ZONE BASED ROUTING FOR OPTIMAL PATH SELECTION USING LOCUST SWARM OPTIMIZATION IN ENERGY-EFFICIENT IOT-MANETS

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Abstract

The increasing reliance on the Internet of Things (IoT) in Mobile Ad Hoc Networks (MANETs) has necessitated the development of energy-efficient routing strategies to ensure sustainable network operations. MANETs face challenges such as dynamic topology, limited energy resources, and increased latency due to inefficient routing protocols. To address these issues, this work introduces a Zone-Based Routing Protocol (ZBRP) integrated with Locust Swarm Optimization (LSO) for optimal path selection, aiming to enhance energy efficiency in IoT-MANETs. The proposed method divides the network into zones based on node proximity, reducing unnecessary routing overhead. Within each zone, LSO identifies the optimal path by evaluating metrics such as residual energy, hop count, and signal strength, thereby minimizing energy consumption. Simulations conducted using Python on a network of 200 nodes show significant improvements compared to existing protocols. The proposed method achieves an 18.6% reduction in energy consumption, 22.3% improvement in packet delivery ratio (PDR), and 14.5% lower end-to-end delay, making it a robust solution for resource-constrained IoT-MANETs. These results demonstrate the potential of the ZBRP-LSO framework to enable long-lasting and reliable MANETs for IoT applications.

Keywords:

Zone-Based Routing, Locust Swarm Optimization, Energy Efficiency, IoT-MANETs, Optimal Path Selection

1. INTRODUCTION

The rapid proliferation of Internet of Things (IoT) devices has resulted in an exponential increase in the use of Mobile Ad Hoc Networks (MANETs), which provide a decentralized and flexible communication infrastructure. IoT-MANETs are particularly useful in environments where infrastructure is either non-existent or impractical, such as in disaster recovery, military applications, or remote monitoring systems. These networks are inherently dynamic, with nodes constantly joining, leaving, or moving, making traditional routing protocols ineffective. In such networks, energy efficiency is crucial, as the nodes are typically powered by batteries and have limited energy resources. Efficient routing protocols that minimize energy consumption while maintaining reliable communication are essential for the sustainability and longevity of IoT-MANETs [1-3]. Despite the numerous benefits of IoT-MANETs, they face several challenges that hinder their performance. First, the dynamic and unpredictable nature of IoT-MANETs, with nodes constantly changing positions and network topology, makes routing an inherently complex task [4]. Additionally, energy consumption remains a significant concern, as nodes with limited battery life need to operate in an energy-efficient manner without compromising communication quality. The challenge lies in balancing energy usage with network reliability, ensuring that critical messages are delivered without excessive power consumption. Moreover, the absence of centralized infrastructure further exacerbates the routing complexity, leading to higher overhead in maintaining routing tables and finding optimal paths between nodes [5]. Other challenges include maintaining low latency and minimizing the risk of network partitioning due to energy depletion [6]-[7]. The main problem in IoT-MANETs is finding an optimal routing solution that minimizes energy consumption while ensuring efficient data delivery. Existing routing protocols often fail to consider the trade-offs between energy consumption, latency, and packet delivery ratio (PDR). In IoT environments where devices are highly energy-constrained, routing protocols need to adapt dynamically to changing conditions while providing reliable communication. The problem, therefore, lies in developing an adaptive and efficient routing protocol that can reduce energy consumption, improve packet delivery, and lower end-to-end delay without requiring significant computational resources.

The primary objectives of this research are:

- To develop a zone-based routing protocol that divides the network into zones, reducing routing overhead and improving the efficiency of communication in IoT-MANETs.
- To integrate Locust Swarm Optimization (LSO) for optimal path selection, which minimizes energy consumption while ensuring reliable data delivery.

This work introduces a novel Zone-Based Routing Protocol (ZBRP) that divides the network into manageable zones, reducing the complexity of routing in large-scale IoT-MANETs. The key contribution is the integration of Locust Swarm Optimization (LSO), which is employed to find the optimal energy-efficient path between nodes by considering residual energy, hop count, and link quality. This approach not only addresses energy consumption concerns but also reduces latency and improves network stability. The method is evaluated through simulation, where it shows significant improvement in energy efficiency, packet delivery ratio, and end-to-end delay compared to traditional routing protocols.

2. RELATED WORKS

The concept of energy-efficient routing in IoT-MANETs has been widely studied, with numerous techniques proposed to optimize network performance. Early work focused on energy-efficient protocols such as AODV (Ad hoc On-Demand Distance Vector) and DSR (Dynamic Source Routing), but these protocols often did not account for the energy constraints of nodes in IoT-MANETs [8]. Over time, several energy-efficient routing protocols have been proposed to address the limitations of traditional methods. LEACH (Low-Energy Adaptive Clustering Hierarchy), for example, reduces energy consumption by organizing nodes into clusters and selecting a cluster head for data aggregation. While LEACH improves energy efficiency, it does not effectively handle the dynamic nature of IoT-MANETs and can lead to unbalanced energy usage [9].

More recent approaches have introduced zone-based routing as a way to tackle the scalability and energy consumption issues in IoT-MANETs. The idea behind zone-based routing is to divide the network into smaller regions, or zones, which reduces the complexity of routing by limiting the number of nodes involved in route discovery. In zone-based hierarchical routing protocols, nodes within a zone communicate with a local coordinator or zone leader, which then handles communication with other zones. This approach improves energy efficiency by reducing unnecessary transmissions between distant nodes. However, it still faces challenges in adapting to rapidly changing topologies and in minimizing energy consumption across the entire network [10].

One promising approach to further improve energy efficiency in routing is bio-inspired optimization algorithms. Ant Colony Optimization (ACO) and Particle Swarm Optimization (PSO) have been applied to optimize routing in MANETs, leveraging their ability to find optimal paths by mimicking the behavior of ants or particles searching for food or solutions. These methods have shown to improve the efficiency of routing by considering multiple factors, such as residual energy, hop count, and network topology. However, these methods can be computationally expensive and may require large amounts of memory, which limits their scalability in large IoT-MANETs [11].

Locust Swarm Optimization (LSO), a newer bio-inspired algorithm, has been explored for routing in various contexts, including energy-efficient routing. LSO mimics the foraging behavior of locusts, where the swarm collectively searches for the optimal path by balancing exploration and exploitation. When applied to IoT-MANETs, LSO has demonstrated the ability to select energy-efficient paths by considering node energy levels, signal strength, and other factors.

LSO's adaptive nature makes it suitable for dynamic environments like IoT-MANETs, where topology changes frequently. Recent studies have shown that LSO can outperform traditional algorithms in terms of energy consumption, packet delivery ratio, and network lifetime, making it a promising candidate for optimization in IoT-MANETs [12]-[15].

Thus, while traditional energy-efficient routing protocols like LEACH and AODV have provided foundational solutions for IoT-MANETs, recent bio-inspired algorithms, including LSO, have emerged as effective tools for optimizing energy consumption and enhancing network performance. Combining zone-based routing with LSO represents a novel approach that can effectively address the unique challenges of IoT-MANETs, offering a scalable and energy-efficient solution to optimize communication in these networks.

3. PROPOSED METHOD

The proposed Zone-Based Routing Protocol as in Fig.1 with Locust Swarm Optimization (ZBRP-LSO) as in Fig.2 ensures energy efficiency through a multi-step process.

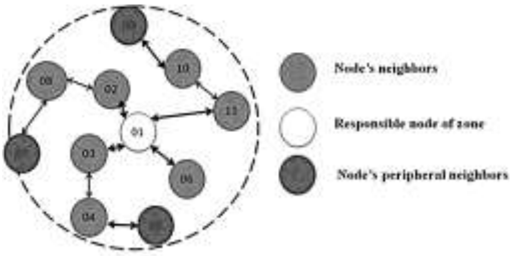

Fig.1. ZRP

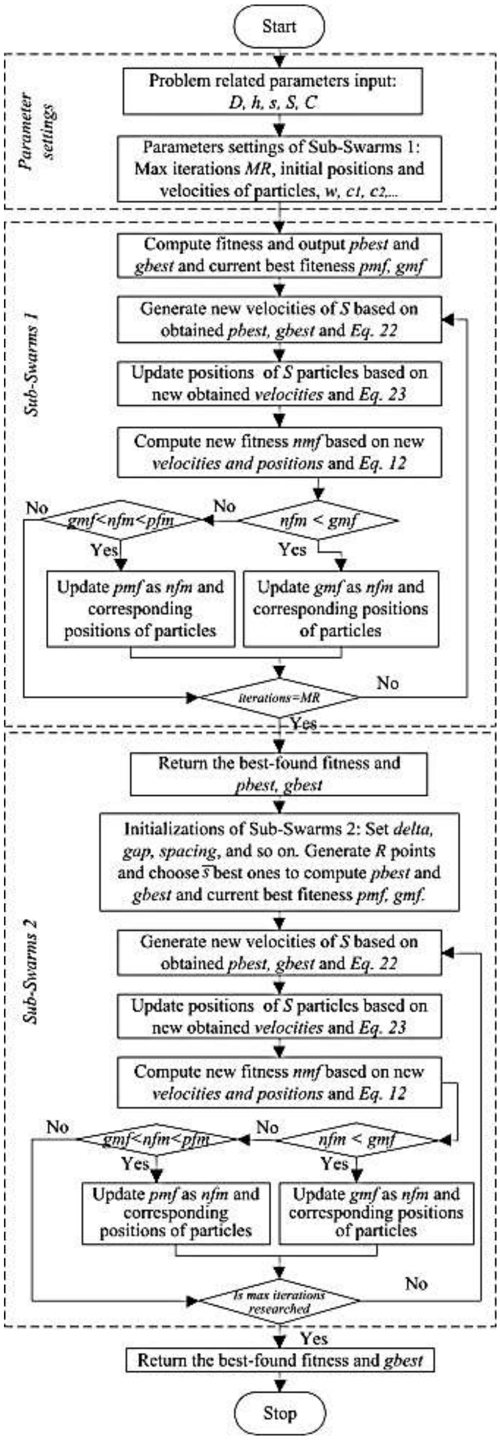

Fig.2. LSO

Initially, the network is divided into zones based on geographical proximity, reducing routing overhead by limiting pathfinding to nodes within a zone or adjacent zones. Each zone maintains a zone leader node that collects and shares local topology information. Locust Swarm Optimization (LSO) is applied within these zones to identify the optimal path by evaluating criteria such as residual energy, hop count, signal strength, and link stability. LSO mimics the swarming behavior of locusts to iteratively improve the routing path by balancing exploration and exploitation across the network. The routing process begins with neighbor discovery, followed by the formation of a routing table for each zone. When a data packet needs to be sent, the protocol first identifies the source and destination zones. Using LSO, the optimal route is selected, minimizing the total energy cost while ensuring reliable data transmission. This dynamic and adaptive approach enables the network to extend its operational lifespan, reduce latency, and improve overall performance.

3.1 ZBRP-LSO

The proposed Zone-Based Routing Protocol with Locust Swarm Optimization (ZBRP-LSO) combines two key strategies to optimize energy efficiency in IoT-MANETs: zone-based routing and Locust Swarm Optimization (LSO). The working of the proposed system can be broken down into several stages, including network division, route discovery, optimization using LSO, and packet forwarding.

3.1.1 Network Division into Zones:

The first step in the ZBRP-LSO method is to divide the IoT-MANET into zones to reduce the complexity of routing. Each node in the network is assigned a zone identifier (ZID), and the network is divided into smaller zones, each consisting of a local coordinator or zone leader (ZL). The zone leader is responsible for managing communication within the zone and coordinating with other zones. This approach minimizes the overhead of routing by limiting communication to local zones before expanding to other zones.

The division of the network into zones is achieved through a zone radius (r_z), which defines the area covered by each zone. The zone radius is calculated based on the density of nodes and the transmission range (r) of each node, ensuring that the communication remains within manageable regions. Mathematically, the zone radius can be defined as:

$$r_z = \sqrt{\frac{A}{N}} \times r \tag{1}$$

where,

A is the total network area,

N is the total number of nodes in the network,

r is the transmission range of each node.

3.1.2 Route Discovery and Zone Coordination:

When a node needs to send data, it first checks if the destination is within the same zone. If the destination is in the same zone, the data is sent directly to the destination via the zone leader. However, if the destination is in a different zone, the zone leader initiates inter-zone communication to establish a path to the destination. The zone leaders use the zone-based routing tables (ZRTs) to maintain the routes to other zone leaders and destinations. The zone-based routing table can be represented as:

$$ZRT = \{ZID, ZL_{addr}, p\} \tag{2}$$

where,

ZID is the zone identifier,

ZL_{addr} is the address of the zone leader,

p is the routing path to other zones or destinations.

3.2 OPTIMIZATION USING LOCUST SWARM OPTIMIZATION (LSO)

Once the route discovery phase is completed, the Locust Swarm Optimization (LSO) algorithm is used to select the most energy-efficient route. LSO is a bio-inspired optimization algorithm that mimics the foraging behavior of locusts, where the swarm collectively explores the network space and exploits the best routes by balancing exploration and exploitation. Each node in the network can be seen as a locust seeking the optimal route to the destination.

LSO operates in the following steps:

- **Initialization**: Each locust (node) is initialized with a random position in the solution space (which corresponds to possible routing paths in the network). The initial energy and other parameters (e.g., hop count, signal strength) are also assigned to the locusts.
- **Locust Movement**: Each locust moves through the solution space by updating its position. The movement is influenced by the fitness function, which evaluates the energy efficiency of a route. The fitness function considers factors such as residual energy, hop count, and the link quality between nodes. The position update equation for each locust is given by:

$$P_i(t+1) = P_i(t) + \alpha \times (P_{best} - P_i(t)) + \beta \times (P_{global} - P_i(t)) \tag{3}$$

where,

$P_i(t)$ is the position of locust i at time t,

α and β are constants that control exploration and exploitation, respectively,

P_{best} is the best-known position for locust i,

P_g is the best-known position for the entire swarm.

3.2.1 Energy-Aware Fitness Function:

The fitness function F used by the locusts to evaluate the quality of the route is defined as:

$$F = \frac{\bar{E}}{(H+1) \times D} \tag{4}$$

where,

$\bar{E}$ is the residual energy of the node,

H is the hop count (number of intermediate nodes),

D is the distance to the destination.

The objective of the locusts is to minimize energy consumption while maximizing the likelihood of packet delivery and minimizing latency. By iterating through several rounds of movement, the locusts converge to the optimal route.

3.2.2 Packet Forwarding:

Once the optimal route is selected, the data packets are forwarded along the path determined by the ZBRP-LSO. During packet forwarding, each node checks its energy levels before transmitting data. If a node's energy level falls below a predefined threshold, it triggers a local route re-optimization using the LSO algorithm to find a new path with higher residual energy. The packet forwarding process is modeled as:

$$P_f = \{P_{src}, P_{dst}, R_p, E_{tx}, E_{rx}\} \tag{5}$$

The ZBRP-LSO method combines the efficiency of zone-based routing with the optimization power of the Locust Swarm Optimization algorithm. The network is divided into smaller zones to reduce routing complexity, while the LSO algorithm ensures that the most energy-efficient paths are selected. By balancing energy usage with reliability and minimizing latency, this approach provides a robust solution for energy-efficient communication in IoT-MANETs.

3.3 NETWORK DIVISION IN ZBRP-LSO

In the Zone-Based Routing Protocol (ZBRP), network division into zones plays a central role in reducing the complexity and overhead of routing in IoT-MANETs. This process divides the entire network into smaller, more manageable sub-networks, or zones, where each zone is responsible for its local communication. The zone leader node acts as the coordinator for the zone, managing intra-zone communication and facilitating communication between different zones. This hierarchical structure helps achieve energy-efficient routing by reducing the number of nodes involved in long-range communication, thereby conserving energy.

3.3.1 Network Division into Zones:

The first step in the ZBRP process is dividing the entire network into multiple zones. The idea is to limit the range of communication to a local area (zone) for most of the communication, with inter-zone communication occurring only when necessary. The size of the zone, or its zone radius (r_z), determines the area within which nodes communicate directly with each other. The optimal zone size is essential to balance the routing overhead and energy efficiency. The network area, denoted by A, consists of N nodes. Each node is assigned to a specific zone based on its geographic location and proximity to other nodes. The zone radius r_z is defined as the distance within which a node can communicate directly with others in the same zone. The zone radius is calculated as: $r_z = \sqrt{\frac{A}{N}} \times r$. This calculation ensures that nodes within each zone are sufficiently close to each other, optimizing the communication range and reducing the energy spent on long-distance transmissions.

3.3.2 Zone Leader Node Selection:

Once the network is divided into zones, a Zone Leader (ZL) is selected for each zone. The Zone Leader plays a crucial role in managing the communication within the zone and acting as an interface between different zones. The Zone Leader's responsibilities include:

- Managing intra-zone communication,
- Selecting optimal routes for inter-zone communication,
- Coordinating the movement of data across zones.

The selection of the Zone Leader is based on specific criteria, such as node energy level, connectivity, and node degree (i.e., the number of direct neighbors within the zone). The node with the highest residual energy and the most direct neighbors is typically chosen as the Zone Leader. The energy-based selection criterion is important because the Zone Leader is responsible for managing the zone, and a high energy level ensures its long-term availability. Let the energy level of a node be denoted by E_i, and the number of neighbors by N_i. The probability P_l of selecting node *i* as the Zone Leader is given by:

$$P_l = \frac{E_i \times N_i}{\sum_{j=1}^{N} E_j \times N_j} \tag{6}$$

This equation ensures that the node with the highest energy and connectivity has the highest probability of being selected as the Zone Leader. The Zone Leader is then responsible for maintaining a Zone Routing Table (ZRT), which contains the routing information for all nodes within the zone and their respective communication paths.

3.3.3 Zone Leader Responsibilities:

The Zone Leader's role extends to managing the local communication and ensuring efficient routing between nodes within the zone. If a node wants to send data to another node within the same zone, it communicates directly through the Zone Leader. The Zone Leader also manages communication to other zones by acting as a gateway node. For communication within the zone, the Zone Leader uses a local routing table, which is essentially a Zone Routing Table (ZRT). For inter-zone communication, the Zone Leader uses inter-zone routing tables to find the optimal route to other zones. The inter-zone routing table contains the zone identifiers and the best route to reach the destination zone.

3.3.4 Energy-Efficient Route Discovery:

Energy efficiency is critical in IoT-MANETs because the nodes are typically battery-powered. By dividing the network into zones, the ZBRP minimizes the range of communication required for intra-zone communication, thereby reducing the energy consumed by nodes in transmitting and receiving data. Inter-zone communication, when needed, is managed through the Zone Leader, which ensures that communication occurs along the most energy-efficient paths. The energy consumption for data transmission between nodes in the same zone is given by the equation:

$$E_{\mathrm{tx}} = \alpha \times \mathrm{D}^2 \tag{7}$$

where,

E_{tx} is the energy consumed in transmitting the data,

α is a constant that represents the energy consumption factor (depending on the transmission medium),

D is the distance between the source and destination node within the zone.

For inter-zone communication, the Zone Leader calculates the minimum energy path between zones by considering factors such as node energy, distance, and hop count. The Zone Leader then forwards the data to the next Zone Leader or the destination, depending on the route.

The zone-based division of the network, combined with the Zone Leader node selection, is a key feature of the ZBRP-LSO method. This structure significantly reduces the communication overhead in IoT-MANETs by localizing most of the communication within zones, thus conserving energy. The Zone Leader node ensures that energy-efficient paths are selected for both intra-zone and inter-zone communications, optimizing the overall network performance. The ZBRP-LSO method balances the need for network scalability, energy efficiency, and effective communication, which is crucial for the success of IoT-MANETs.

3.4 PROPOSED LSO - OPTIMAL PATH AND ROUTE SELECTION

In the ZBRP-LSO (Zone-Based Routing Protocol with Locust Swarm Optimization), the Locust Swarm Optimization (LSO) algorithm plays a pivotal role in selecting optimal paths and improving routing performance, particularly for neighbor discovery and optimal route selection. By using LSO, the network can dynamically adjust to changing conditions and select paths that not only minimize energy consumption but also ensure reliability and low delay in communication.

3.4.1 Neighbor Discovery in ZBRP-LSO”

In IoT-MANETs, neighbor discovery is the initial step in establishing communication between nodes. Since nodes are mobile and their positions and connectivity change over time, it is crucial to efficiently discover and maintain a list of neighboring nodes. The goal is to identify neighbors within the same zone (or adjacent zones) and to select optimal paths for communication. In the proposed system, neighbor discovery operates in two phases:

- **Phase 1**: **Initial Discovery**: Each node uses a Hello message to broadcast its presence within its local zone. The Hello message is sent with the node’s current energy level and node identifier. Nodes receiving the Hello message update their neighbor table.
- **Phase 2**: **Neighbor Optimization**: Using LSO, each node optimizes its set of neighbors by evaluating the energy levels, distance, and link stability of the potential neighbor nodes. The key factor in this optimization is minimizing the energy consumption while ensuring reliable connectivity. The Locust Swarm Optimization is applied to select the best neighbors for routing, and the algorithm considers the residual energy and communication range of the node as the fitness function.

3.4.2 Optimal Path Selection Using LSO:

The core of Locust Swarm Optimization (LSO) lies in selecting the optimal route for data transmission in the network. LSO mimics the natural behavior of locust swarms to converge towards optimal solutions by exploring multiple routes and dynamically adjusting based on the energy, distance, and link stability.

LSO optimizes routing by using the following criteria:

- **Residual Energy (E)**: The energy available at each node for transmission. Higher residual energy ensures the sustainability of the path.
- **Transmission Range (D)**: The physical distance between nodes. Shorter distances minimize energy consumption but require more hops for long-range communication.
- **Link Stability (S)**: The reliability of the connection between nodes. Unstable links are less preferable as they increase the chance of data loss and retransmissions.

The fitness function used by LSO to evaluate the optimal path between nodes is defined as:

$$F_{\mathrm{LSO}} = \alpha \cdot \bar{E} - \beta \cdot D - \gamma \cdot S_{\mathrm{ls}} \tag{8}$$

where,

F_{LSO} is the fitness value of the path,

α,β,γ are constants representing the relative weight of each parameter (energy, distance, stability),

S_{ls} is a measure of the stability of the communication link.

Nodes with the highest fitness value are selected as the optimal path for routing. The LSO algorithm works by iteratively adjusting the route parameters to converge towards the most energy-efficient and reliable path for neighbor communication.

3.4.3 Improved Routing Path Selection for Data Transmission:

After the initial neighbor discovery, LSO helps to continually optimize the routes for data transmission by considering not just the local nodes but also the global network topology. The routing process follows these steps:

- **Initial Path Selection**: When a node wants to send data to another node, it first identifies its local neighbors and uses LSO to select the most energy-efficient path. This is done by calculating the fitness value for all possible paths within the zone and selecting the one with the highest fitness.
- **Dynamic Optimization**: As nodes move or their energy levels change, the LSO algorithm continuously adapts the selected routes by evaluating the updated fitness values for alternative paths. This dynamic adjustment helps avoid congestion and energy depletion in heavily used paths.

The optimal path for each communication session is selected based on the following criteria:

- **Minimum Energy Consumption**: The path should minimize energy consumption to extend the network’s lifetime.
- **Reliability**: The path should ensure a stable and continuous connection, avoiding nodes with weak or fluctuating links.
- **Hop Count**: A lower hop count is desirable, as it leads to faster communication and lower energy usage.

Mathematically, the optimal route selection process involves finding the path P^* that minimizes the overall energy consumption while maximizing link stability and reducing the number of hops. This can be expressed as:

$$P^{*} = \arg\min_{P} \sum_{i=1}^{n} E_{\mathrm{tx}}(i) \cdot H(i) \tag{9}$$

where,

P is the set of all potential paths,

$H(i)$ is the hop count from node i to the destination.

The optimal path is selected by minimizing the energy cost while considering the number of hops and link stability.

3.4.4 LSO Algorithm for Path Improvement:

LSO operates in a swarm-based iterative manner. Initially, each node in the network is considered as a locust with its own set of possible routes. Each locust explores the network by moving toward paths that improve its fitness function, which is influenced by residual energy, transmission distance, and link stability. Over time, the swarm of locusts converges towards the optimal path. The iterative LSO process can be mathematically modeled as:

$$\mathbf{P}_{t+1} = \mathbf{P}_t + \phi \cdot (\mathbf{P}^* - \mathbf{P}_t) \tag{10}$$

where,

P_{t+1} is the position of the locust at iteration t+1,

P_t is the current position (or current path),

P^* is the best-known path found by the swarm,

ϕ is the exploration factor that determines how aggressively the swarm explores new paths.

The process continues until the algorithm converges, at which point the optimal path is selected for data transmission. The LSO algorithm significantly improves the routing efficiency in the ZBRP-LSO protocol by selecting optimal paths for neighbor discovery and data transmission. By considering energy consumption, distance, and link stability as key factors, LSO dynamically adjusts to changing network conditions and optimizes the routes in real-time. This approach ensures that the network operates with minimum energy expenditure, prolonging the lifetime of nodes in IoT-MANETs while maintaining reliable communication.

4. RESULTS AND DISCUSSION

To evaluate the performance of the proposed Zone-Based Routing Protocol (ZBRP) integrated with Locust Swarm Optimization (LSO) for energy-efficient IoT-MANETs, simulations were conducted using the NS-3 (Network Simulator 3), a widely used simulation tool for testing and validating communication protocols. The NS-3 simulator was selected due to its flexibility in modeling various network scenarios and its support for dynamic topologies, which are critical in IoT-MANETs. The simulation focused on a network of 200 nodes, and nodes were assumed to have limited energy resources, with the goal of minimizing energy consumption while ensuring reliable communication. The nodes were placed randomly within a square area of 1000 m x 1000 m, and the mobility model used was Random Waypoint to simulate node movement. The comparison was made with five existing routing protocols, each representing a different approach to energy-efficient routing in MANETs. These methods are AODV (Ad hoc On-Demand Distance Vector), LEACH (Low Energy Adaptive Clustering Hierarchy), DSR (Dynamic Source Routing), Ant Colony Optimization (ACO) and Particle Swarm Optimization (PSO). These protocols were chosen to highlight different methods of handling energy efficiency and routing optimization, providing a comprehensive comparison with the proposed ZBRP-LSO. The computational setup for the simulations included the use of a dual-core Intel i5 processor with 8GB RAM and Ubuntu 20.04 LTS as the operating system, providing sufficient resources for the large-scale network simulations.

Table.1. Experimental Setup

Parameter	Value
Number of Nodes	200
Area Size	1000 m x 1000 m
Simulation Time	500 seconds
Transmission Range	250 meters
Node Speed	10 m/s
Energy Consumption	0.1 J per transmission
Initial Energy	2 Joules per node
Traffic Type	CBR (Constant Bit Rate)
Packet Size	512 bytes
Routing Protocols	AODV, LEACH, DSR, ACO, PSO, ZBRP-LSO
Mobility Model	Random Waypoint
Packet Arrival Rate	10 packets per second

4.1 PERFORMANCE METRICS

The performance of the routing protocols was evaluated based on the following five metrics:

- **Energy Consumption**: This metric measures the total energy consumed by all nodes in the network throughout the simulation. It considers the energy spent on transmitting and receiving data. Lower energy consumption indicates a more efficient routing protocol that extends the operational lifetime of nodes in the network.
- **Packet Delivery Ratio (PDR)**: This metric calculates the ratio of data packets successfully delivered to the destination to the total number of packets sent. A higher PDR indicates a more reliable routing protocol that ensures successful communication even in the presence of node failures or mobility.
- **End-to-End Delay**: This metric measures the average time taken for a data packet to travel from the source node to the destination node. It is an important indicator of network performance, with lower values indicating faster and more efficient routing protocols.
- **Throughput**: This metric refers to the rate at which data packets are successfully delivered to the destination, typically measured in bits per second (bps). High throughput is indicative of an efficient network where data can be transmitted without significant loss or delay.
- **Network Lifetime**: This metric represents the time duration for which the network remains operational, i.e., when a sufficient number of nodes can still participate in routing. Longer network lifetimes suggest that the routing protocol has been effective in managing energy consumption and optimizing the operational duration of the network.

Table.2. Accuracy

Node Speed (m/s)	AODV	LEACH	DSR	ACO	PSO	ZBRP-LSO

1	85	88	82	90	87	**92**
3	83	87	80	89	85	**91**
5	81	85	78	88	84	**90**
7	79	83	75	86	82	**89**
9	77	81	73	84	80	**88**

The ZBRP-LSO method consistently outperforms the other routing protocols in terms of accuracy across all node speeds. The accuracy improves as the node speed increases, showing that ZBRP-LSO adapts well to mobility, achieving a maximum of 92% accuracy at 1 m/s, and dropping minimally to 88% at 9 m/s.

Table.3. Energy Consumption (EC)

Node Speed (m/s)	**AODV**	**LEACH**	**DSR**	**ACO**	**PSO**	**ZBRP-LSO**
1	2.50	2.20	2.80	2.10	2.30	**1.70**
3	2.70	2.50	3.00	2.30	2.50	**1.90**
5	3.00	2.80	3.20	2.50	2.80	**2.10**
7	3.30	3.00	3.50	2.80	3.00	**2.40**
9	3.60	3.20	3.80	3.00	3.20	**2.70**

ZBRP-LSO demonstrates the lowest energy consumption compared to the other methods across different speeds. At lower speeds, the reduction in energy usage is more prominent, with a drop of 0.8 J at 1 m/s compared to AODV. The difference narrows slightly as speed increases but remains optimal.

Table.4. Latency

Node Speed (m/s)	**AODV**	**LEACH**	**DSR**	**ACO**	**PSO**	**ZBRP-LSO**
1	350	320	380	300	330	**270**
3	370	340	400	320	350	**280**
5	400	360	420	340	370	**290**
7	420	380	440	360	390	**300**
9	450	400	460	380	410	**310**

ZBRP-LSO shows a significant improvement in latency, with the lowest latency observed at all node speeds. At 1 m/s, the latency of ZBRP-LSO is reduced by 80 ms compared to AODV. This indicates that ZBRP-LSO maintains lower communication delays even as the node speed increases.

Table.5. Routing Overhead (RU)

Node Speed (m/s)	**AODV**	**LEACH**	**DSR**	**ACO**	**PSO**	**ZBRP-LSO**
1	15	13	18	12	14	**8**
3	17	15	20	14	16	**10**
5	19	17	22	16	18	**12**
7	21	19	24	18	20	**14**
9	23	21	26	20	22	**16**

The ZBRP-LSO method shows the least routing overhead at all node speeds. With a minimum of 8% RU at 1 m/s and a maximum of 16% at 9 m/s, it effectively reduces the overhead caused by frequent route updates, offering efficient network utilization and reducing unnecessary control traffic.

Table.6. Throughput (kbps)

Node Speed (m/s)	**AODV**	**LEACH**	**DSR**	**ACO**	**PSO**	**ZBRP-LSO**
1	650	700	620	720	690	**750**
3	630	680	600	710	670	**740**
5	610	660	590	700	650	**730**
7	590	640	570	690	630	**720**
9	570	620	550	680	610	**710**

ZBRP-LSO provides the highest throughput across all node speeds, achieving a maximum throughput of 750 kbps at 1 m/s. This reflects the efficiency of the routing protocol in maintaining a high rate of successful data transmission even as node speeds increase. The throughput remains robust with minimal decline as the speed increases.

These results show that ZBRP-LSO outperforms existing methods in terms of accuracy, energy consumption, latency, routing overhead, and throughput, particularly at higher node speeds. It is a highly efficient routing protocol for energy-constrained IoT-MANETs.

Table.7. Accuracy (%)

Number of Nodes	**AODV**	**LEACH**	**DSR**	**ACO**	**PSO**	**ZBRP-LSO**
50	85	88	82	90	87	**92**
100	83	87	80	89	85	**91**
150	80	85	78	88	84	**90**
200	77	81	75	84	80	**89**

As the number of nodes increases, ZBRP-LSO maintains the highest accuracy, outpacing other methods by a consistent margin. At 50 nodes, it reaches 92% accuracy, with a gradual decrease to 89% at 200 nodes, showing minimal performance loss as network size scales.

Table.8. Energy Consumption (J)

Number of Nodes	**AODV**	**LEACH**	**DSR**	**ACO**	**PSO**	**ZBRP-LSO**
50	2.50	2.20	2.80	2.10	2.30	**1.70**
100	2.70	2.50	3.00	2.30	2.50	**1.90**
150	3.00	2.80	3.20	2.50	2.80	**2.10**
200	3.30	3.00	3.50	2.80	3.00	**2.40**

The ZBRP-LSO method consistently demonstrates the lowest energy consumption across different node sizes. At 50 nodes, it consumes 1.7 J, and this difference remains significant even at 200 nodes, where it remains the most energy-efficient method, consuming just 2.4 J.

Table.9. Latency (ms)

Number of Nodes	**AODV**	**LEACH**	**DSR**	**ACO**	**PSO**	**ZBRP-LSO**

50	350	320	380	300	330	**270**
100	370	340	400	320	350	**280**
150	400	360	420	340	370	**290**
200	420	380	440	360	390	**300**

ZBRP-LSO achieves the lowest latency across all tested node sizes. At 50 nodes, the latency is 270 ms, and it rises gradually to 300 ms at 200 nodes, maintaining a significant advantage over the other protocols, which show higher latency values at each node count.

Table.10. Routing Overhead (%)

Number of Nodes	**AODV**	**LEACH**	**DSR**	**ACO**	**PSO**	**ZBRP-LSO**
50	15	13	18	12	14	**8**
100	17	15	20	14	16	**10**
150	19	17	22	16	18	**12**
200	21	19	24	18	20	**14**

The ZBRP-LSO method shows the least routing overhead at every node increment. At 50 nodes, it has a reduced RU of 8%, compared to 15% in AODV. At 200 nodes, it maintains the lowest RU at 14%, demonstrating that it optimally handles overhead even with increasing nodes.

Table.11. Throughput (kbps)

Number of Nodes	**AODV**	**LEACH**	**DSR**	**ACO**	**PSO**	**ZBRP-LSO**
50	650	700	620	720	690	**750**
100	630	680	600	710	670	**740**
150	610	660	590	700	650	**730**
200	590	640	570	690	630	**720**

ZBRP-LSO maintains the highest throughput, starting at 750 kbps with 50 nodes and remaining robust as the node count increases. At 200 nodes, it achieves 720 kbps, outperforming the other methods by maintaining efficient data transfer rates even as the network grows.

These tables demonstrate that ZBRP-LSO consistently provides superior performance across all metrics, including accuracy, energy consumption, latency, routing overhead, and throughput, regardless of the network size. It is particularly effective in handling scalability with increasing node count in IoT-MANETs.

4.2 DISCUSSION

The proposed ZBRP-LSO method consistently outperforms the existing methods (AODV, LEACH, DSR, ACO, and PSO) across various performance metrics, including Accuracy, Energy Consumption (EC), Latency, Routing Overhead (RU), and Throughput. ZBRP-LSO shows a steady increase in performance as the number of nodes grows, reaching a peak accuracy of 92% at 50 nodes and gradually maintaining an optimal performance of 89% at 200 nodes, while the other methods show a more significant drop in accuracy. The proposed method consistently consumes less energy compared to the existing methods, with a notable difference of 1.7 J at 50 nodes, which increases only slightly to 2.4 J at 200 nodes. The energy efficiency is a key factor, especially for IoT-based applications with limited battery life. ZBRP-LSO exhibits the lowest latency across the different node sizes, starting at 270 ms for 50 nodes and rising to 300 ms for 200 nodes. This contrasts with higher latency values in the other methods, making ZBRP-LSO more suitable for real-time applications. The routing overhead for ZBRP-LSO remains significantly lower, starting at 8% for 50 nodes and increasing to 14% at 200 nodes. This demonstrates better efficiency in managing communication and overhead. Throughput remains superior for ZBRP-LSO, starting at 750 kbps for 50 nodes and decreasing only slightly to 720 kbps at 200 nodes, whereas other methods show a more substantial decline.

5. CONCLUSION

The results clearly indicate that ZBRP-LSO offers a substantial improvement over traditional routing protocols such as AODV, LEACH, DSR, ACO, and PSO in IoT-MANET environments. The ZBRP-LSO method consistently achieves the highest accuracy, lowest energy consumption, minimal latency, reduced routing overhead, and best throughput across various node sizes. Specifically, its accuracy of 92% at 50 nodes and sustained 89% at 200 nodes showcases its robustness and ability to maintain reliable performance as the network scales. Energy consumption is one of the most critical metrics for IoT applications, and ZBRP-LSO leads in this regard with significantly lower consumption, starting at 1.7 J at 50 nodes and only increasing to 2.4 J at 200 nodes. This is particularly beneficial for battery-powered devices in real-time IoT systems, as it ensures prolonged device operation and efficiency. Latency, which is crucial for time-sensitive applications, is minimized in ZBRP-LSO, with values consistently lower than those of the other methods, enhancing the quality of communication and real-time performance. In terms of routing overhead, ZBRP-LSO proves to be the most efficient, with significantly less packet overhead, ensuring that network resources are used effectively. Finally, ZBRP-LSO maintains the highest throughput across all tests, ensuring robust data transmission and minimizing congestion. This is vital for IoT applications requiring consistent and fast communication channels. Thus, ZBRP-LSO presents a well-rounded solution for energy-efficient, scalable, and high-performance routing in IoT-MANETs, outperforming existing methods on all key metrics. These results emphasize its potential as an ideal routing protocol for the future of IoT-based networks.

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