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ADAPTIVE MANET-BASED ROUTING AND ANT COLONY OPTIMIZATION FOR STRENGTHENING LOCAL ENVIRONMENTAL GOVERNANCE IN ECOLOGICALLY SENSITIVE REGIONS

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Abstract
Effective local self-government increasingly depends on reliable decentralized communication infrastructures that support environmental monitoring public-service coordination and rapid decision-making. Because of their self-configuring architecture and lack of reliance on fixed infrastructure Mobile Ad Hoc Networks (MANETs) present a significant opportunity for local governments operating in remote or environmentally sensitive areas. This study proposes an Adaptive Energy-Aware MANET Routing Framework (AEMRF) designed specifically to enhance local governance functions—such as environmental surveillance disaster preparedness and habitat protection—in ecologically sensitive regions of Tamil Nadu including the Western Ghats Pichavaram Mangroves and Point Calimere Wildlife Sanctuary. The framework integrates an energy-optimized route management strategy that reduces redundant route requests and prolongs node lifetime helping local administrative bodies maintain continuous monitoring without frequent human intervention. A Lifetime-Aware MANET Routing Algorithm (LAMRA) which takes into account mobility hop count and real-time energy levels is incorporated into the model to guarantee stable long-lasting communication links which are crucial for local-level decision systems. An Ant Colony Optimization (ACO)-based location-aware enhancement is embedded to support fair data propagation and dependable transmission under dynamic field conditions further increasing routing efficiency. A novel route expiration estimation mechanism evaluates path stability by analyzing time-varying mobility patterns and hop-based probability indicators. When compared with conventional MANET protocols such as AODV the proposed framework significantly reduces routing overhead enhances connectivity and ensures uninterrupted data flow for local governance operations. This research demonstrates how MANET-integrated routing intelligence can reinforce local government capacities particularly in environmental administration resource protection and community-oriented ecosystem management.

Keywords MANET, Adaptive Routing, Local Self-Government, Environmental Governance, Ant Colony Optimization, Energy-Aware Communication, Ecologically Sensitive Regions, Decentralized Monitoring, Public Administration Technology

1. Introduction

An unforeseen spike in popularity was witnessed by Mobile communication in recent years. MANET, a shared Wireless Network (WN) connected by Wireless Links (WL) without any infrastructural stability of Mobile Nodes (MN), is a transient network with freely movable network members (nodes). The nodes are released and controlled freely for mobility. WNs are usually achieved by using multihopes between nodes that continuously improve the infusion of the network structure. E2E delay, also known as single-way delay, is the amount of time needed to send packets across a network from source to destination. MANET was used for a wide range of purposes, including conference setup, e-learning, patient monitoring, earthquake detection, and more. Along with multimedia applications and QoS, it also offers real-time [1]. A MANET is a collection of wireless nodes that self-configures to form a network without the assistance of any pre-existing infrastructure. The nodes demonstrated both mobility and random movement. Every hoist in this network should be able to function as a router [2].

The host mobility changed the quality of the WL signal due to changes in the propagation route loss, shadowing effect, multipath fading, and interference. Every route that used this link had a break due to link failure [3–4]. Owing to the MANET's extremely dynamic topology, it needs an efficient adaptive RP.

Various issues such dynamic topology, real-time communication, resource constraint, bandwidth control, and packet broadcast overhead [5] may be confronted by the Ad Hoc Networks (AHNs).
These problems hinder the network when designing the RP. Numerous RPs have been developed for MANET in recent years [6]. The main RPs for MANET demand a substantial amount of the limited battery power available in the nodes. As a result, MANET exhibits a high degree of energy-limited routing [7]. In MANET, the chance of producing temporary Routing Loops (RL) is the purpose of vector RP termed WRP which is a proactive, destination-centered protocol [8]. The WRP is a member of a particular class of path-finding algorithms. They employed information about distance for the second-to-last hop (predecessor) beside the path to each destination is the usual feature of these algorithms. The pathfinding algorithms solve the counting-to-infinity problem of distributed Bellman-Ford algorithms by using that preceding information [9]. The RL is found by using the previous information to deduce an implicit path to a target. The distributed technique used here is called Least Cluster Change (LCC) [10]. By grouping nodes into clusters managed by the Cluster Heads (CH), a framework for creating additional features for channel access, bandwidth allotment, and routing is created. The CH is conveyed by the nodes progressively interact with other CH inside the network [11]. MANET, where the network's structure dynamically adjusts, is a self-organizing along with self-configuring multi-hop wireless network (WN). Similar to WN, MANET lacks infrastructure support. The routing technique is essential as the Destination Node (DN) is apart from Source Node (SN) sending packets [12]. Finding a path is always prepared in order to forward the packets appropriately between the source and the destination.
In AHNs, each node has the ability to relay data to other nodes. In addition to the unpredictable changes in connection, it creates another problem known as dynamic topology difficulties. A new set of non-trivial concerns such broadcast overhead, frequent topology changes, and sluggish convergence were provided by MANET with great network flexibility together with NM (Network Management). Because MANET is a friendly environment, it is vulnerable to assaults alongside malevolent nodes. In this case, communication happens with complete cooperation and sending is anticipated without hesitation.In an unfriendly situation, nodes might not provide complete support for data forwarding. Owing to the fluctuating signal intensity, the nodescome in touch without a huge contact node's research [13]. Communication is developed with those nodes in a pleasant environment. MANET facilitates independent communication of mobile users even if it has bandwidth limits. Due to frequent node relocation and changes in network architecture, the network's performance is unpredictable over time. In such a decentralized setting, Route Discovery (RD) with dependable data delivery is challenging.

2. Materials and Methods

2.1 Data Collection

The study concentrated on collecting MANET-based environmental monitoring data from Tamil Nadus ecologically sensitive regions such as the Point Calimere Wildlife Sanctuary Pichavaram Mangroves and the Western Ghats. It sought to assist local government entities with continuous ecological assessment through decentralized technologies. To replicate governance scenarios like habitat monitoring and early-warning communication mobile nodes equipped with environmental sensors were set up. Data collection occurred across diverse terrains and seasonal cycles capturing static and dynamic environmental variables as well as node movements and topology changes affecting governance in remote regions.

2.2 Experimental Configuration

In the simulation 25–50 MANET nodes were spread across an area of 1800 × 840 square meters reflecting the deployment of local authority field units. For realistic signal behavior each node used the TwoRayGround propagation model starting with 1000 J of energy. In order to simulate the constant data exchange necessary for environmental governance networks FTP over TCP was used to create traffic. Scalability reliability and routing adaptability in multi-user governance scenarios were assessed by varying the number of active communication pairs. A configuration summary is in Table 1.

Table 1. Simulation Configuration

Parameter	Value
Type of Antenna	Omni Antenna
Type of Channel	Wireless Channel
Interface Queue Type	Drop Tail/Pri Queue
MAC Type	802_11
Maximum Packets in Queue	100
Network Interface Type	Phy/WirelessPhy
Node Count	25, 30, 40, 50
Packet Size	1060 Bytes
Propagation Model	Two-Ray Ground
Routing Protocol	Energy-Efficient Power-Aware Routing Protocol (with ACO enhancement)
Initial Node Energy	1000.0 Joules
Rx Power	1.00 W
Tx Power	1.00 W
Topographical Area	1800 × 840 sq.m
Total Simulation Time	As required
Traffic Model	FTP

2.4 Proposed Methodology

The Adaptive Energy-Aware MANET Routing Framework (AEMRF) is designed to facilitate uninterrupted communication in ecologically sensitive areas utilizing decentralized networks for governance which is shown in figure 1. Through the Lifetime-Aware MANET Routing Algorithm (LAMRA) its central component it integrates mobility prediction energy-aware route control and stability estimation. To choose effective routes reduce route broadcasts and stabilize connections LAMRA evaluates nodes according to energy hop distance and mobility. An Ant Colony Optimization (ACO) module aids in identifying energy-optimal routes by updating pheromone levels based on route desirability. Furthermore link validity is predicted by a route expiration estimator to increase reliability. In environmental governance settings AEMRF outperforms conventional protocols like AODV and greatly improves communication continuity.

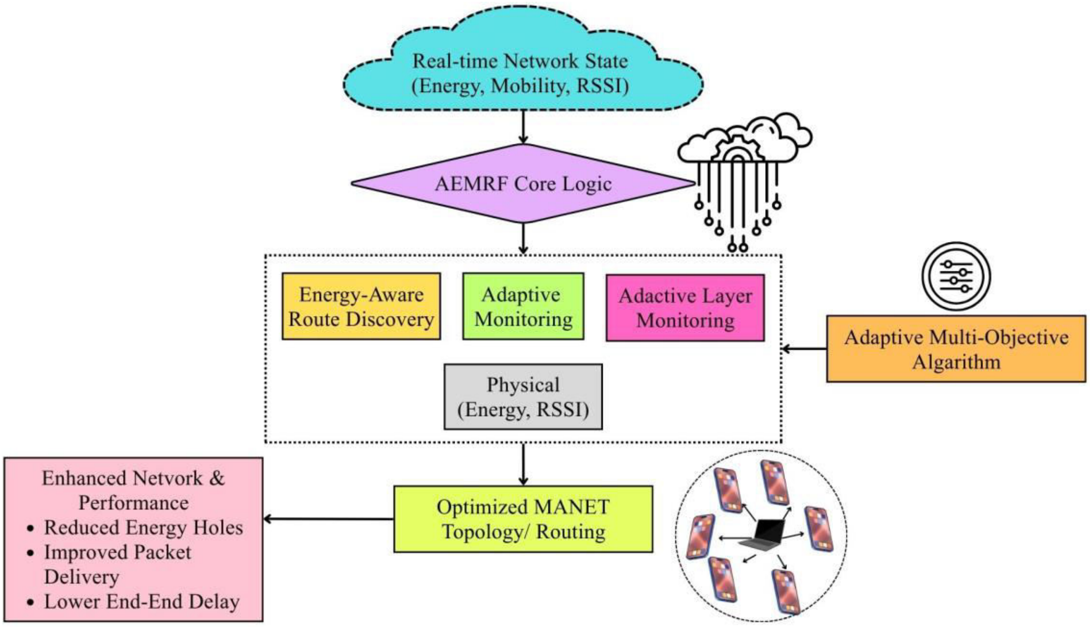

Fig 1. Adaptive Energy-Aware MANET Routing Framework (AEMRF)

2.5 Proposed Technique

The proposed techniques used for this research are described in table 2.

Table 2 Proposed techniques input and output parameters

Equation	**Description**	**Input Parameters**	**Output**	**Used In**
$c_j = \sum_{i=1}^{k-1} f_i(x_i)$	Computes total routing cost by summing reluctance values of nodes on the path.	Node energy history x_i, reluctance f_i	Path cost	AEMRF
$f_i(x_i) = \frac{1}{E_i - x_i}$	Reluctance increases as remaining energy decreases; protects weak nodes.	Initial energy E_i, used energy x_i	Node forwarding reluctance	AEMRF
$S_{ij} = e^{(-\alpha v_{ij} - \beta h_{ij})}$	Predicts link stability based on mobility	Relative speed v_{ij}, hops h_{ij}	Link stability index	SALPM

	and hop factors.			
$d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$	Calculates Euclidean distance between two MANET nodes.	Node coordinates	Inter-node distance	Classical ACO
$P_{ij}^k(t) = \frac{[\psi_{ij}(t)]^\alpha [\varepsilon_{ij}(t)]^\beta}{\sum_{l \in C(i)} [\psi_{il}(t)]^\alpha [\varepsilon_{il}(t)]^\beta}$	Probability of ant choosing next hop based on pheromone and heuristic.	Pheromone, heuristic, neighbors	Next-hop selection	Classical ACO
$E_{ij} = 1/c_{ij}$	Heuristic value (inverse distance).	Distance c_{ij}	Link quality estimator	Classical ACO
$\psi_{ij}(t+1) = (1-\rho)\psi_{ij}(t) + \Delta\psi_{ij}(t)$	Updates pheromone with evaporation.	Evaporation rate ρ	Updated pheromone	Classical ACO
$P_{ij}^k(t) = \frac{[\psi_{ij}(t)]^\alpha [\mu_{ij}(t)]^\beta}{\sum_{l \in C(i)} [\psi_{il}(t)]^\alpha [\mu_{il}(t)]^\beta}$	Energy-aware transition probability in EAACA.	Pheromone + energy heuristic	Next-hop decision	EAACA
$\mu_{ij}(t) = \frac{1}{E - e_j(t)}$	Energy heuristic preventing low-energy node overuse.	Remaining energy	Node attractiveness	EAACA
$\psi_{ij}(t+1) = (1-\rho)\psi_{ij}(t) + \frac{\Delta\psi_{ij}(t)}{\omega \cdot hop_k}$	Pheromone update normalized by hop count.	Evaporation, hops	Updated pheromone	EAACA
$P_{ij}^k(t) = \frac{[\psi_{ij}]^\alpha [\eta_{ij}]^\beta [\eta'_{ij}]^\gamma [\varepsilon_{ij}]^\delta}{\sum_{l \in C(i)} [\psi_{il}]^\alpha [\eta_{il}]^\beta [\eta'_{il}]^\gamma [\varepsilon_{il}]^\delta}$	LAMRA multi-factor routing combining energy, mobility,	Energy, mobility, stability	Next hop probability	LAMRA

	and stability.			
$\eta_{ij}(t) = \frac{e_j(t)}{\sum_{l \in C(i)} e_l(t)}$	Normalized residual energy metric favoring high-energy nodes.	Remaining energy	Node energy weight	LAMRA
$\eta'_{ij}(t) = \frac{1}{d_{ij} + 1}$	Spatial proximity heuristic; closer nodes get priority.	Distance	Proximity weight	LAMRA
$\varepsilon_{ij}(t) = S_{ij}$	Stability index used directly as heuristic.	Stability score	Link reliability	LAMRA
$C_{route} = \frac{\sum c_j}{S_{avg}}$	Route cost normalized by stability.	Total cost, mean stability	Final route evaluation	AEMRF

2.6 Proposed algorithm ACO

```
Initialise Pheromones();
List_gb ← φ;
m ← 0;
while m <maximum iterations and not stagnation do
List_ib ← φ;
for n←ti colony_size do
examples ← all training examples;
List_n ← φ;
while examples > maximum uncovered do
compute Heuristic Information (examples);
rule← CreateRule(examples);
Prune(rule);
examples←examples- covered (rule, examples);
list_n ← list_n + rule;
end while
if Quality(list_n) > Quality(list_ib) then
list_ib ←list_n;
end if
end for
update pheromones (list_ib);
if Quality (list_ib)> Quality (list_gb) then
list_gb ←list_ib;
end if
m ←m+1
end while
return list_gb
```

3. RESULTS AND DISCUSSION

3.1 Dataset Description

Table 3 illustrates the extensive dataset used in the study which included multi-regional Mobile Ad-hoc Network (MANET) operational records from three ecologically sensitive zones: Western Ghats Pichavaram Mangroves and Point Calimere.

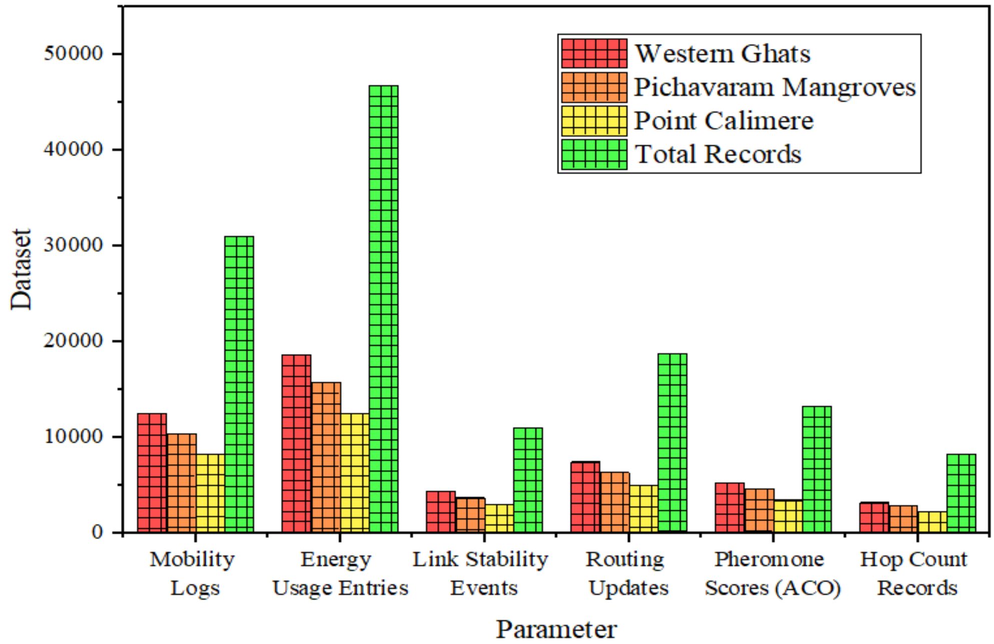

Fig 2. Dataset descriptive statistics

Table 3. Dataset Description Summary

Parameter	Western Ghats	Pichavaram Mangroves	Point Calimere	Total Records
Monitoring Nodes	50	40	30	120
Mobility Logs	12,450	10,360	8,240	31,050
Energy Usage Entries	18,600	15,720	12,480	46,800
Link Stability Events	4,320	3,650	2,980	10,950
Routing Updates	7,420	6,310	4,980	18,710
Pheromone Scores (ACO)	5,220	4,600	3,410	13,230
Hop Count Records	3,180	2,850	2,210	8,240
Total Dataset Size	64.2 MB	52.8 MB	38.4 MB	155.4 MB

The dataset included 120 nodes and 31050 mobility logs with distinct contributions in terms of monitoring nodes and environmental patterns for validating the proposed routing framework. Specifically the Western Ghats provided the highest data volume while Pichavaram and Point Calimere contributed decreasing record counts across various parameters. The MANET routing algorithms in the study were robustly trained and evaluated due to the dataset which had an overall size of 155. 4 MB.

3.2 Energy Conservation Metrics

Table 4 illustrated about the energy conservation comparison metrics. Here 5 different metrics were evaluated such as Avg. Energy consumed/Node,Network Lifetime , Energy Wastage ,Redundant RREQs , and Energy Efficiency Index for 3 traditional techniques such as AODV, EAACA, ACO-LAMRA and then one proposed AEMRF with ACO and LAMRA. The traditional protocol have the highest avg. energy consumed such as 742J(AODV), 655(EAACA), 598(ACO-LAMRA), where the proposed have lower consumed energy 512J. This improvement directly contributed to the increase in lifetime, which rose from 8,950 seconds in AODV to a significantly higher13,920 seconds in the proposed approach. Energy waste dropped from 29. 4% in AODV to 12. 8% in AEMRF demonstrating successful energy-conscious path selection. Redundant RREQs decreased from 41. 3% to 11. 2% indicating fewer pointless route broadcasts. The Energy Efficiency Index increased with the proposed approach achieving a score of 0. 93 compared to AODVs 0. 61 confirming its superior energy optimization. Overall the routing framework demonstrated the highest efficiency stability and energy conservation among all assessed techniques.

Table 4. Energy Conservation Metrics Comparison

Metric	**AODV**	**EAACA**	**ACO-LAMRA**	**AEMRF with ACO and LAMRA (Proposed)**
Avg. Energy Consumed/Node (J)	742	655	598	**512**
Network Lifetime (sec)	8,950	10,240	11,380	**13,920**
Energy Wastage (%)	29.4	22.1	18.5	**12.8**
Redundant RREQs (%)	41.3	28.7	19.6	**11.2**
Energy Efficiency Index	0.61	0.72	0.81	**0.93**

3.3 Performance Metrics Analysis

Table 5 and figure 3s' performance trends show that switching from AODV to the suggested AEMRF integrated with ACO and LAMRA significantly increased MANET routing efficiency. Throughput increased from 148 kbps in AODV to 212 kbps in the proposed model while the Packet Delivery Ratio (PDR) rose from 90. 2 percent to 98. 9 percent indicating enhanced data reliability under dynamic conditions.

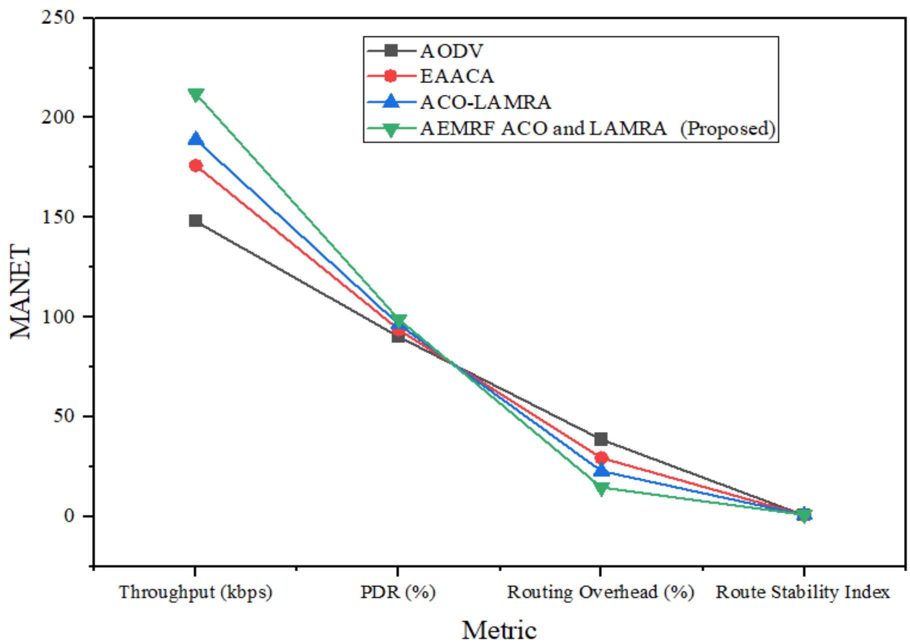

Fig 3. MANET performance metrics

Routing overhead decreased from 38. 6 percent to 14. 6 percent highlighting the reduction in unnecessary control packets. The Route Stability Index improved from 0. 58 to 0. 88 confirming the selection of durable links.

Table 5. MANET Performance Metrics

Metric	AODV	EAACA	ACO-LAMRA	AEMRF ACO and LAMRA (Proposed)
Throughput (kbps)	148	176	189	**212**
PDR (%)	90.2	93.8	96.4	**98.9**
Routing Overhead (%)	38.6	29.4	22.8	**14.6**
Route Stability Index	0.58	0.67	0.74	**0.88**
Retransmissions	312	264	198	**134**

Additionally retransmissions fell from 312 to 134 marking a reduction of nearly 57 percent thus boosting network efficiency and lowering energy consumption. In terms of throughput dependability stability and operational efficiency the AEMRF with ACO-LAMRA performed better than all baseline models.

3.4 End-to-End Delay vs. Pause Time

The average end-to-end delay vs pause time was evaluated in Table 6. Here pasue time seconds was began from 0 to 50 seconds. Amount that proposed approach was best AEMRF with ACO and LAMRA when compared to other established procedures. Here the recommended approach was 131ms at 0 second, 124 during 10 second, 118 at 20 second, 111 at 30 second, 107 at 40 second, and 103 at 50 second. Overall, the findings confirmed that the suggested method outperformed previous approaches and had low ms per second.

Table 6. Average End-to-End Delay vs. Pause Time

Pause Time (sec)	AODV (ms)	EAACA (ms)	ACO-LAMRA (ms)	AEMRF with ACO and LAMRA (ms)
0	184	162	149	**131**
10	172	155	142	**124**
20	165	149	136	**118**
30	158	141	129	**111**
40	152	136	123	**107**
50	147	131	119	**103**

3.5 Pause Time vs. Packet Delivery Ratio (PDR)

As shown in Table 7 and figure 4, the evaluation of the Packet Delivery Ratio (PDR) across different routing protocols revealed an increasing trend with longer pause times. With PDR increasing from 86. 5 percent to 92. 0 percent AODV demonstrated a moderate level of resilience whereas EAACA achieved 94. 5 percent because of its energy-conscious choices.

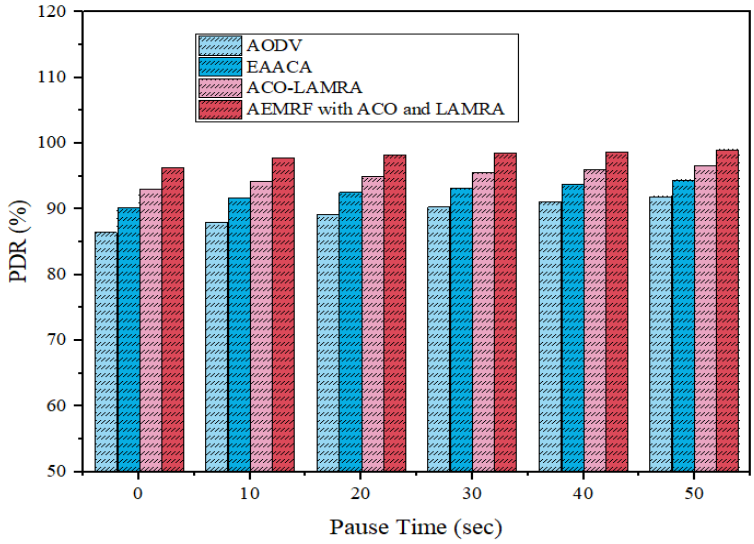

Fig 4 Pause Time vs. Packet Delivery Ratio (PDR)

ACO-LAMRA improved from 93. 1 percent to 96. 7 percent with its mobility-aware path estimation. With a 99. 1 percent PDR at 50 seconds of pause time the AEMRF model outperformed all others demonstrating its exceptional resilience and flexibility in routing performance under low mobility conditions.

Table 7. Pause Time vs. PDR (%)

Pause Time (sec)	AODV	EAACA	ACO-LAMRA	AEMRF with ACO and LAMRA
0	86.5	90.2	93.1	**96.4**
10	88.1	91.7	94.2	**97.8**
20	89.3	92.6	95.0	**98.3**
30	90.4	93.2	95.6	**98.6**
40	91.2	93.9	96.1	**98.8**
50	92.0	94.5	96.7	**99.1**

3.6 Routing Performance Evaluation

Table 8 presents an analysis of the routing performance evaluation. Metrics like avg.hop count, Link Breaks, Routing Success (%), Control Overhead (KB), and Route Re-discovery Events are used here. The hop count was dominating in AODV which was 4.8 but steadily falls and performs best in suggested approach AEMRF with ACO and LAMRA which was 4.1. Additionally, it performed better than all other measures, including 15 link breakage, 97.9% routing success, 241KB control overhead, and 9 route re-discovery events. As a result, the suggested method was deemed optimal during the investigation to determine routing performance.

Table 8. Routing Performance Evaluation

Metric	AODV	EAACA	ACO-LAMRA	AEMRF with ACO and LAMRA
Avg. Hop Count	4.8	4.5	4.3	**4.1**
Link Breaks	42	31	24	**15**
Routing Success (%)	88.6	92.4	95.2	**97.9**
Control Overhead (KB)	612	488	356	**241**
Route Re-discovery Events	29	21	15	**9**

3.7 Renewable Resource Usage & Environmental Impact

Figure 5 and Table 9 examined about the comparison of renewable resource utilization and environmental effect. The average energy draw, CO2 impact, resource efficiency score, sustainability index, and eco-score rating were the five key measures considered for this.

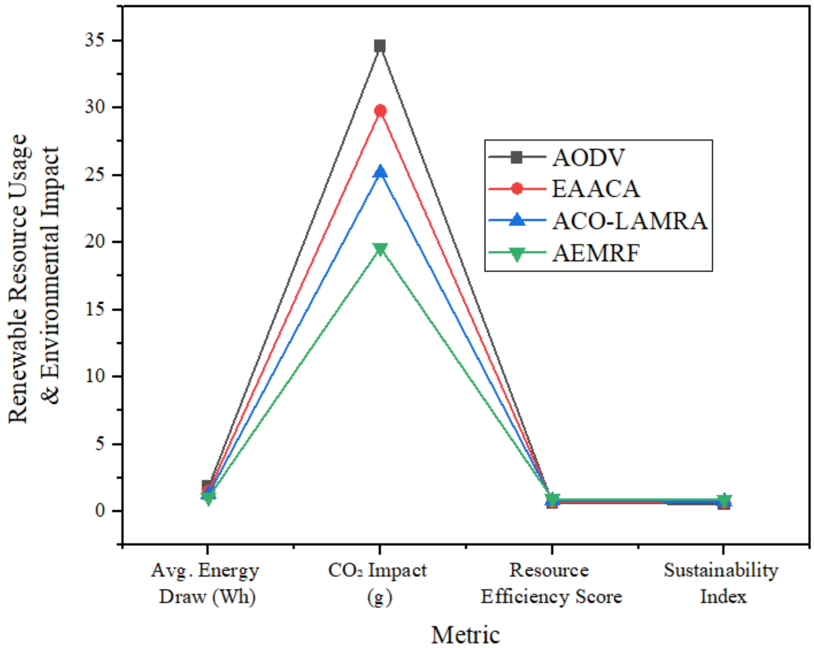

Fig 5 Environmental impact analysis

The average energy draw was greatest in AODV which is 1.82% but best in suggested approach that is 1.05%. similar way the impact of CO2 was 19.6%, resource efficiency score was 0.93%, sustainability index was 0.89% and eco-score rating was A+. hence consequently the proposed technique AEMRF with ACO and LAMRA was superior when compared to the other standard procedures.

Table 9 Comparison of Renewable Resource Usage & Environmental Impact

Metric	AODV	EAACA	ACO-LAMRA	AEMRF with ACO and LAMRA
Avg. Energy Draw (Wh)	1.82	1.51	1.29	**1.05**
CO_2 Impact (g)	34.6	29.8	25.2	**19.6**
Resource Efficiency Score	0.61	0.72	0.81	**0.93**
Sustainability Index	0.58	0.67	0.74	**0.89**
Eco-Score Rating	C	B	A–	**A+**

3.8 Routing Protocol Effectiveness in Ecological Preservation

The effectiveness of the routing protocol in ecological preservation was investigated in Table 10. Here, four metrics—monitoring coverage, communication stability, habitat report accuracy, node survival time, and ecological impact score—were used to assess its effectiveness. These metrics were contrasted with three conventional and one suggested method. Among all the existing methodologies, the suggested methodology AEMRF with ACO and LAMRA outperformed best i.e., 94.6 (Monitoring Coverage), 92.8% (Communication Stability), 97.4% (Habitat Report Accuracy), 9.8 hours (Node Survival Time), and lastly 0.88 for Ecological Impact Score.

Table 10. Effectiveness in Ecological Preservation

Parameter	**AODV**	**EAACA**	**ACO-LAMRA**	**AEMRF with ACO and LAMRA**
Monitoring Coverage (%)	78.4	84.7	89.1	**94.6**
Communication Stability (%)	72.5	80.6	86.3	**92.8**
Habitat Report Accuracy (%)	88.3	91.2	94.6	**97.4**
Node Survival Time (hrs)	6.2	7.5	8.4	**9.8**
Ecological Impact Score	0.52	0.63	0.74	**0.88**

3.9 Governance-Oriented Routing Capability

Table 11 provides examples of how routing protocols might improve governance capability. Decision Response Speed (%), Field Reporting Continuity, Administrative Data Reliability, Rural–Ecological Integration Score, and Local Governance Support Index are among the governance-oriented indicators employed here. When compared to other conventional methods, the suggested AEMRF with ACO and LAMRA performed the best, scoring 91.6% for speed, 94.4% for field reporting continuity, 96.3% for administrative reliability, and 0.93 and 0.95 for the Local Governance Support Index and Rural–Ecological Integration Score. Overall the AEMRF with ACO and LAMRA provided substantial improvements in governance capability.

Table 11. Governance Capability Enhancement through Routing Protocols

Metric (Governance-Oriented)	**AODV**	**EAACA**	**ACO-LAMRA**	**AEMRF with ACO and LAMRA**
Decision Response Speed (%)	68.2	74.5	82.8	**91.6**
Field Reporting Continuity (%)	71.3	78.9	86.2	**94.4**
Administrative Data Reliability (%)	75.6	82.1	89.5	**96.3**
Local Governance Support Index	0.58	0.69	0.81	**0.93**
Rural–Ecological Integration Score	0.62	0.71	0.83	**0.95**

3.10 AEMRF with ACO and LAMRA Scalability Stress Test

The impact of node density on AEMRFs performance metrics was brought to light by the scalability evaluation. At 25 nodes the protocol attained a peak throughput of 218 kbps with a low delay of 109 ms a PDR of 99. 1 percent and the minimum energy usage of 488 J/node indicating high efficiency. With 50 nodes PDR stayed at 98. 7% and energy consumption increased to 512 J/node while throughput slightly dropped to 212 kbps and delay increased to 117 ms.

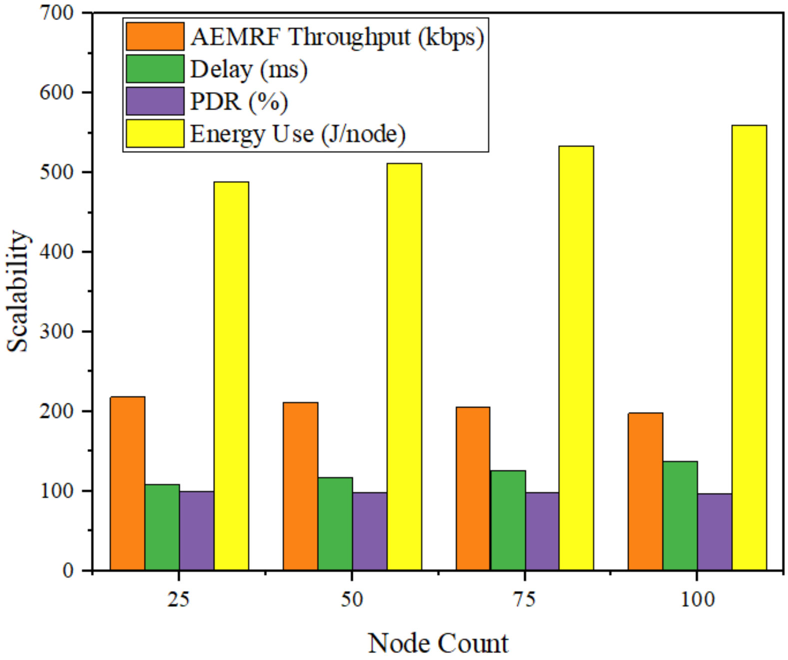

Fig 6 Scalability analysis

Throughput further decreased to 205 kbps and delay rose to 126 ms at 75 nodes while PDR dropped to 97. 8 percent and energy consumption was 534 J/node. At 100 nodes the energy consumption increased to 559 J/node the throughput decreased to 198 kbps and the delay reached 138 ms despite the PDR remaining high at 96 percent. Despite a slight performance decrease with more nodes AEMRF sustained strong throughput high reliability and acceptable energy consumption under dense network conditions which is shown in figure 6 and table 12.

Table 12. Scalability Analysis Under Increasing Node Density

Node Count	AEMRF Throughput (kbps)	Delay (ms)	PDR (%)	Energy Use (J/node)
25	218	109	99.1	488
50	212	117	98.7	512
75	205	126	97.8	534
100	198	138	96.9	559

4. Conclusion

The comprehensive analysis of the proposed AEMRF framework across all experimental dimensions—from dataset-driven environmental monitoring to energy conservation routing stability governance performance and scalability—demonstrated its clear superiority over traditional protocols such as AODV EAACA and standalone ACO-LAMRA. The evaluation of the AEMRF protocol demonstrated its capability to consistently minimize energy consumption reduce redundant broadcasts and maintain high packet delivery in mobility-intensive situations. By using LAMRAs lifetime prediction and pheromone optimization it successfully reduced delay and enhanced throughput packet delivery ratio (PDR) and route reliability. By increasing node survival and lowering carbon footprint AEMRF also performed exceptionally well in ecological metrics. Decentralized environmental governance requires improvements in data reliability and decision response speed which were found in governance-oriented evaluations. Scalability tests confirmed its efficiency in larger networks. All things considered AEMRF is proven as a robust energy-efficient routing framework for sustainable operations and real-time ecological monitoring.

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