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AN ENERGY-EFFICIENT AND HIGHLY SECURED STARLING MURMURATION-OPTIMIZED DSR ROUTING PROTOCOL FOR FLYING AD-HOC NETWORKS

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ABSTRACT

Flying Ad-Hoc Networks (FANETs), consisting of unmanned aerial vehicles (UAVs), are increasingly used in aerial surveillance, disaster response, and environmental monitoring applications. Due to their dynamic topology, limited energy resources, and need for reliable communication these networks pose significant challenges in terms of routing, energy efficiency, and security. To address these challenges, the Starling Murmuration Optimization-based Dynamic Source Routing (SMO-DSR) protocol is proposed, which integrates advanced swarm intelligence principles with secure and energy-efficient routing mechanisms. The SMO-DSR protocol optimizes communication in FANETs by dynamically adapting to network conditions, utilizing the natural behavior of starling flocks for path optimization. A critical feature of the protocol is the integration of RSA encryption during the route discovery process, ensuring that data communication is secure from eavesdropping and unauthorized access. The energy efficiency of the protocol is further enhanced through energy-driven clustering and dynamic power adjustment techniques. SMO-DSR was implemented in the NS-3 network simulator, with extensive simulations showing that the proposed protocol significantly improves energy efficiency and ensures secure communication, outperforming traditional routing protocols in both metrics. The results demonstrate that SMO-DSR is a promising solution for secure, energy-efficient communication in UAV-based systems, making it highly suitable for real-world FANET applications

Keywords: *Dynamic Source Routing, Energy Efficiency, Flying Ad-Hoc Networks, RSA Encryption, Starling Murmuration Optimization*

1. INTRODUCTION

Routing protocols enable seamless communication and coordination in Flying Ad-Hoc Networks (FANETs). These networks, composed of drones operating in dynamic and highly mobile environments, face unique challenges compared to traditional wireless ad hoc networks. Among the available routing protocols, the Dynamic Source Routing (DSR) protocol is widely adopted for its on-demand route discovery mechanism, which reduces control overhead by establishing routes only when required [1]. However, DSR faces limitations in FANETs, particularly in addressing critical issues like energy efficiency and security, which are vital for the effective functioning of these networks.

Energy efficiency is a serious problem in FANETs due to the limited power resources of drones. Each drone must allocate its energy sensibly across multiple tasks, including flight, sensing, processing, and communication [2]. Inefficient routing can lead to rapid energy depletion, uneven node power distribution, and network fragmentation, potentially disrupting mission-critical operations. Ensuring balanced energy consumption across the network is imperative to extend the operational lifespan of drones and maintain reliable communication. Traditional protocols like DSR often overlook these energy constraints, necessitating enhancements that integrate energy-aware mechanisms [3].

Security is another significant challenge in FANETs [4]. The wireless nature of communication makes these networks vulnerable to threats such as eavesdropping, data tampering, spoofing, and denial-of-service attacks. These vulnerabilities can compromise the integrity and confidentiality of transmitted data, disrupt communication, and undermine the network's reliability. Adding to the complexity, the decentralized and dynamic topology of FANETs makes it challenging to implement robust security measures without imposing additional computational or energy overhead [5]. A routing protocol tailored for FANETs must balance energy efficiency and security to ensure reliable and secure communication in resource-constrained environments.

The Starling Murmuration Optimization (SMO) algorithm, inspired by starling flocks' synchronized and adaptive movements, is a bio-inspired optimization technique designed to address complex problems in dynamic environments [6]. SMO is grounded in the principles of swarm intelligence, drawing on natural behaviors such as alignment, cohesion, and separation that enable starlings to navigate efficiently and adapt to environmental changes. When translated into computational models, these behaviors provide a robust framework for achieving optimal solutions by balancing exploration and exploitation. SMO is particularly effective in applications requiring adaptability, resource optimization, and real-time decision-making, making it an ideal choice for addressing the challenges in FANETs [7].To tackle the critical challenges of routing efficiency, energy optimization, and security in FANETs, the SMO-based Dynamic Source Routing (SMO-DSR) protocol is proposed. By integrating the adaptive and intelligent features of the SMO algorithm, SMO-DSR transforms traditional DSR into a more efficient and resilient routing protocol. Energy-aware flocking rules inspired by SMO guide drone nodes to consider their residual energy during route discovery and selection, ensuring balanced energy consumption and extending the overall network lifetime[8]. The dynamic optimization capabilities of SMO enable real-time identification and maintenance of energy-efficient routes, even in the face of rapid topology changes and high mobility inherent in FANETs[9].In addition to energy efficiency and routing performance, SMO-DSR addresses the critical need for secure communication in FANETs. The protocol incorporates lightweight security mechanisms that safeguard data integrity and protect against common network threats while imposing minimal computational overhead. SMO's principles of separation and cohesion are adapted to prevent network congestion and improve route stability, ensuring reliable communication. By leveraging SMO's adaptive and self-organizing capabilities, SMO-DSR achieves a comprehensive solution that optimizes routing, minimizes energy consumption, and ensures secure communication. This makes it a robust and scalable protocol, well-suited for next-generation drone communication networks operating in dynamic and resource-constrained environments.

1.1 Problem Statement

FANETs play a crucial role in applications such as disaster management, surveillance, and military operations, but they face significant challenges due to their dynamic and highly mobile nature. Frequent topology changes, unstable communication links, and limited energy resources prevent maintaining reliable and efficient network performance. Inefficient energy utilization can lead to premature node failures, reduced network lifespan, and disrupted operations. At the same time, the vulnerability of FANETs to security threats such as eavesdropping, data tampering, and unauthorized access further complicates their deployment. These threats can compromise sensitive information and disrupt mission-critical activities, with the decentralized and dynamic nature of FANETs making it difficult to implement robust security mechanisms without imposing significant computational and energy overhead. Existing routing protocols lack the adaptability to handle high mobility and energy constraints effectively while offering minimal inherent security measures. The combination of inefficient routing, energy limitations and exposure to security risks significantly impacts the reliability and effectiveness of FANETs in dynamic and mission-critical applications.

1.2 Motivation

The increasing reliance on UAVs for applications such as disaster management, environmental monitoring, and military operations highlights the critical need for efficient and secure communication networks. FANETs, which connect UAVs in dynamic and rapidly changing environments, present unique challenges, including high mobility, frequent topology changes, and limited energy resources. Traditional routing protocols often fail to meet these demands, reducing network performance and reliability. Moreover, the growing prevalence of cyber threats, such as data interception and tampering, underscores the need for robust security measures in FANETs to ensure the confidentiality and integrity of mission-critical information. Motivated by these challenges, this work focuses on optimizing the DSR protocol using the SMO algorithm inspired by starling birds' efficient, coordinated behavior. The integration of RSA encryption ensures secure communication, protecting data and routing information from unauthorized access. This combination of energy-efficient routing and advanced security mechanisms addresses the need for reliable and secure communication in FANETs. The proposed approach aims to enhance network performance and resilience, ensuring UAV-based systems can effectively operate in demanding and critical scenarios.

1.3 Objective

The primary objective of this research is to enhance the performance, efficiency, and security of routing in FANETs by optimizing the DSR protocol using the SMO algorithm. FANETs, composed of highly mobile UAVs, play a critical role in disaster management, military surveillance, and environmental monitoring applications. However, their dynamic nature, characterized by frequent topology changes, high mobility, limited energy resources, and vulnerability to security threats, poses significant challenges to reliable and secure communication. This work addresses these challenges by integrating the swarm intelligence principles of SMO into DSR. Inspired by the collective behavior of starlings, SMO enables adaptive decision-making, energy-efficient routing, and dynamic adjustments to the network environment. The proposed approach incorporates RSA encryption to ensure data confidentiality, integrity, and secure communication between UAVs, protecting the network from cyber threats like eavesdropping and data tampering. The objectives of the proposed work include:

1. Developing an energy-aware and secure routing mechanism to extend the network lifetime of FANETs.
2. Enhancing route stability by dynamically adapting to high UAV mobility.
3. Reducing energy consumption during route discovery and maintenance.
4. Improving overall network performance metrics such as throughput, packet delivery ratio, and latency.
5. Securing routing information and data transmission through robust encryption techniques.

1.4 Organization of the Paper

The rest of this paper is organized as follows: Section 2 presents a review of related work, highlighting existing routing protocols and optimization techniques for FANETs, along with their limitations. Section 3 explains the proposed SMO-DSR framework, including its design principles and implementation details. Section 4 describes the simulation setup and evaluation metrics, followed by the results and discussion. Finally, Section 5 concludes the paper by summarizing the key findings and suggesting directions for future research

2. RELATED WORK

Taehwan Kim et al.[10] analyzed the performance of different routing protocols under reconnaissance scenarios to identify the most suitable routing protocol. This research also evaluates the mobility model with the highest performance under reconnaissance scenario. However it did not focus on the energy efficiency of UAVs. FANETs face unique challenges due to the high mobility of nodes, dynamic topology, and limited energy resources. Many studies have proposed routing protocols to address these challenges. Qing Liang et al.[11] proposed a DSR routing protocol based on the reliability of the path for data transmission between UAVs. To improve the data transmission, this research monitors the link state information and efficiently repairs broken links. DSR is widely used in FANETs due to its on-demand route discovery feature, which helps in environments with frequent topology changes. However, traditional routing protocols, including DSR, suffer from instability and high energy consumption in highly dynamic UAV environments. Tyas Nurfitriana et al. [12] analyzed the energy consumption of the DSR routing protocol on MANET. The experimental results show that the protocol suffers a low packet delivery ratio when the node movement is high.

Recent studies have proposed variations of DSR to adapt it to FANET-specific challenges. Using machine learning techniques, S. Jothi Lakshmi & M. Karishma [13] proposed a modified DSR routing protocol for MANETs. The experimental results prove that the proposed protocol performs efficient data transfer while minimizing computational overhead by adopting reinforced learning. Despite these advances, issues like energy efficiency and route stability remain inadequately addressed, highlighting the need for more robust solutions. Optimization techniques, particularly those inspired by nature, have gained attention for improving FANET routing performance. Swarm intelligence techniques like Particle Swarm Optimization (PSO) and Ant Colony Optimization (ACO) have been applied to routing in FANETs, demonstrating improvements in energy efficiency and route discovery. R. C. Karpagalakshmi et al. [14] proposed a bio-inspired whale optimization algorithm for building clusters in FANET. This algorithm selects the suitable cluster head for optimal path and minimal energy consumption. Amrita Yadav[15] analyzed swarm intelligence and genetic algorithms to enhance routing performance. This research work proposes a modified firefly algorithm, which is integrated with a novel clustering technique. Starling Murmuration Optimization(SMO), a newer approach inspired by the collective behavior of starling birds, has shown promise in optimizing dynamic network environments. These techniques offer adaptive, energy-efficient solutions to routing by mimicking biological behaviors that enhance decision-making processes and resource allocation. Hoda Zamani et al. [16] proposed a novel SMO algorithm to solve different engineering problems. The experimental results show that the algorithm can be applied to mechanical engineering problems. However, these methods improve performance but have not been extensively integrated with routing protocols like DSR in FANETs.

The security of UAV networks is a growing concern, as FANETs are particularly vulnerable to threats such as eavesdropping, data tampering, and unauthorized access. Vinay Bhardwaj and Navdeep Kaur [17] proposed a secured and energy-efficient routing protocol for FANET. The proposed work has two phases, where the first phase deals with routing and the second phase deals with security. Studies have explored several security mechanisms, including public key cryptography and trust-based models, to safeguard communications in FANETs. For example, RSA encryption has been widely implemented for securing data transmission because it provides data confidentiality and integrity. Sahabul Alam et al.,[18] used Ant Colony Optimization for selecting the trusted leader drone. This research also focuses on fuzzy-based routing schemes for FANETs. While encryption techniques like RSA enhance security, many existing studies do not fully consider the trade-off between security, routing performance, and energy efficiency in FANETs. Yatao Yang et al. [19] proposed a cryptographic algorithm for secured data transmission between drone nodes. The experimental results show that the data, images, and control instructions are transmitted in encrypted form to enhance security using the proposed lightweight algorithm. INAM ULLAH KHAN et al.[20] proposed a routing protocol by modifying the base protocol AntHocNet and evaluating the performance of the routing protocol. Hua Yang and Zhiyong Liu [21] proposed a novel protocol to optimize the route using a Continuous Hopfield Neural Network(CHNN) based on the DSR protocol. Bio-inspired optimization has become a crucial domain in networking to attain better results [22]-[46].

Table 1 highlights the summarized view of the methodology, advantages and disadvantages of the research work in the literature

Table 1: Comparison of State-of-the-Art Methodologies

State-of-the-art methodology	**Problem Identified**	**Solution**	**Strength**	**Weakness**
Performance evaluation of proactive, reactive, and hybrid routing protocols[10]	To evaluate the performance of FANET routing protocols in disaster scenarios	A temporary communication network is created, and UAVs are used for data transmission.	Routing protocols perform better in data delivery	Routing overhead is identified in different scenarios
Path reliability and link monitoring repair(DSR-PM) [11]	To improve the quality of communication between UAV nodes.	Data transmission is done through the most reliable path	Ensures effective data transmission through link detection	Performance is low when nodes have high-speed motion
Energy Consumption of DSR[12]	To determine energy consumption and residual energy	Energy consumption is calculated for the scenario of increasing node speed and network area	Faster node movement requires less energy	Low packet delivery ratio when node movement speed increases

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DSR protocol using Reinforced Learning [13]	To improve DSR protocol using a deep reinforced learning technique	Instead of the random path, the optimal path is chosen to handle routing errors	Minimal computational overhead during route discovery after failure	The cross-layer protocol is vulnerable to security threats
Fuzzy logic based zonal clustering algorithm(EEBMC-p-WOA)[14]	To increase cluster longevity and decrease routing traffic	Bio-inspired optimization and fuzzy-based clustering algorithms are used	Increased cluster lifetime	Packet scheduling is required to increase efficiency
Performance evaluation of nature-inspired algorithms(MFA)[15]	To evaluate the performance of nature-inspired algorithms	The modified firefly algorithm (MFA) is used to evaluate routing performance	Enhanced routing efficiency	Energy efficiency is not considered
Starling Murmuration Optimizer (SMO) [16]	To provide global optimal solutions for mechanical engineering problems	Dynamic multi-flock construction with different searching strategies	Well-balanced exploration and exploitation	The model did not consider large-scale, real-world problems
Secured Energy Efficient Dynamic Routing Protocol(SEEDRP) [17]	To develop an energy-efficient and secured routing protocol	Two distinct algorithms are developed for routing and security, and the AES encryption model is used for security	Enhances quality of service with a cost-effective method	The cross-layer optimization increases complexity
Trusted fuzzy routing scheme[18]	To build a bio-inspired routing technique	Fuzzy logic is used to find the trusted route	Simplified routing through clustering	Computational complexity
Encryption communication system for drones (19)	To solve the security issues during drone communication	Encrypted data transmission using the CARX algorithm	Secured transmission of data and images	The model is resource-intensive
Hopfield Neural Network Optimized Routing(CHNN-DSR)[20]	To optimize the route for FANET	Continuous Hopfield Neural Network is used for route optimization	Increased stability and communication efficiency in the network	High computational requirement
eAntHocNet[21]	To solve routing issues with a metaheuristic-based routing protocol	Modified ant colony metaheuristics are used for routing	Improved energy efficiency through energy stabilizing parameter	Computational overhead

Despite significant progress in routing, optimization, and security in FANETs, most existing research addresses only one or two aspects. Few studies have integrated swarm intelligence-based optimization with secure routing protocols in FANETs, and the trade-offs between security, energy efficiency, and routing stability are often overlooked. The proposed work seeks to bridge these gaps by combining the SMO algorithm with DSR, offering an energy-efficient, stable, and secure routing solution. Additionally, integrating RSA encryption ensures secure communication, addressing the critical issue of data protection in UAV networks. This research aims to create a more resilient and efficient communication framework for FANETs by focusing on energy-aware routing, dynamic adaptability, and robust security

3. STARLING MURMURATION OPTIMISED DYNAMIC SOURCE ROUTING (SMO-DSR) PROTOCOL

The Starling Murmuration Optimization (SMO) algorithm is a swarm intelligence technique inspired by starling birds' coordinated and collective flight behavior. Murmuration, characterized by the fluid and dynamic patterns formed by large groups of starlings, demonstrates remarkable coordination, adaptability, and energy efficiency. Each bird in the flock adjusts its movement based on the position and velocity of its neighbors while maintaining cohesion and avoiding collisions, enabling the group to achieve optimal collective outcomes in dynamic environments. SMO leverages these principles to solve complex optimization problems. It models a system of agents (analogous to birds) interacting locally, sharing information to find optimal solutions in a multi-dimensional search space. The algorithm incorporates three primary behaviors: alignment, ensuring consistent direction; cohesion, promoting group unity; and separation, avoiding overcrowding. Additionally, energy-awareness is embedded into the decision-making process, prioritizing sustainable operations. SMO is particularly effective in network routing because it adapts dynamically to changing conditions. It ensures optimal path selection by balancing exploration (searching for new paths) and exploitation (refining existing paths). The algorithm's energy-efficient and decentralized nature makes it well-suited for applications like FANETs, where dynamic topologies and energy constraints demand innovative, adaptive solutions. The following sections explain the various steps involved in the SMO-DSR algorithm.

3.1 Initialise Node States and Energy Levels

Initializing the node states and energy levels is crucial for setting a foundation for energy-efficient and dynamic routing. Each node in the FANET is represented with specific attributes: energy level, location, velocity, and state. Initialization of these parameters ensures that subsequent routing and optimization steps adhere to energy constraints, providing a stable starting point for the SMO process in enhancing DSR. Let each node i have an initial energy level.E_i, initial position coordinates(x_i, y_i, z_i), and velocity vector $\vec{v_i}$. The following equations govern the initialization and set the basis for route discovery and selection.The energy level E_iFor node i is represented as in Eq.(1):

$$E_i = E_{max} - \alpha . d_i \quad (1)$$

where E_{max} denotes the maximum energy capacity of a node, α is the energy depletion rate per distance unit, and d_iIt is the distance travelled by the node from a base position. By setting initial energy levels, nodes can begin operations within defined constraints.For each node i, the position vector$\vec{p_i}$ is defined as in Eq.(2):

$$\vec{p_i} = (x_i, y_i, z_i) \quad (2)$$

where $(x_i, y_i, z_i)$are the coordinates in a three-dimensional space? This vector allows SMO to calculate flocking distances and neighbor proximity, which is vital for route optimization and alignment.The velocity vector $\vec{v_i}$Of each node i is given in Eq.(3):

$$\vec{v_i} = v_{init} . \hat{d_i} \quad (3)$$

where $\boldsymbol{v_{init}}$is the initial speed of the node and $\hat{d_i}$ is a unit direction vector. The initial velocity influences the relative positioning among nodes, which impacts energy consumption due to movement.Nodes are assigned an operational state S_i to indicate their status as in Eq.(4):

$$S_i = \begin{cases} \text{active} & \text{if } E_i > E_{threshold} \\ \text{inactive} & \text{otherwise} \end{cases} \quad (4)$$

where $E_{threshold}$ is the minimum required energy for activity. By defining an initial state, nodes are prepared for potential role assignments in the routing process. The rate of energy consumption $C_i$for node i is expressed as in Eq.(5):

$$C_i = \beta \cdot P_t + \gamma \cdot P_r \quad (5)$$

where P_t is the transmission power, P_r is the reception power, $\beta$and γ are constants associated with energy costs for transmission and reception, respectively. This equation estimates how quickly a node might deplete its energy, influencing route selection later in SMO-DSR. The communication range$R_i$for each node i is initialized as in Eq.(6):

$$R_i = \sqrt{\frac{P_t \cdot G_t \cdot G_r}{L \cdot N}} \quad (6)$$

where G_t and G_r are the gains of the transmitting and receiving antennas, L is the path loss factor, and N is the noise power. Initializing the communication range ensures nodes can accurately estimate their connectivity within the FANET.Initial Neighbourhood Radius $r_{neighbour}$ for node i is set as in Eq.(7):

$$r_{neighbour} = \mathcal{E} \cdot R_i \quad (7)$$

where $\mathcal{E}$ is a scaling factor. This parameter is essential for SMO-based interactions, as it defines which nodes influence one another based on proximity, affecting path optimisation.

For reliability assessment, the probability of initial link failure P_{fail} between node i and node j is calculated as in Eq.(8):

$$P_{fail} = 1 - e^{-\delta \cdot d_{ij}} \quad (8)$$

where δ is a decay factor, and d_{ij} represents the distance between nodes i and j. The probability of link failure plays a role in route selection by determining the stability of initial node connections. In the above equations, variables are defined to capture the essential characteristics of each node in the FANET. E_i represents the energy level of node i while α is a rate that controls how energy decreases as distance d_i increases. The position vector $\vec{P_i}$ $=(x_i, y_i, z_i)$ places the node within a spatial frame and $\vec{v_i}$ sets the movement rate based on v_{init} and the unit direction vector $\hat{d_i}$. The state S_i depends on $E_{threshold}$, categorizing nodes as active or inactive based on their energy levels.

Energy consumption C_i is influenced by the transmission power P_t and reception power P_r , with β and γ factoring in respective costs. The communication range R_i depends on power P_t, antenna gains G_t and G_r , path loss L, and noise N. The neighborhood radius $r_{neighbour}$, determined by $\mathcal{E}$ and communication range R_i , defines the vicinity within which nodes interact. Finally, P_{fail}, dependent on decay δ and distance d_{ij} estimates link stability, guiding route selection as SMO-DSR progresses.This initial setup accurately depicts each node's energy, location, and state, supporting future optimization within SMO-DSR. This initialization ensures that nodes interact in an energy-efficient manner, enabling the establishment of resilient paths in subsequent steps.

3.2 Applying Energy-Based Flocking Rules

Energy-based flocking rules guide nodes' movement and positioning within the FANET through alignment, cohesion, and separation. This mechanism emulates the flocking behaviour observed in starling murmurations, where each node dynamically adjusts its movement based on energy levels and the behaviour of neighbouring nodes. Energy-based flocking is essential to enhance connectivity and prolong network lifespan, as it minimizes unnecessary energy depletion while maximizing the efficiency of route selection and stability. In FANET, the energy-based flocking rules are governed by three primary behaviours: alignment, cohesion, and separation. Each behaviour is defined concerning the energy constraints of each node to balance individual movement with collective network performance. Let E_i be the energy level of node i, $\vec{v_i}$ be its velocity vector, and $\vec{p_i}$its position vector.The alignment rule, aimed at synchronizing the movement of neighboring nodes, is defined by adjusting each node's velocity to match the average velocity of its neighbours. This is shown in Eq.(9):

$$\vec{v_i'} = \vec{v_i} + k \cdot \left(\frac{1}{N_i}\sum \vec{v_j} - \vec{v_i}\right) \quad (9)$$

where N_i is the set of neighboring nodes of node i, k is an alignment factor, and $\vec{v_j}$ represents the velocity vector of the neighboring node j. This adjustment aligns the movement of node i with its neighbors, reducing individual deviation and enhancing connectivity.Cohesion maintains the proximity of nodes by directing each node toward the center of its neighbors. This behavior is energy-weighted, where nodes with higher energy levels have a stronger pull. It is shown in Eq.(10)

$$\overrightarrow{F_{cohesion}} = \eta \cdot \left(\frac{\sum_{j\epsilon N_i} E_j \cdot \vec{P_j}}{\sum_{j\epsilon N_i} E_j} - \vec{p_i}\right) \quad (10)$$

where η is a cohesion factor, E_j represents the energy level of neighboring node j and $\vec{p_j}$ is its position vector. This energy-weighted cohesion ensures that nodes with higher energy influence the movement of others, enhancing path stability by encouraging stronger nodes to form the network's backbone. The separation rule prevents node overcrowding by creating a repulsive force between closely spaced nodes. This repulsion is energy-based, where nodes with higher energy generate a stronger separation force, which is represented in Eq.(11):

$$\vec{F}_{separation} = \sum_{j\epsilon N_i} C \cdot \frac{E_j}{d_{ij}^2} \cdot (\vec{p}_i - \vec{p}_j) \quad (11)$$

where C is a separation constant, d_{ij} is the distance between nodes i and $j$and E_j is the energy of node j. This rule mitigates collision risks and minimizes energy consumption by maintaining an optimal distance between nodes. The combined flocking velocity for each node i is a weighted sum of the alignment, cohesion, and separation behaviors as in Eq.(12):

$$\vec{v}_i'' = \lambda \cdot \vec{v}_i' + \mu \cdot \vec{F}_{cohesion} + v \cdot \vec{F}_{separaion} \quad (12)$$

where λ, μ, and $v$are weighting factors for alignment, cohesion, and separation, respectively. This final velocity guides each node's movement based on the calculated influences, providing balance across behaviors. To prioritize energy efficiency, the movement direction for node$i$ is influenced by its residual energy, given in Eq.(13):

$$\vec{D}_i = \omega \cdot E_i \cdot \vec{v}_i'' \quad (13)$$

where ω is an energy-scaling factor. This equation ensures that nodes with higher energy contribute more actively to maintaining network cohesion and alignment, aiding in conserving the energy of lower-energy nodes.The updated position of each node i considering the flocking behaviours is given by Eq.(14):

$$\vec{\mathrm{p}}_{\mathrm{i}}' = \vec{p}_i + \vec{D}_i \cdot \Delta t \quad (14)$$

where Δt is the time interval for each update. This update allows nodes to adjust their locations based on their energy-weighted velocities, thereby conserving energy while maintaining connectivity. The effective communication range R_i' for each node i based on its energy level, is shown in Eq.(15):

$$\mathrm{R}_{\mathrm{i}}' = \mathrm{R}_{\mathrm{i}} \cdot \frac{\mathrm{E}_{\mathrm{i}}}{\mathrm{E}_{\max}} \quad (15)$$

where E_{max} is the maximum initial energy of any node. This adjustment modifies the range, allowing high-energy nodes to connect more widely, stabilizing the network. To guide nodes towards energy-rich areas, an energy gradient field $G_i$for each node i is defined byEq.(16):

$$G_i = \sum_{j \epsilon N_i} \frac{E_j - E_i}{d_{ij}} \quad (16)$$

This field helps in energy-based clustering, where nodes gravitate towards higher energy nodes, enhancing overall network robustness.

3.3 Execute Dynamic Route Discovery Using SMO with RSA Encryption

The dynamic route discovery is executed using the SMO algorithm, with an added layer of security through the RSA encryption algorithm. This step aims to find optimal, energy-efficient, robust, and secure paths, addressing potential vulnerabilities in the FANET. RSA encryption provides confidentiality and integrity during route discovery, ensuring that routing information and data transmitted across the network are protected against eavesdropping and unauthorized access. The route discovery process leverages the energy-efficient flocking principles defined in previous steps to guide each node's movement while employing RSA encryption to secure route requests (RREQ) and route replies (RREP) exchanged between nodes. By combining SMO's path optimization with RSA's security, SMO-DSR offers a reliable and secure routing mechanism tailored for dynamic FANET environments. Each source node S initiates a route discovery by generating a Route Request (RREQ) packet that contains the destination node$D$, timestamp T, and a unique sequence number N_{seq} for identification as in Eq.(17):

$$RREQ_{original} = \{S, D, T. N_{seq}\} \quad (17)$$

This initial RREQ structure forms the foundation for encrypted transmission across the FANET. To secure the RREQ, the RSA encryption algorithm is applied to the RREQ packet. The encrypted RREQ,$RREQ_{encrypted}$ is calculated as in Eq.(18).

$$RREQ_{encrypted} = RREQ_{original}^{e} \ mod \ n \quad (18)$$

where e and n are the public key components in RSA encryption, generated as $n = p \cdot q$ with p and q being large prime numbers. This encryption secures the RREQ contents, preventing unauthorized nodes from accessing routing information.When an intermediate node i receives an encrypted RREQ, it decrypts it using its private key$d$ as in Eq.(19):

$$RREQ_{decrypted} = RREQ_{encrypted}^{d} \ mod \ n \quad (19)$$

After decryption, the node checks its energy level E_i , to determine whether to participate in routing. If $E_i \geq E_{threshold}$ where $E_{threshold}$ is a minimum energy threshold, the node forwards the RREQ; otherwise, it discards it. This energy-aware decision ensures that only nodes with sufficient resources engage in route discovery, optimizing energy usage across the network. To select the most efficient path, the SMO algorithm applies dynamic weights based on each node's energy E_i and distance d_{ij}between nodes. The objective functionf_{path} for a route,P is calculated as in Eq.(20):

$$f_{path} = \sum_{i,j \in P} \left(\frac{1}{d_{ij}} + \gamma \cdot \frac{1}{E_i} \right) \quad (20)$$

where γ is a weight balancing distance and energy factors, this function guides SMO to select paths that minimize energy consumption and maximize proximity among nodes, maintaining efficient connectivity.Once a route is established, the destination node$D$ generates a Route Reply (RREP) packet containing the path P and a confirmation timestamp $T_{confirm}$ as in Eq.(21):

$$RREP_{original} = \{P, T_{confirm}\} \quad (21)$$

This RREP is then encrypted using the RSA public key of the source node S, ensuring secure transmission back to the source. The encrypted RREP, $RREP_{encrypted}$ is created as in Eq.(22):

$$RREP_{encrypted} = RREP_{original}^{e} \ mod \ n \quad (22)$$

This encryption ensures that only the intended source node S, which possesses the corresponding private key d, can decrypt the RREP and confirm the selected route.Upon receiving$RREP_{encrypted}$the source node S encrypts it using its private key d as in Eq.(23):

$$RREP_{decrypted} = RREP_{encrypted}^{d} \bmod n \quad (23)$$

This decryption enables the source node to retrieve the path P and confirmation timestamp $T_{confirm}$ completing the secure route discovery process.Before initiating data transmission, the source node S performs a final energy validation to ensure that each node in the path P has sufficient energy E_i as shown in Eq.(24):

$$\sum_{i\epsilon P} E_i \geq E_{min} \times |P| \quad (24)$$

where $E_{min}$is the minimum acceptable energy for route participation and $|P|$ is the total number of nodes in P. This validation step helps to confirm that the path is stable and capable of sustaining data transmission.

3.4 Optimize Energy-Based Path Selection

This step focuses on optimizing energy-based path selection, which aims to select routes that maintain network connectivity and minimize energy consumption across the FANET. This step ensures that the routes established in the dynamic route discovery phase are refined to extend the network's lifespan by conserving the battery resources of individual nodes. This optimization integrates energy thresholds, path weights, and adaptive selection criteria inspired by the SMO algorithm, which simulates the adaptive, efficient flocking behaviour seen in starling murmurations.

The optimization of energy-based path selection begins with calculating a weighted cost for each path, considering node energy levels and distances. Let each path P in FANET contain nodes.$\{i_1, i_2, \cdots, i_n\}$ where each node i has a corresponding energy level E_i and distance $d_{ij}$to its neighboring nodes j. The energy-based path cost C_{path} for a given path P is derived usingEq.(25) that considers both energy and distance as critical factors:

$$C_{path} = \sum_{(i,j)\in P} \propto \cdot \frac{1}{E_i} + \beta \cdot d_{ij} \quad (25)$$

where $\propto$ and β are weighting factors for energy and distance, respectively. By minimizing C_{path} the SMO-DSR algorithm identifies paths that favor nodes with higher energy reserves and shorter transmission distances.To ensure that nodes with sufficient energy participate in the optimized path, an energy threshold $E_{min}$is set. Each node i in path P must satisfy the condition shown in Eq.(26):

$$\mathrm{E_i} \geq \mathrm{E_{min}} \quad (26)$$

The path is excluded from consideration if any node does not meet this threshold. This threshold-based filtering minimizes the risk of path failure due to low-energy nodes, thereby enhancing route stability. Once the feasible paths are filtered, the SMO algorithm assigns a selection probability based on energy levels, ensuring that paths with higher energy are prioritized. The selection probabilityP_{path} for path P is given in Eq.(27):

$$\mathrm{P_{path}} = \frac{\sum_{i\epsilon P} \mathrm{E_i}}{\sum_{k\epsilon P} \sum_{i\epsilon k} \mathrm{E_i}} \quad (27)$$

where $P$is the set of all candidate paths. Paths with higher cumulative energy levels $\sum_{i\epsilon P} \mathrm{E_i}$ have higher probabilities, aligning node selection with energy preservation goals. Path weights are adjusted dynamically according to real-time energy depletion and node positions to adapt to network changes. The updated path weight W_{path} for path P at time t is recalculated as in Eq.(28):

$$W_{path}(t) = W_{path}(t-1) \times \left(1 - \frac{\delta \cdot (E_{initial} - E_{current})}{E_{initial}}\right) \quad (28)$$

where δ is the energy depletion scaling factor, $E_{initial}$ is the initial energy of the node, and $E_{current}$ is the current energy. This reweighting ensures that paths adjust dynamically as node energy levels fluctuate.To select the optimal path, the SMO algorithm evaluates each path's fitness,F_{path} considering both path cost and node energy levels as in Eq.(29):

$$\mathrm{F_{path}} = \frac{1}{\mathrm{C_{path}}} \cdot \left(\frac{\sum_{i\epsilon P} \mathrm{E_i}}{|\mathrm{P}|}\right) \quad (29)$$

where $|\mathrm{P}|$ is the number of nodes in P Paths with higher fitness values indicate a favorable balance of low path cost and high average energy.To prevent over-reliance on specific nodes, an energy-balancing factor $B_i$for each node i along a path is introduced in Eq.(30):

$$\mathrm{B_i} = \frac{\mathrm{E_i}}{\sum_{\mathrm{j} \in \mathrm{N_i}} \mathrm{E_j}} \quad (30)$$

where N_i is the set of neighbouring nodes for i. This factor minimizes the likelihood of exhausting individual nodes by distributing the routing load based on neighbouring nodes energy levels. The SMO-DSR algorithm employs an adaptive interval$T_{maintenance}$ for path re-evaluation as shown in Eq.(31):

$$\mathrm{T_{maintenance}} = \frac{\theta}{\sum_{\mathrm{i} \in \mathrm{P}} \mathrm{E_i}/|\mathrm{P}|} \quad (31)$$

where θ is a scaling constant, high-energy paths are maintained for longer intervals, reducing the frequency of re-evaluation and lowering energy consumption.Based on the fitness evaluations, a final decision metric D_{final} is derived for each path P by integrating both the fitness and energy balancing factors as shown in Eq.(32):

$$\mathrm{D_{final}} = \mathrm{F_{path}} \times \sum_{\mathrm{i} \in \mathrm{P}} \mathrm{B_i} \quad (32)$$

The path with the highest D_{final} is chosen as the optimal path for data transmission

3.5 Adjust Transmission Power with SMO Rules

Transmission power is adaptively adjusted according to SMO principles, optimizing energy consumption while maintaining robust connectivity in the FANET. Adjusting transmission power dynamically is essential for conserving energy, minimizing interference, and ensuring reliable data transmission in a FANET environment. By incorporating SMO-inspired rules, nodes can collectively adjust their power output based on local energy levels, node density, and distance to neighbouring nodes, resulting in a balanced, efficient network. This power adjustment step uses energy-based and distance-based parameters to set transmission levels for each node in the network. Given that FANETs are highly dynamic, with nodes in constant motion, real-time adjustment to transmission power is crucial to maintain network stability and performance. SMO's principles, such as alignment, cohesion, and separation, inspire this transmission power adjustment by creating an adaptive approach that responds to network changes. Each node i begins with an initial transmission power $P_{i,initial}$ set based on its initial energy $E_{i,initial}$ and maximum communication range R_{max} as shown in Eq.(33):

$$\mathrm{P_{i,initial}} = \frac{\mathrm{E_{i,initial}}}{\mathrm{R_{max}}} \quad (33)$$

This initial setting ensures that nodes with higher energy can transmit over greater distances while nodes with lower energy use less power to preserve battery life. As nodes move within the FANET, the distance D_{ij} between a node i and its neighbour j varies. To ensure stable communication while conserving energy, a dynamic power adjustment factor ΔP_i is calculated as in Eq.(34):

$$\Delta \mathrm{P_i} = \gamma \cdot \left(\frac{1}{\mathrm{d_{ij}}} \right) \quad (34)$$

where γ is a scaling constant that adjusts power based on proximity to neighbors, shorter distances require lower power, reducing energy waste.Following SMO's alignment rule, nodes align their transmission power with nearby nodes to avoid excessive interference. The aligned transmission power $P_{i,aligned}$ for node i is given in Eq.(35):

$$\mathrm{P_{i,aligned}} = \frac{1}{|\mathrm{N_i}|} \sum_{\mathrm{j} \in \mathrm{N_i}} \mathrm{P_j} \quad (35)$$

where N_i represents the set of neighboring nodes for i. This alignment encourages uniform power levels among neighboring nodes, stabilizing communication and avoiding interference. SMO's cohesion principle encourages nodes to adjust power based on the density of neighbouring nodes. For a dense cluster of nodes, transmission power $P_{i,cohesion}$ is reduced to minimize energy consumption, as shown in Eq.(36):

$$\mathrm{P_{i,cohesion}} = \mathrm{P_{i,initial}} \cdot \left(1 - \delta \cdot \frac{|\mathrm{N_i}|}{\mathrm{N_{max}}} \right) \quad (36)$$

where δ is cohesion scaling constant and $\mathrm{N_{max}}$ is the maximum expected neighbor count in a given region. Lower power settings in dense areas prevent excessive energy usage. SMO's separation rule is applied to prevent interference and collisions, whereby nodes increase transmission power if neighbours move too far apart. The separation-adjusted power $P_{i,separation}$ is shown in Eq.(37):

$$\mathrm{P_{i,separation}} = \mathrm{P_{i,initial}} + \lambda \cdot \left(\mathrm{d_{ij}} - \mathrm{d_{min}} \right) \quad (37)$$

where λ is a separation scaling factor, and $\mathrm{d_{min}}$is the minimum distance threshold. This increase in power helps maintain connectivity when nodes are farther apart. To balance energy consumption across nodes, transmission power $P_{i,energy}$ is adjusted based on the remaining energy E_i as shown in Eq.(38):

$$P_{i,energy} = P_{i,initial} \cdot \frac{E_i}{E_{initial}} \quad (38)$$

where $E_{initial}$ is the initial energy of the node. Nodes with higher remaining energy transmit at higher power, while nodes with lower energy reduce their power to conserve resources.The optimal transmission power $P_{i,opt}$ for each node combines the effects of alignment, cohesion, separation, and energy balancing as shown in Eq.(39):

$$\mathrm{P_{i,opt}} = \mathrm{P_{i,aligned}} + \mathrm{P_{i,cohesion}} + \mathrm{P_{i,separation}} + \mathrm{P_{i,energy}} \quad (39)$$

This aggregation of factors allows each node to select a power level that supports effective, energy-efficient communication in changing network conditions. To prevent frequent recalculations, the power adjustment interval T_{adjust} is set dynamically based on node movement and energy, as shown in Eq.(40):

$$T_{adjust} = \frac{\theta}{\sum_{j\epsilon N_i} d_{ij}/|N_i|} \quad (40)$$

where θ is a scaling factor. Nodes in more dynamic environments adjust their power more frequently, while those in stable conditions conserve resources at longer intervals.

3.6 Maintain Routes Using Energy-Driven Clustering

This step involves maintaining routes using energy-driven clustering to group nodes based on their energy levels and spatial proximity. This approach enhances the network's stability by organizing nodes into clusters that can communicate efficiently, thereby reducing the overhead of individual route maintenance. Energy-driven clustering also addresses energy consumption and load balancing issues by selectively assigning routing responsibilities to high-energy nodes, preserving the energy of nodes with limited battery reserves. In FANET environments, where node mobility and energy constraints are significant, clustering aids in extending the network's overall lifespan. In energy-driven clustering, nodes are grouped around a cluster head (CH), which manages intra-cluster communication and acts as an intermediary between clusters. SMO principles are applied to ensure that cluster head selection and maintenance processes are adaptive to energy levels and node mobility. The clustering process can be divided into three key phases: cluster formation, CH selection, and route maintenance within clusters. These phases enable SMO-DSR to maintain stable, energy-efficient clusters that support long-term network connectivity. To initiate clustering, nodes calculate their energy-based clustering criterion.C_i which considers a node's energy level E_i and its distance d_{ij} to nearby nodes as in Eq.(41):

$$\mathrm{C_i} = \alpha \cdot \mathrm{E_i} - \beta \cdot \sum_{\mathrm{j\epsilon N_i}} \mathrm{d_{ij}} \quad (41)$$

where α and β are weighting factors for energy and distance, respectively. Nodes with higher $C_i$values are more favorable for clustering, as they indicate nodes with high energy levels close to other nodes.Once the clustering criterion is established, each node calculates a probability P_{CH} for becoming a cluster head based on its energy level relative to its neighbours as shown in Eq.(42):

$$\mathrm{P_{CH}} = \frac{\mathrm{E_i}}{\sum_{\mathrm{j\epsilon N_i}} \mathrm{E_j}} \quad (42)$$

Nodes with higher energy levels have higher probabilities of becoming CHs, ensuring that routing responsibilities are assigned to nodes with sufficient energy resources. The intra-cluster communication cost C_{intra}, shown in Eq.(43), for a given cluster is minimized by choosing a CH that reduces the average distance d_{avg} among cluster members:

$$C_{intra} = \frac{1}{|N_{cluster}|} \sum_{j\epsilon N_{cluster}} d_{ij} \quad (43)$$

where $N_{cluster}$represents the set of nodes in the cluster. Selecting a CH close to the cluster's center minimizes transmission costs for intra-cluster communication, conserving energy across the cluster.Nodes join a cluster only if they meet a minimum energy threshold E_{min} to ensure that low-energy nodes are preserved and not overburdened by routing duties. This is shown in Eq.(44).

$$E_i \geq E_{min} \quad (44)$$

This threshold prevents the exhaustion of low-energy nodes, promoting balanced energy usage within clusters and extending the network lifespan. As nodes move and energy levels change, cluster head re-election may be required. The CH re-election threshold T_{CH} is calculated based on the average energy E_{avg} of the cluster members as shown in Eq.(45):

$$T_{CH} = \boldsymbol{\delta} \cdot E_{avg} \quad (45)$$

where $\boldsymbol{\delta}$ is a re-election scaling factor. When the CH's energy falls belowT_{CH} , a new CH is elected from the cluster members, maintaining the cluster's energy balance.To facilitate communication between clusters, an inter-cluster communication cost C_{inter} is calculated using Eq.(46) for each CH based on its distance to other CHs and its energy:

$$C_{\mathrm{inter}} = \sum_{k \in N_{CH}} \left(\frac{\mathbf{d}_{\mathbf{CH_i,CH_k}}}{\mathbf{E}_{\mathbf{CH_i}}} \right) \quad (46)$$

where N_{CH} is the set of neighbouring CHs and $\mathbf{d}_{\mathbf{CH_i,CH_k}}$represents the distance between CH_i and CH_k. Minimizing C_{inter} ensures efficient routing between clusters and reduces the energy overhead for CHs. SMO's principles of cohesion and separation are applied to manage cluster density. The cluster density $D_{cluster}$ in Eq.(47) is calculated based on the average distance d_{avg} within the cluster and the maximum allowable density D_{max}:

$$\mathrm{D_{cluser}} = \frac{1}{\mathrm{d_{avg}}} \cdot |\mathrm{N_{cluster}}| \quad (47)$$

If $\mathrm{D_{cluster}}$exceeds D_{max} the cluster is split, ensuring that clusters remain manageable and do not become overcrowded, which would increase communication costs.To select the optimal routing path from one cluster to another, each CH calculates a path cost C_{path} that considers both intra-cluster and inter-cluster communication costs as in Eq.(48):

$$C_{path} = C_{intra} + C_{inter} \quad (48)$$

The path with the lowest C_{path} is chosen as the optimal route, ensuring efficient data transmission across clusters with minimal energy consumption.

3.7 Prevent Congestion with SMO's Separation Principle

Here, congestion control is implemented using the Separation Principle of SMO. Congestion in FANETs can arise due to high node density, frequent communication overlaps, and dynamic mobility patterns. Congestion leads to packet collisions, delayed transmissions, and increased energy consumption due to retransmissions, reducing the network's overall efficiency. SMO's separation principle mimics how starlings maintain a balanced distance from one another to avoid overcrowding. By applying this principle, each node in the network dynamically manages its position and transmission behaviour based on proximity to neighbouring nodes, thus minimizing congestion and interference in communication channels. This congestion prevention strategy involves calculating optimal separation distances, adjusting transmission parameters based on network density, and employing dynamic routing weights that reduce congestion probabilities. These adjustments help maintain smooth data flow in the network while conserving energy by reducing unnecessary communication overhead.

Each node monitors the local congestion based on the congestion detection metric Θ_{cong} as in Eq.(49), which considers the packet arrival rate $\lambda_i$and current queue lengthQ_i:

$$\Theta_{cong} = \lambda_i \times Q_i \quad (49)$$

This metric identifies nodes experiencing high traffic, enabling nodes to implement SMO-based separation to avoid congested paths proactively. To maintain adequate separation between nodes, an optimal separation distance d_{sep} is calculated as in Eq.(50), based on the average node distance d_{avg} and a congestion factor η that scales with node density:

$$d_{sep} = d_{avg} + \eta \cdot \frac{1}{|\mathrm{N_i}|} \quad (50)$$

where is the number of neighbouring nodes. This equation provides a minimum separation distance that adjusts based on the node's local environment, ensuring reduced risk of communication overlaps.

To preserve communication while maintaining separation, each node adjusts its transmission power P_i based on d_{sep} as shown in Eq.(51):

$$P_i = \alpha \cdot \mathrm{d}_{\mathrm{sep}}^2 \quad (51)$$

where α is a scaling factor for power transmission, adjusting transmission power helps reduce the communication radius in dense areas, preventing interference and conserving energy.SMO-DSR incorporates a congestion-aware routing weight W_{cong} which assists in avoiding congested routes. This weight takes into account the queue length Q_i and separation distance d_{ij} to the next hop as shown in Eq.(52):

$$W_{cong} = \frac{Q_i}{d_{ij}} \quad (52)$$

Paths with lower W_{cong} are preferred, reducing the likelihood of congestion by balancing traffic across less congested routes. Inspired by SMO's separation rule, each node computes a separation vector $\vec{S}_i$ using Eq.(53) to adjust its position relative to neighbouring nodes. This vector $\vec{S}_i$ helps maintain ideal spacing:

$$\vec{S}_i = -\sum_{\mathrm{j \in N_i}} \frac{\vec{\mathrm{p}}_\mathrm{j} - \vec{\mathrm{p}}_\mathrm{i}}{|\vec{\mathrm{p}}_\mathrm{j} - \vec{\mathrm{p}}_\mathrm{i}|} \quad (53)$$

where $\vec{p}_i$ and $\vec{p}_j$ are positions of nodes i and j. This separation vector aids in relocating nodes to avoid overcrowding, especially in congested areas.To prevent constant node adjustments, a repositioning threshold T_{sep} as shown in Eq.(54) is set based on the network's average congestion level $\bar{\Theta}_{cong}$:

$$T_{sep} = \beta \cdot \bar{\Theta}_{cong} \quad (54)$$

where β is a scaling constant. Node repositioning is triggered only if local congestion exceeds T_{sep} reducing unnecessary movement and saving energy.In addition to spatial separation, each node adapts its transmission rate R_i based on its congestion level Θ_{cong} and separation distance d_{sep} as shown in Eq.(55):

$$R_i = \frac{R_{max}}{1 + \Theta_{cong} \cdot d_{sep}} \quad (55)$$

where R_{max} is the maximum transmission rate. Reducing transmission rates in dense areas helps limit the load on the network, thereby preventing congestion build-up.The optimal path selection P_{opt} considers separation distance, queue length, and transmission rate to compute a path cost C_{path} as in Eq.(56):

$$C_{path} = \sum_{i \in P_{opt}} \left(d_{sep} + W_{cong} + R_i\right) \quad (56)$$

This cost function prioritizes paths with optimal separation, low congestion, and appropriate transmission rates, thus ensuring efficient routing with minimal traffic interference.

3.8 Enable self-healing routes through murmuration patterns

This step introduces self-healing mechanisms to maintain resilient and continuous routes in FANETs, leveraging the murmuration patterns observed in starling behaviour. FANETs face unique challenges, including frequent route breakages due to node mobility, fluctuating environmental factors, and intermittent connectivity. A self-healing mechanism is vital to address these challenges and ensure that routes can autonomously adapt to maintain network stability and continuity. Inspired by the murmuration behaviour of starlings, where each bird dynamically adapts to its neighbours' movements to sustain cohesive formations, this step in SMO-DSR integrates these adaptive patterns to allow nodes to reconfigure themselves promptly, maintaining functional and energy-efficient routes even under unpredictable conditions.In this self-healing approach, each node proactively monitors route stability and triggers murmuration-based adjustments when disruption is detected. This process is governed by swarm-inspired behaviours, such as cohesion, alignment, and separation, which maintain connectivity and route reliability. By implementing these behaviours, nodes can collectively respond to disruptions and reroute data along alternative paths, thereby preserving connectivity and preventing data loss.

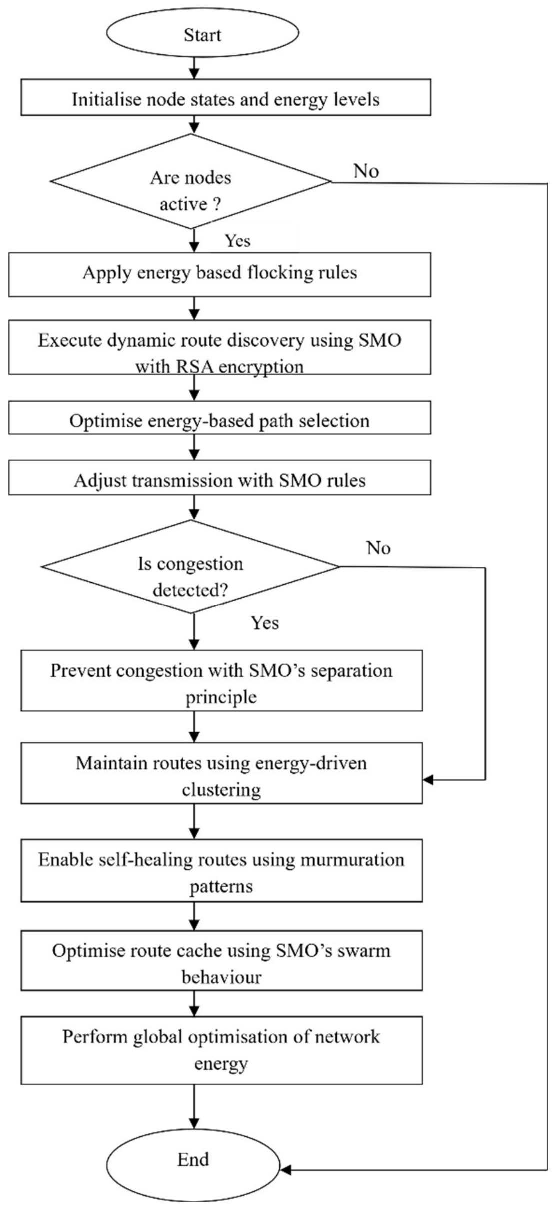

Figure 1: Framework of SMO-DSR

Each node continuously evaluates the stability of its active route based on the Received Signal Strength Indicator (RSSI) R_{ssi} and link lifespan L_{life} as shown in Eq.(57):

$$S_{route} = R_{ssi} \times L_{life} \quad (57)$$

The route stability S_{route} metric helps in predicting potential route breakages. A decrease in S_{route} signals a possible disruption, prompting self-healing actions.Upon detecting route instability, nodes apply a cohesion principle to select neighboring nodes that maintain connectivity. The cohesion distance d_{coh} is calculated as in Eq.(58) using the average distance d_{avg} and stability factor δ:

$$d_{coh} = d_{avg} - \delta \times \frac{S_{route}}{S_{max}} \quad (58)$$

where S_{max} is the maximum stability threshold. Nodes that meet d_{coh} criteria are integrated into the route to maintain continuous connectivity.Each node adjusts its transmission direction according to the alignment vector to re-establish a disrupted route.$\vec{A}_i$ of neighbouring nodes as in Eq.(59):

$$\vec{A}_i = \frac{1}{|N_i|} \sum_{j \in N_i} \vec{d}_{ij} \quad (59)$$

where $\vec{d}_{ij}$ is the directional vector from node i to neighboring node j, and $|N_i|$ represents the number of neighbours. Aligning transmission vectors improves the probability of finding a stable alternative path. Nodes incorporate the separation principle to avoid congestion while establishing a new route. The separation distance d_{sep} between nodes adjusts based on node density and congestion factor k as in Eq.(60):

$$d_{sep} = d_{avg} + k \times \frac{1}{|N_i|} \quad (60)$$

This separation helps prevent interference, ensuring the new route does not overlap with congested areas. During route recovery, a priority metric P_{route} as in Eq.(61) is calculated for alternative paths based on their stability S_{route} , transmission rate R_i and distance d_{ij} to the destination.

$$P_{route} = \frac{S_{route}}{R_i \times d_{ij}} \quad (61)$$

Paths with higher P_{route} values are preferred, indicating stability and minimal delay, thus enabling reliable data forwarding.Upon finding an optimal route, the node updates its routing table with the new path's stability and priority values. The update factorU_{route} is calculated based on the difference in priority as in Eq.(62):

$$U_{route} = \omega \times (P_{new} - P_{current}) \quad (62)$$

where ω is a weighting factor. The route table is updated only if U_{route} exceeds a set threshold, ensuring stable paths are retained and minor fluctuations are ignored. To prevent frequent route failures, nodes proactively monitor link status through a maintenance factorM_{link} as in Eq.(63), by combining transmission delay T_{delay} and signal strength R_{ssi}:

$$M_{link} = T_{delay} \times R_{ssi} \quad (63)$$

Nodes with low M_{link} values are flagged for potential disconnection, triggering route adaptation before the link fully degrades.The murmuration-inspired swarm behavioroptimizes the overall route by balancing cohesion, separation, and alignment factors. The route optimization score O_{route} aggregates these behaviors as in Eq.(64):

$$\mathrm{O}_{\mathrm{route}} = \boldsymbol{\lambda} \cdot \mathbf{d}_{\mathbf{coh}} + \boldsymbol{\mu} \cdot \mathbf{d}_{\mathbf{sep}} + \mathbf{v} \cdot |\vec{\mathbf{A}}_{\mathbf{i}}| \quad (64)$$

where $\boldsymbol{\mu}$,$\boldsymbol{\lambda}$ and v are tuning parameters. This score directs the selection of routes with the best balance of connectivity, congestion avoidance, and directional alignment.

3.9 Optimize Route Cache Using SMO's Swarm Behaviour

This step employs swarm behaviour to optimize route caching, a critical function in FANETs. Traditional caching mechanisms in highly dynamic networks like FANETs often face challenges due to frequent route changes, high node mobility, and limited caching capacity. Optimizing the route cache is essential to ensure that the stored paths remain relevant and accessible, allowing for faster data forwarding and reduced latency. This step leverages swarm intelligence—specifically, the flocking behaviours in SMO to manage the cache in a way that prioritizes the most stable, efficient, and frequently used routes while discarding outdated or redundant information. SMO-based cache optimization uses a combination of swarm principles like cohesion, alignment, and separation. Each node dynamically evaluates cached routes based on these principles, maintaining the cache's relevance and adapting to network topology changes. Doing so makes the cache system more resilient to route fluctuations, supporting efficient communication and resource conservation. Each route in the cache is assigned a priority metric C_{route} as in Eq.(65), which helps determine the relevance of each route in terms of stability S_{route} , usage frequency F_{use} and energy consumption E_{cons}:

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$$\mathrm{C_{route}} = \frac{\mathrm{S_{route}} \times \mathrm{F_{use}}}{\mathrm{E_{cons}}} \quad (65)$$

Routes with a high $\mathrm{C_{route}}$ value is deemed more valuable to retain in the cache, indicating greater stability, higher usage, and lower energy costs.Inspired by SMO's cohesion principle, nodes calculate a cohesion score.R_{coh} as in Eq.(66) to keep frequently accessed routes close within the cache:

$$\mathrm{R_{coh}} = \sum_{\mathrm{i=1}}^{\mathrm{n}} \frac{\mathrm{C_{route,i}}}{\mathrm{d_{i,j}}} \quad (66)$$

where $\mathrm{d_{i,j}}$ is the distance between nodes i and j in the route cache. Routes with higher R_{coh} values are retained for longer periods, while less cohesive routes are deprioritized.The alignment behavior directs nodes to prioritize routes that align with network stability. The alignment factor A_{align} is calculated as in Eq.(67) , based on the average stability S_{avg} of routes in the cache:

$$A_{align} = \frac{\sum_{i=1}^{n} S_{route,i}}{n} \quad (67)$$

Routes with stability close to A_{align} are prioritized in the cache, ensuring that stable routes are more likely to be reused.To prevent overcrowding of similar routes in the cache, SMO's separation principle is applied through a separation threshold T_{sep} as in Eq.(68) , which defines the minimum difference in route stability and frequency:

$$\mathrm{T_{sep}} = \left|\mathrm{S_{route,i}} - \mathrm{S_{route,j}}\right| + \left|\mathrm{F_{use,i}} - \mathrm{F_{use,j}}\right| \quad (68)$$

Routes with differences below $\boldsymbol{T_{sep}}$ are considered redundant, and the least used one is removed from the cache. This separation maintains diversity within the cache, ensuring efficient memory use.The cache is dynamically updated based on an update metric.$U_{cache,}$ as in Eq.(69) which combines the priority C_{route} and alignment factor A_{align}:

$$\mathrm{U_{cache}} = \mathrm{C_{route}} + \gamma \times \mathrm{A_{align}} \quad (69)$$

where γ is a scaling parameter. Routes are retained or removed based on the U_{cache} value, allowing the cache to adjust dynamically to network changes.To conserve energy, the energy threshold $E_{threshold}$ limits the inclusion of high-energy routes in the cache as in Eq.(70):

$$E_{threshold} = \varsigma \times E_{cons} \quad (70)$$

where ς is an adjustment factor. Routes exceeding $E_{threshold}$ are excluded, ensuring that cached routes maintain energy efficiency.Each route's usage rate U_{rate} reflects its access frequency over time, as shown in Eq.(71):

$$\mathrm{U_{rate}} = \frac{\mathrm{F_{use}}}{\mathrm{T_{access}}} \quad (71)$$

where T_{access} represents the time since the last access. High U_{rate} values indicate active routes that should remain in the cache, as they support ongoing data transmissions.The cache's maximum capacity C_{max} is adjusted dynamically as in Eq.(72), based on network density N_{nodes} and mobility rateM_{rate} :

$$C_{max} = \sigma \times \frac{N_{nodes}}{M_{rate}} \quad (72)$$

where σ is a constant that scales with the network's dynamics. Adjusting C_{max} prevents cache overflow while ensuring sufficient storage for high-priority routes.

3.10 Perform Global Optimization of Network Energy

The final step in SMO-DSR focuses on achieving global optimization of network energy, which is essential for the efficient functioning of FANETs. Since FANETs involve high-mobility nodes and limited energy resources, optimizing energy consumption across the entire network helps prolong the network lifetime and ensures consistent communication. This global optimization phase uses SMO's collective swarm behaviour principles to balance energy usage across nodes and reduce the risk of premature energy depletion in critical nodes. Swarm behaviours—cohesion, alignment, and separation—guide nodes to share energy load and minimize redundancy. Nodes adjust their transmission power, reroute data when necessary, and strategically balance energy use based on real-time feedback from the network. This adaptive, global approach enhances network energy efficiency while maintaining performance and robustness. The energy consumption rate E_{rate} for each node, as in Eq.(73), is calculated as the function of its transmission power P_{tx} reception power P_{rx} and processing power P_{proc}:

$$E_{rate} = P_{tx} + P_{rx} + P_{proc} \quad (73)$$

Monitoring E_{rate} for each node enables the network to identify high-energy-consuming nodes and redistribute tasks to reduce localized energy depletion.To ensure balanced energy usage, the network computes an energy distribution index E_{dist} as in Eq.(74), across all nodes, calculated as the standard deviation of the nodes' residual energy E_{res}:

$$E_{dist} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(E_{res,i} - \overline{E_{res}}\right)^2} \quad (74)$$

where N represents the total nodes and $\overline{E_{res}}$ is the average residual energy. Lower E_{dist} values indicate a balanced distribution, reducing the likelihood of isolated energy exhaustion in specific areas. Tasks are allocated based on each node's energy level. The task allocation score T_{alloc} as shown in Eq.(75), prioritizes nodes with higher residual energy E_{res} and lower data load D_{load}:

$$T_{alloc} = \alpha \times E_{res} - \beta \times D_{load} \quad (75)$$

where α and β are weights to balance energy and load factors. Nodes with higher T_{alloc} are preferred for data routing, ensuring energy-heavy tasks are not assigned to low-energy nodes.Adaptive power control reduces excess energy use. The adjusted transmission powerP_{adj}as shown in Eq.(76),is calculated based on the target signal strength S_{target} and current distance d between nodes:

$$P_{adj} = \frac{S_{target}}{d^2} \quad (76)$$

Nodes close to one another reduce P_{adj} saving energy while maintaining connection quality. SMO's alignment behaviour directs nodes to optimize their energy in alignment with neighbouring nodes. Each node calculates its alignment energy adjustment.E_{align} as the average of nearby nodes' energy consumption rates $E_{rate,i}$ as shown in Eq.(77):

$$E_{align} = \frac{\sum_{i \in N_j} E_{rate,i}}{|N_j|} \quad (77)$$

where $N_j$is the set of neighboring nodes. This average guides each node to synchronize its energy consumption with the network's broader energy usage, promoting overall balance.To conserve energy across the network, routing decisions favour energy-efficient paths based on the cumulative energy cost E_{path} along a route as shown in Eq.(78):

$$E_{path} = \sum_{i=1}^{n} E_{rate,i} \quad (78)$$

Lower E_{path}values indicate preferred paths, reducing total network energy expenditure and ensuring long-term connectivity.The network minimizes redundant data transmission using a redundancy index R_{index}as shown in Eq.(79) , which compares data overlaps across nodes:

$$R_{index} = \frac{\sum_{i=1}^{N} D_{overlap,i}}{D_{total}} \quad (79)$$

where $D_{overlap,i}$ is the redundant data for node i and D_{total} is the total transmitted data. Lower R_{index} values signal minimized redundancy, reducing unnecessary energy use across nodes.The overall energy optimization score E_{opt} aggregates energy distribution, task allocation, and path selection metrics as shown in Eq.(80):

$$\mathrm{E_{opt}} = \lambda \times \mathrm{E_{dist}} + \mu \times \mathrm{T_{alloc}} + \mathrm{v} \times \mathrm{E_{path}} \quad (80)$$

where λ, μ, and $v$are weights assigned to each component. Maximizing $\mathrm{E_{opt}}$ improves the network's energy efficiency, ensuring that tasks are evenly distributed and paths are energy-efficient.

Global optimization through SMO's swarm-inspired behaviours ensures FANET nodes work collectively to balance their energy resources, improving the network's lifespan and operational stability. Nodes with low energy avoid excessive tasks, while adaptive power controls prevent waste, and redundant transmissions are minimized. This global energy management strategy allows FANET to operate sustainably under dynamic conditions, essential for real-time applications and long-range data exchanges. This final step consolidates SMO-DSR's objectives by promoting a sustainable, energy-efficient network, extending the operational lifetime of FANETs, and ensuring consistent data flow across all nodes. By optimizing energy globally, FANETs become resilient, reliable, and efficient, meeting the demands of high-mobility environments and supporting complex aerial applications in both civilian and military contexts.

Based on the above details, the pseudo-code of SMO-DSR is shown in Algorithm1. The framework of SMO-DSR is shown in Figure 1:

Algorithm 1: SMO-DSR

Input:

- Network topology with UAV nodes and their initial energy levels.
- Source and destination nodes for communication.
- Parameters for Starling Murmuration Optimization (SMO) behaviour.
- Security keys for RSA encryption.

Output:

- Optimized, energy-efficient, and secure routes for data transmission.
- Balanced energy consumption across UAV nodes.
- Securely transmitted data between source and destination.

Process:
1. Initialize Node States and Energy Levels: Set up UAVs with initial positions, energy levels, and network topology.
2. Apply Energy-Based Flocking Rules: Use proximity and energy levels to guide UAV movements and maintain stable clusters.
3. Perform Dynamic Route Discovery: Initiate route discovery with control packets and secure communication (RSA encryption).
4. Optimize Path Selection Based on Energy: Select the most energy-efficient and stable path for data transmission.
5. Adjust Transmission Power Dynamically: Adapt transmission power based on distance and link quality to minimize energy usage.
6. Maintain Routes Through Clustering: Group UAVs into energy-driven clusters to simplify routing management.
7. Prevent Congestion with the Separation Principle: Ensure optimal spacing between UAVs to avoid congestion and redirect traffic as needed.
8. Enable Self-Healing of Routes: Detect route failures and reassign nodes or find alternate routes to restore connectivity.
9. Optimize Route Cache Using Swarm Behaviour: Use swarm intelligence to update and maintain relevant, efficient route information.
10. Perform Global Energy Optimization: Balance energy consumption across the network to extend overall lifetime.
11. Transmit Data Securely: Encrypt data using RSA before transmission and decrypt at the destination for security.
12. Monitor and Update: Continuously monitor network status and dynamically adjust routing based on real-time parameters.

4. SIMULATION SETTINGS AND PERFORMANCE METRICS

The simulation for the proposed SMO-DSR protocol was conducted using the NS-3 simulator in a 1000m x 1000m area with 100 UAV nodes. The nodes were configured to follow the Random Waypoint mobility model to emulate realistic FANET behaviour. A wireless channel with a transmission range of 250m and a data rate of 1 Mbps was employed for communication. The Constant Bit Rate traffic model generated 512-byte packets at regular intervals. Each UAV node was initialized with 100 Joules of energy, and the energy model accounted for energy consumption during data transmission and reception. The SMO-DSR protocol was compared with CHNN-DSR and eAntHoc-Net under identical simulation conditions. The optimization parameters for SMO included a swarm size of 30 agents and 50 iterations to discover energy-efficient routes. The simulation was run for a total duration of 500 seconds, and performance metrics such as Packet Delivery Ratio (PDR), End-to-End Delay, Network Lifetime, and Energy Consumption were evaluated to assess the efficiency and robustness of the proposed approach. Table 2 summarizes the network simulation parameters used for SMO-DSR evaluation.

Table 2: Network Simulator Parameters

Parameter	Value
Simulator	NS-3
Simulation Area	1000m x 1000m
Number of Nodes	100
Node Mobility Model	Random Waypoint
Traffic Type	Constant Bit Rate
Packet Size	512 bytes
Radio Range	250m
Routing Protocols	CHNN-DSR,eAntHoc-Net, SMO-DSR
Initial Energy per Node	100 Joules
Channel Type	Wireless
Data Rate	1 Mbps
MAC Protocol	IEEE 802.11
Simulation Time	500 seconds
Swarm Size (SMO)	30
Iterations(SMO)	50
Energy Model	Basic Energy Model

4.1. Packet Delivery and Drop Ratio Analysis

Figure 2 presents an analysis of the performance of three routing protocols: CHNN-DSR, eAntHoc-Net, and SMO-DSR. CHNN-DSR exhibits a moderate Packet Delivery Ratio (PDR) due to its reliance on cluster-based hierarchical neural networks, which can falter under the high mobility and dynamic topology changes of FANETs, leading to a higher Packet Drop Ratio caused by frequent link failures and inter-cluster communication issues. eAntHoc-Net improves upon

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CHNN-DSR with its ant colony-based optimization, resulting in better PDR and reduced Packet Drop Ratio by dynamically adapting to topology changes. However, its performance is still hindered by slower convergence times, especially in highly dynamic or congested network scenarios. In contrast, the proposed SMO-DSR achieves the highest PDR and the lowest Packet Drop Ratio among the three protocols. By leveraging the Starling Murmuration Optimization algorithm, SMO-DSR dynamically adjusts routes based on energy levels and mobility patterns, ensuring stable and reliable data delivery while minimizing packet loss even in challenging network conditions. This comparative analysis highlights the robustness and efficiency of SMO-DSR over existing protocols.

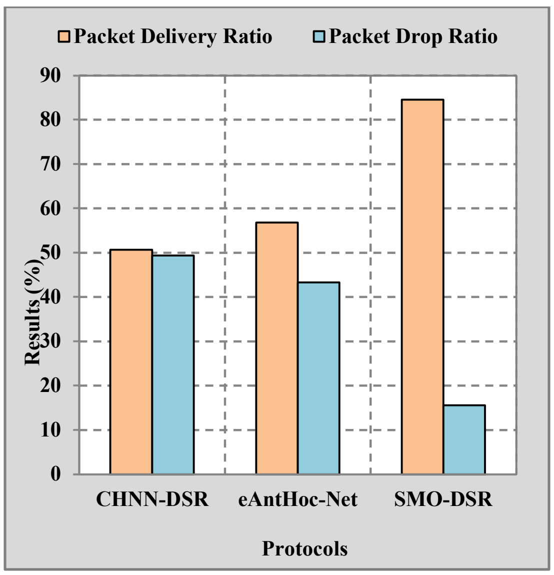

Figure 2. Packet Delivery and Drop Ratio Analysis

The proposed SMO-DSR protocol achieves a PDR of 84.4983%, significantly outperforming the existing CHNN-DSR and eAntHoc-Net protocols, which achieve 50.6333% and 56.7537%, respectively. Compared to CHNN-DSR, SMO-DSR improves the PDR by 66.85%, and compared to eAntHoc-Net, it achieves a 48.92% enhancement. This superior performance is due to SMO-DSR's effective use of Starling Murmuration Optimization, which dynamically adapts routes based on energy efficiency, congestion handling, and swarm behaviour to ensure reliable packet delivery.

Table 3: Packet Delivery Ratio

Nodes	CHNN-DSR	eAntHoc-Net	SMO-DSR
10	54.996	62.624	88.291
20	53.825	64.499	87.027
30	55.637	64.061	87.727
40	51.468	60.731	86.154
50	50.769	60.211	84.929
60	51.594	58.957	82.489
70	49.16	55.112	84.099
80	48.408	53.071	82.409
90	47.302	48.216	81.623
100	43.174	40.055	80.235
Average	50.6333	56.7537	84.4983

SMO-DSR protocol reduces the Packet Drop Ratio to 15.50%, demonstrating a marked improvement over CHNN-DSR with 49.3667% and eAntHoc-Net with 43.25%**.** This represents a 68.6% reduction in Packet Drop Ratio compared to CHNN-DSR and a64.15%reduction compared to eAntHoc-Net. The drastic decrease in packet loss is attributed to SMO-DSR's advanced mechanisms, including energy-driven clustering**,** self-healing routes, and congestion avoidance, which collectively enhance network reliability and robustness. Table 3 shows the packet delivery ratio, and Table 4 shows the packet drop ratio of the proposed work.

Table 4:Packet Drop Ratio

Nodes	CHNN-DSR	eAntHoc-Net	SMO-DSR
10	45.004	37.376	11.709
20	46.175	35.501	12.973
30	44.363	35.939	12.273
40	48.532	39.269	13.846
50	49.231	39.789	15.071
60	48.406	41.043	17.511
70	50.84	44.888	15.901
80	51.592	46.929	17.591
90	52.698	51.784	18.377
100	56.826	59.945	19.765
Average	49.3667	43.25	15.50

4.2. Throughput Analysis

Throughput is a critical performance metric that evaluates the efficiency of a network protocol by measuring the amount of data successfully delivered to the destination per unit of time, typically expressed in bits per second. For the proposed SMO-DSR protocol, the throughput analysis demonstrates its effectiveness in handling the dynamic and challenging nature of FANET environments. The proposed SMO-DSR leverages the Starling Murmuration Optimization (SMO) algorithm to dynamically adapt routing decisions based on node mobility, energy levels, and real-time network conditions. This approach minimizes packet loss and optimizes the data flow across the network.

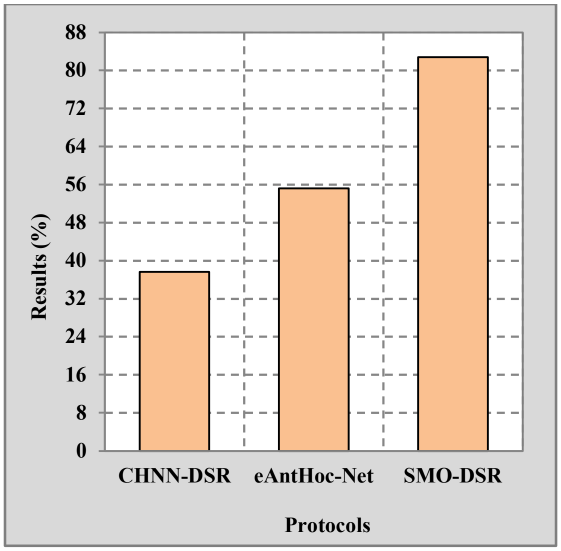

Figure 3. Throughput Analysis

SMO-DSR consistently achieves higher throughput compared to existing protocols such as CHNN-DSR and eAntHoc-Net. In high-mobility scenarios, where traditional protocols often suffer from frequent route failures and increased packet drops, SMO-DSR maintains stable and energy-efficient routes. The integration of swarm intelligence principles allows SMO-DSR to converge on optimal paths and rapidly manage network congestion. Energy-aware clustering mechanism ensures that nodes with sufficient energy are prioritized for routing, further enhancing throughput by reducing the likelihood of route disruptions. The throughput performance of SMO-DSR is particularly evident in scenarios with varying traffic loads and node densities. Figure 3 depicts the throughput of the proposed work.

Table 5: Throughput

Nodes	CHNN-DSR (%)	eAntHoc-Net	SMO-DSR
10	31.204	50.305	78.275
20	33.589	50.667	80.144
30	34.958	52.375	81.875
40	35.471	55.482	82.286
50	38.656	55.808	83.047
60	38.882	55.935	83.842
70	39.173	57.117	84.315
80	40.707	57.269	84.571
90	41.125	58.294	84.73
100	42.123	58.901	84.786
Average	37.589	55.215	82.787

The proposed protocol achieves an average throughput of 82.787 kbps, significantly surpassing the performance of the existing protocols CHNN-DSR and eAntHoc-Net, which record throughput values of 37.589 kbps and 55.215 kbps, respectively. The substantial gain in throughput by SMO-DSR is due to its efficient route optimization, which minimizes delays, balances network load, and reduces congestion. This is shown in Table 5. Under heavy traffic conditions, SMO-DSR demonstrates superior scalability and load-balancing capabilities, ensuring consistent data delivery rates without compromising network reliability. In contrast, CHNN-DSR and eAntHoc-Net experience throughput degradation due to delayed route updates and higher control overhead. Overall, the throughput analysis confirms that SMO-DSR outperforms existing protocols by providing higher data transmission rates. It is a robust and efficient solution for FANET applications requiring reliable and high-speed communication.

4.3End-to-End Delay Analysis

End-to-end delay measures the time a data packet travels from the source to the destination, making it a critical metric for evaluating the responsiveness and efficiency of routing protocols, especially in real-time applications. The proposed protocol achieves an average delay of 406.8 milliseconds, substantially outperforming CHNN-DSR at 665.4 milliseconds and eAntHoc-Net at 643.8 milliseconds. This translates to a 38.87% reduction in delay compared to CHNN-DSR and a 36.8% reduction compared to eAntHoc-Net. The improvement stems from SMO-DSR's integration of the Starling Murmuration Optimization (SMO) algorithm, which dynamically selects routes based on energy efficiency and congestion-free paths. These optimized routes ensure faster packet traversal, minimizing delays caused by route discovery or traffic congestion. Figure 4 shows the end-to-end delay analysis.

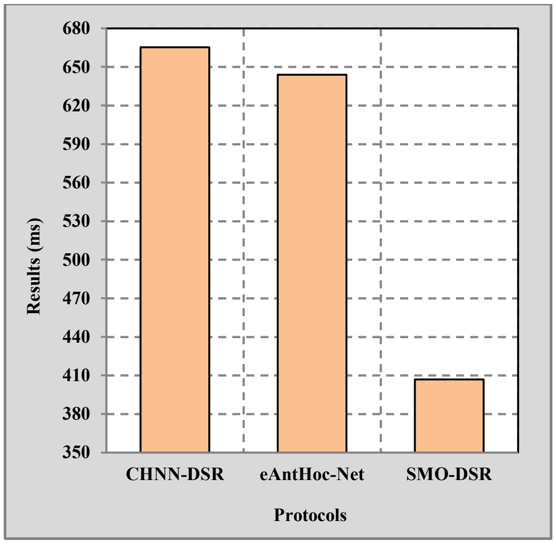

Figure 4: End-to-end Delay Analysis

The superior performance of SMO-DSR is further supported by its advanced congestion avoidance and self-healing mechanisms. Using SMO's separation principle, the protocol reduces packet collisions and congestion, which are primary contributors to high delay in dynamic networks like FANET. Additionally, its energy-aware routing prioritizes stable nodes with sufficient energy, avoiding disruptions and delays caused by node failures. In contrast, CHNN-DSR suffers from higher delay due to its slower adaptation to network changes and limited route optimization capabilities. While eAntHoc-Net exhibits better delay management than CHNN-DSR through ant-inspired optimization, it lacks the robustness and efficiency of SMO-DSR's swarm-based approach. Overall, the significant reduction in end-to-end delay underscores SMO-DSR's suitability for real-time applications, ensuring timely and reliable data delivery even in the dynamic and challenging environments of FANETs. This is shown in Table 6.

Table 6: End-to-end Delay

Nodes	CHNN-DSR	eAntHoc-Net	SMO-DSR
10	632	604	366
20	639	613	374
30	646	621	387
40	655	639	396
50	661	643	398
60	668	647	412
70	675	652	423
80	682	661	434
90	691	675	437
100	705	683	441
Average	665.4	643.8	406.8

4.4 Energy Consumption

Energy consumption is a critical performance metric for FANETs due to the limited power resources of flying nodes. The proposed SMO-DSR protocol demonstrates remarkable energy efficiency with an average energy consumption of 43.747 units, significantly lower than CHNN-DSR (83.658 units) and eAntHoc-Net (73.391 units). This represents a 47.73% reduction compared to CHNN-DSR and a 40.37% reduction compared to eAntHoc-Net. The improved efficiency of SMO-DSR is primarily attributed to its advanced optimization strategies, which include energy-aware routing, dynamic transmission power adjustment, and efficient resource allocation through Starling Murmuration Optimization**.** Figure 5 depicts the energy consumption analysis.

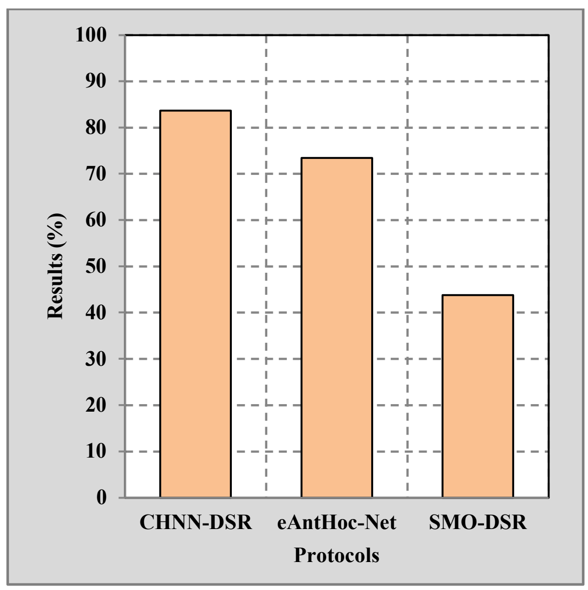

Figure 5: Energy Consumption Analysis

Table 7: Energy Consumption

Nodes	CHNN-DSR	eAntHoc-Net	SMO-DSR
10	79.475	66.295	37.491
20	80.215	68.921	39.899
30	82.661	69.867	40.845
40	83.346	70.338	41.389
50	83.717	71.268	42.138

60	84.104	74.179	44.731
70	84.987	76.85	45.854
80	85.963	77.499	46.986
90	86.992	78.553	48.657
100	85.117	80.142	49.477
Average	83.658	73.391	43.747

SMO-DSR achieves these gains by employing key mechanisms such as energy-based flocking rules that adapt nodes behaviours based on their remaining energy, optimized path selection to ensure minimal energy expenditure, and energy-driven clustering that reduces overhead. Its self-healing route mechanism minimizes the energy-intensive process of frequent route rediscovery, further enhancing efficiency. In contrast, CHNN-DSR exhibits high energy consumption due to its lack of dynamic energy management. While eAntHoc-Net offers moderate improvements, it is still outperformed by SMO-DSR's more sophisticated energy-saving strategies, as shown in Table 7. This reduced energy consumption extends the lifetime of individual nodes and enhances the network's overall sustainability and operational lifespan, making SMO-DSR a highly effective choice for energy-constrained FANET applications.

Reduced energy consumption minimizes the frequency of battery recharges or replacements, lowering operational costs and reducing downtime. This is particularly significant in remote or inaccessible locations where maintenance is challenging. Improved energy efficiency also enhances network stability by maintaining higher residual energy in nodes, reducing the likelihood of node failures, and preventing network fragmentation. Furthermore, SMO-DSR's energy-saving features facilitate scalability by enabling larger networks to operate effectively without compromising performance. These results highlight the holistic benefits of energy conservation achieved by the SMO-DSR protocol, making it a robust solution for energy-constrained FANET applications.

5. COMPARATIVE STUDY AND PERFORMANCE INSIGHTS OF SMO-DSR

Several studies have explored routing optimization techniques for FANETs, primarily focusing on enhancements to reactive protocols like DSR. Traditional optimization methods such as Ant Colony Optimization(ACO), Genetic Algorithms(GA) and Particle Swarm Optimization(PSO) have been employed to improve route selection, energy efficiency, and link stability. However, these approaches often suffer from high computational complexity, slow convergence, and an inability to adapt to dynamic FANET environments.

The proposed protocol offers a biologically inspired approach that enhances network adaptability and energy efficiency. Unlike PSO and GA, SMO leverages swarm intelligence principles based on real-world murmuration behaviours, ensuring self-organized, flexible, and dynamic route formation. Key differences from prior work include:

1. **Energy-Aware Routing:** Unlike existing optimization techniques that focus on shortest paths or link stability, SMO-DSR integrates energy-based flocking rules, optimizing routes based on residual energy and dynamic power adjustments.
2. **Swarm Intelligence for Congestion Control:** While traditional approaches struggle with congestion mitigation, our method applies SMO’s separation principle to prevent link failures and maintain stable routes.
3. **Self-Healing Mechanism:** Compared to conventional DSR and PSO-based routing, our method enhances route recovery through murmuration-based self-healing patterns, reducing route discovery latency.
4. **Global Network Optimization:** Unlike local optimization strategies seen in GA and ACO, SMO-DSR continuously refines the route cache and global network state using swarm behaviour, improving long-term performance.

The SMO-DSR protocol offers several advantages over existing approaches, including improved energy efficiency through adaptive transmission power control, faster route discovery due to dynamic swarm-based adaptation, and reduced congestion and link failures by leveraging SMO’s separation principle. Its ability to continuously refine routing paths enhances adaptability to dynamic topologies, while its lightweight local interactions lower computational overhead compared to GA and ACO-based methods. However, SMO-DSR also has certain limitations. Its performance is sensitive to parameter tuning, requiring careful calibration to prevent excessive path oscillations. Additionally, the initial implementation may involve a learning curve, but once deployed, the protocol efficiently manages FANET routing dynamics, balancing performance and scalability.

6. CONCLUSION

The increasing reliance on FANETs for mission-critical applications highlights the urgent need for a routing protocol that balances efficiency, reliability, and security in highly dynamic environments. Traditional optimization techniques, such as CHNN-DSR and eAntHoc-Net, struggle to maintain optimal performance due to high computational overhead, limited adaptability to topology changes, and energy inefficiency. Our proposed SMO-DSR protocol effectively addresses these challenges by leveraging the Starling Murmuration Optimization technique, enabling self-organized, energy-aware, and congestion-free routing. Experimental results confirm that SMO-DSR significantly improves Packet Delivery Ratio, reduces Packet Drop Ratio, enhances Throughput, and lowers Energy Consumption, outperforming existing solutions. Beyond optimizing routing performance, SMO-DSR integrates RSA encryption, making it one of the few routing protocols that simultaneously tackle both network efficiency and security by safeguarding data transmission against unauthorized access and cyber threats. This ensures confidentiality, integrity, and reliability, which are crucial for applications in disaster response, military surveillance, and real-time data transmission. While SMO-DSR presents a substantial improvement, future research could further refine its effectiveness through machine learning integration for adaptive decision-making, multi-hop communication, and heterogeneous drone networks to enhance performance in complex environments. Additionally, real-world deployment and evaluation under diverse operational constraints would provide deeper insights into its practical scalability. In conclusion, SMO-DSR is a transformative advancement in FANET routing, offering a robust, secure, and energy-efficient solution for next-generation aerial networks while addressing both performance and security concerns to enable more resilient and intelligent FANET communication systems.

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