing protocol should consider the application's specific needs, including the importance of energy efficiency, reliability, throughput, and responsiveness. Network designers can make informed decisions to optimize network performance by understanding the trade-offs associated with each protocol.

4.8 IEE-DLSA's Superior Performance in All Scenarios

- **Integrated Energy-Efficient Design:** The IEE-DLSA protocol integrates the strengths of three existing protocols: DLSA, EE-LEACH, and AC-OLSR. This comprehensive approach combines the best practices of each, particularly in terms of energy efficiency, link stability, and network optimization. By holistically addressing multiple aspects of network operation (e.g., stability, energy consumption, and data transmission), IEE-DLSA is better equipped to handle diverse scenarios than protocols focusing on only one or two areas.

- **Optimized Relay Mechanism:** IEE-DLSA introduces a sophisticated relay mechanism that optimizes routing paths based on the distance and number of nodes, minimizing energy usage. This dynamic relay mechanism ensures that the most energy-efficient paths are selected for data transmission, which directly reduces the overall energy consumption of the network, especially in large and complex FANET deployments. The mathematical formulation of the relay mechanism (Eqs. (2) and (3)) supports this by minimizing energy expenditure across all nodes.
- **Enhanced Network Stability:** The enhanced DLSA scheme within IEE-DLSA focuses on improving network stability by considering node mobility and link duration. This is crucial in FANETs, where UAVs are constantly in motion, and maintaining stable communication links is challenging. The stability function (Eq. (4)) ensures that the network remains operational and stable over longer periods, even under conditions of high mobility and varying node density, which is a significant advantage over other protocols.
- **Efficient Use of R-B Tree Method:** The R-B tree method used in IEE-DLSA ensures balanced load distribution among nodes, which prevents any single node from becoming overburdened. This load balancing is critical for maintaining energy efficiency across the network, as it ensures that no node is disproportionately drained of energy, thereby prolonging the overall network lifetime. The fairness index (Eq. (6)) further ensures equitable energy consumption, which the comparison protocols do not address explicitly.
- **Advanced Energy Management:** IEE-DLSA incorporates a comprehensive energy management strategy that includes neighborhood support, stability period assessment, energy utilization, and key deployment. Each phase of this management process (described in Sections "UAV's Stability Period (Network Operational Time Phase)" to "UAV's Concluding Substantial Weight (Merging Strategy of UAVs)) contributes to the protocol's ability to efficiently manage energy resources, making it superior when energy conservation is critical. This multi-phase approach optimizes energy from network initialization to final data transmission.
- **Merging Strategy for Multi-Objective Optimization:** The final phase of IEE-DLSA's operation involves combining multiple parameters (UNS, USP, UE, and UKD) to generate a multi-objective feature (Eq. (14)). This merging strategy allows the protocol to adapt to various operational demands, prioritizing the most critical energy efficiency factors. This adaptability is key to IEE-DLSA's superior performance, as it can dynamically adjust to changing network conditions, unlike more rigid protocols like EE-LEACH or DLSA.
- **Algorithmic Efficiency:** The detailed algorithms (Algorithms 1 and 2) within IEE-DLSA focus on enhancing energy efficiency through iterative and neural approaches, which optimize energy consumption patterns dynamically. The R-B tree structure, neural approaches for energy updates, and the loop mechanism for continuous refinement all contribute to the protocol's ability to maintain energy efficiency over time, providing a clear advantage in scenarios where network longevity and energy conservation are paramount.
- **Robust Relay and Search Mechanism:** The combined scheme for energy consumption (Eq. (22)) encapsulates the impact of IEE-DLSA on the drone's energy efficiency through optimized hover, flight, transmission, and search operations. This comprehensive approach to energy management, especially in the relay and search mechanisms, ensures that IEE-DLSA outperforms other protocols by reducing unnecessary energy expenditure during active and idle periods. In short, IEE-DLSA's superior performance in all scenarios is due to its holistic, energy-efficient design, advanced relay and stability mechanisms, balanced load distribution, and dynamic

adaptability to changing network conditions. These factors collectively ensure that IEE-DLSA outperforms protocols like EE-LEACH, AC-OLSR, and DLSA, particularly in complex and energy-sensitive FANET environments.

4.9 Innovations and Advantages of IEE-DLSA over Existing Technologies

The IEE-DLSA routing protocol introduces several significant innovations and advantages over existing technologies, particularly in the context of FANETs (Flying Ad Hoc Networks). Below are the key advancements that set IEE-DLSA apart.

4.9.1 Enhanced Transmission Loss Management

Innovation: IEE-DLSA effectively minimizes transmission loss using advanced relay nodes and the R-B tree concept, which ensures a balanced and prioritized utilization of nodes based on their energy levels and proximity. This method significantly reduces transmission distances, directly correlating with lower transmission loss.

Advantage: The protocol achieves the lowest average transmission loss of 62.4 dBm compared to DLSA (173.8 dBm), EE-LEACH (105.6 dBm), and AC-OLSR (223 dBm), highlighting its superior efficiency in maintaining signal integrity.

4.9.2 Minimized Network Delay

Innovation: IEE-DLSA employs 25 advanced energy-efficient nodes that prioritize minimizing network delay by optimizing node deployment and communication paths. This focus on reducing delay enhances overall network performance, especially in dynamic environments.

Advantage: The protocol records the lowest average network delay of 19.3 ms, outperforming EE-LEACH (35.5 ms), AC-OLSR (26.7 ms), and DLSA (27.6 ms). This reduction in delay is crucial for applications requiring timely data transmission.

4.9.3 Improved Packet Delivery Ratio (PDR)

Innovation: The protocol ensures a high PDR by leveraging a combination of random and fixed waypoint mobility models, which maintain optimal distances between nodes during data transmission. The inclusion of energy-efficient relay nodes further supports consistent packet delivery.

Advantage: IEE-DLSA achieves an impressive average PDR of 93.131%, surpassing DLSA (85.82%), EE-LEACH (79.227%), and AC-OLSR (73.464%). This indicates the protocol's robustness in maintaining high data integrity during transmission.

4.9.4 Higher Network Throughput

Innovation: By efficiently managing node deployment and utilizing energy-efficient nodes for both normal and relay operations, IEE-DLSA maximizes the network's data throughput. The protocol's design allows dynamic adjustment to node distances and traffic conditions.

Advantage: With an average throughput of 93,615.14 bps, IEE-DLSA outperforms DLSA (87,083.76 bps), EE-LEACH (76,376.21 bps), and AC-OLSR (82,218.19 bps). This ensures that the network can handle a higher volume of data transmission, which is crucial for FANET applications.

4.9.5 Optimized Energy Consumption

Innovation: IEE-DLSA's energy-efficient design focuses on prolonging network operation by minimizing the energy consumption of nodes, especially UAVs. The protocol incorporates advanced node management to distribute energy usage evenly across the network.

Advantage: The protocol exhibits the lowest average energy consumption at 7.644 joules, significantly better than DLSA (8.309 joules), AC-OLSR (8.694 joules), and EE-LEACH (10.759 joules). This extends the network's operational life, making it more sustainable for long-term missions.

4.9.6 Superior Network Stability

Innovation: IEE-DLSA enhances network stability by delaying the onset of node failure, achieved through intelligent energy management and efficient routing strategies. The protocol's design ensures that nodes are utilized in a way that extends their operational life.

Advantage: The network stability of IEE-DLSA is demonstrated by the longest stability period of 500 s before the first node dies, compared to DLSA (400 s), EE-LEACH (300 s), and AC-OLSR (200 s). This indicates a more reliable and longer-lasting network.

The IEE-DLSA protocol offers substantial improvements over existing routing protocols in FANETs by addressing key challenges such as transmission loss, network delay, packet delivery, throughput, energy consumption, and stability. Its advanced techniques, including energy-efficient node deployment and intelligent relay node management, make it a highly effective solution for energy-constrained and dynamic network environments.

4.10 Future Trends of IEE-DLSA in Light of Innovations and Advantages

Given the substantial innovations and advantages that IEE-DLSA presents over existing technologies in FANETs, its future trends are likely to evolve in several promising directions, which are discussed below.

4.10.1 Integration with Next-Generation UAV Technologies

Trend: As UAV technologies advance, incorporating AI and machine learning for autonomous operations, IEE-DLSA could evolve to leverage these capabilities. The protocol could dynamically integrate predictive analytics to optimize routing decisions, enhancing real-time adaptability in rapidly changing environments.

4.10.2 Expansion into Multi-Platform Communication Networks

Trend: With the growing trend of integrating FANETs with terrestrial and satellite networks, IEE-DLSA could be adapted to support multi-platform communication. This would involve the protocol's expansion to manage communication between diverse platforms, ensuring seamless data flow across different network layers.

4.10.3 Adoption in Large-Scale, High-Density UAV Networks

Trend: As the deployment of large-scale UAV swarms becomes more prevalent, IEE-DLSA could be further refined to handle the complexities of high-density network environments. Enhancements in scalability and node management could enable the protocol to maintain performance metrics, such as low latency and high PDR, even in extremely dense UAV networks.

4.10.4 Energy Harvesting and Sustainable Network Operations

Trend: The trend toward sustainable energy solutions could lead to integrating energy harvesting technologies within the IEE-DLSA framework. This would involve developing techniques for UAVs to harvest energy from environmental sources, thereby extending network lifespan and reducing reliance on conventional power sources.

4.10.5 Enhanced Security and Resilience

Trend: As FANETs are increasingly used in critical applications, the security and resilience of routing protocols like IEE-DLSA will become paramount. Future protocol versions could incorporate advanced cryptographic methods and resilience mechanisms to protect against cyber threats and ensure reliable communication in hostile environments.

4.10.6 Real-Time Optimization via Edge Computing

Trend: The integration of edge computing into FANETs could allow IEE-DLSA to perform real-time optimization of routing paths. This would enable more efficient processing of data close to its source, reducing latency and improving the overall responsiveness of the network in mission-critical applications.

4.10.7 Adaptation to Emerging Communication Standards

Trend: With the ongoing development of 6G and other advanced communication standards, IEE-DLSA could be adapted to align with these new technologies. This would involve upgrading the protocol to support higher data rates, lower latency, and improved reliability in line with future communication infrastructures.

4.10.8 Collaborative and Autonomous Mission Planning

Trend: The future of UAV networks may emphasize collaborative and autonomous mission planning. IEE-DLSA could evolve to support these capabilities, enabling UAVs to autonomously collaborate on tasks, optimize their routes, and adjust to real-time mission dynamics, thus enhancing mission efficiency and success rates. In short, the future trends of IEE-DLSA are likely to involve its integration with cutting-edge technologies, expansion into new application areas, and enhancement of its existing capabilities to meet the growing demands of FANETs in various advanced and critical applications.

5 Conclusion

Energy is a major concern in FANET, and because the nodes are airborne, it has recently become a critical issue. This research aims to address energy consumption and design an energy-efficient routing protocol. This paper introduces an energy-efficient routing technique, IEE-DLSA, as an extension of the DLSA routing scheme. Unlike existing schemes, the proposed IEE-DLSA has achieved higher throughput, minimum delay, lowest transmission loss, lowest energy consumption, and the highest network stability period. The simulations have shown that the IEE-DLSA routing scheme can work effectively with advanced relay nodes to optimize energy consumption and enhance the network's stability period. These advanced relay nodes have been introduced to improve the network, utilizing all protocols for energy efficiency. With 1000 s of MATLAB simulation execution and other proposed parameters for the simulation setup, this work has gained significant attention concerning the proposed evaluation parameters. The IEE-DLSA has outperformed all the performance evaluation parameters. It is also evident that the proposed IEE-DLSA has performed better than EE-LEACH, AC-OLSR, and DLSA, the existing approaches in FANET. The results from this study highlight the potential of the IEE-DLSA routing technique to significantly improve energy efficiency in FANETs, which is crucial given the limited energy resources of flying nodes. By achieving better throughput, reducing delay, minimizing transmission loss, and extending the network stability period, IEE-DLSA presents a robust solution to the energy challenges in FANETs.

While the IEE-DLSA routing scheme has demonstrated promising results, there are several avenues for future research to enhance its performance and applicability further. *Scalability Testing*: Future research should focus on evaluating the scalability of the IEE-DLSA protocol in larger networks with a higher number of nodes. This will help to understand how well the protocol performs as the network size increases. *Real-World Implementation*: Transitioning from simulation to real-world implementation will be critical. Testing the IEE-DLSA in practical scenarios, possibly through field trials with drones, will help validate the simulation results and ensure the protocol's robustness under various environmental conditions. *Adaptive Algorithms*: Developing adaptive algorithms that dynamically adjust real-time parameters based on changing network conditions could improve energy efficiency and network stability. *Integration with Other Technologies*: Exploring the integration of IEE-DLSA with other emerging technologies, such as machine learning and artificial intelligence, could enhance the protocol's decision-making capabilities, leading to even greater energy savings and performance improvements. *Security Enhancements*: Ensuring the security of FANETs is paramount, given their potential use in sensitive applications. Future work should include developing security mechanisms to protect against potential attacks while maintaining energy efficiency. *Cross-Layer Optimization*: Investigating cross-layer optimization techniques where the IEE-DLSA protocol can interact with other network stack layers to optimize energy usage and overall network performance further. By addressing these areas, future research can build upon the foundation laid by this study, contributing to the development of more efficient and robust FANETs.

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