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Advances in Energy Efficiency and Routing Optimization in Mobile Ad Hoc Networks: A Comprehensive Literature Review

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Abstract

Mobile Ad Hoc Networks (MANETs) are dynamic and decentralized wireless networks requiring adaptive solutions for energy efficiency, routing optimization, and fault tolerance. This literature review explores recent advances in MANET technologies, focusing on innovations such as the Deep Reinforcement Learning for Energy-Efficient Routing (DRLER) protocol and the Trust-based Secure Routing Protocol (TSRP), which optimize energy consumption and enhance network reliability. These innovations have significantly contributed to extending network lifetime and improving scalability under dynamic conditions. Findings highlight significant progress in extending network lifetime, optimizing resource usage, and maintaining reliable communication in challenging conditions. Despite these advancements, challenges such as high computational overhead, node mobility, and limited scalability persist. Recent developments include the integration of MANETs with IoT systems, enabling applications such as livestock monitoring, and the adoption of artificial intelligence(AI) techniques that enhance routing efficiency and energy management in practical, real-world scenarios. The review suggests future research directions to address these challenges and further improve MANET efficiency and reliability.

Keywords: *Mobile Ad Hoc Network (MANET), Energy Efficiency, Routing Optimization, Internet of Things (IoT),Wireless Sensor Network (WSN).*

1 Introduction

Mobile Ad Hoc Networks (MANETs) are dynamic networks consisting of wireless nodes that communicate directly with one another without the need for a fixed infrastructure [1]. The growing affordability and availability of compact wireless communication devices have significantly boosted interest in Mobile Ad Hoc Networks (MANETs) across academic and industrial fields in recent years. MANETs offer great potential. With increasing interest in their applications across fields such as mobile classrooms, military communications, and disaster relief, MANETs hold great potential to revolutionize wireless communication systems. By enabling mobile nodes to function as routers, clients, and servers, these networks provide versatile solutions for various scenarios, including livestock monitoring through sensors attached to grazing animals [2].

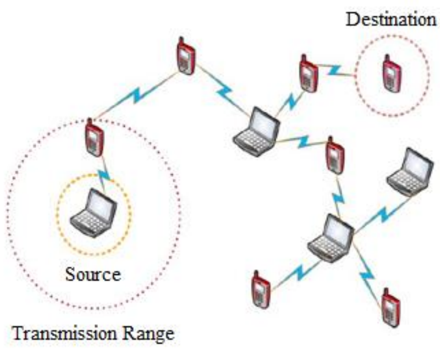

Figure 1: A Mobile Ad hoc Network (MANET) Architecture [3]

Despite this promise, MANETs face critical challenges that hinder their widespread deployment. High computational overhead, energy inefficiency, and limited scalability in dynamic environments are persistent issues [4]. Additionally, fault tolerance and reliable communication remain difficult to achieve in networks with high node mobility. While many innovative routing protocols and energy-efficient solutions have been proposed, these often focus on narrow use cases or fail to

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address the trade-offs between performance, energy consumption, and network adaptability [5]. This gap in addressing scalable, energy-efficient, and robust solutions for diverse real-world applications motivates this literature review. By analyzing recent advances in routing optimization, energy management, and the integration of artificial intelligence with MANETs, this review aims to provide a comprehensive understanding of the current state of the field and identify pathways for future research.

Routing optimization and energy efficiency are pivotal concerns in Mobile Ad Hoc Networks (MANETs) due to the inherent characteristics of these networks [6]. The dynamic and decentralized nature of MANETs presents significant challenges to routing protocols, as node mobility leads to frequent topology changes. These changes require continuous route recalculation and maintenance, which increases routing overhead and delays data transmission [7]. Additionally, achieving low-latency, high-throughput communication becomes increasingly complex in networks with high node mobility and limited resources.

Energy efficiency is equally critical, as most MANET nodes are battery-powered. Prolonged operation in energy-constrained environments necessitates careful management of energy consumption to avoid rapid depletion of node resources [8]. However, many routing protocols prioritize performance metrics such as throughput or reliability, often at the expense of energy efficiency. For instance, protocols that rely on frequent broadcasting or complex algorithms may improve reliability but consume significant amounts of energy [9].

The interdependence between routing and energy efficiency further compounds these challenges. Efficient routing strategies can reduce energy consumption by minimizing retransmissions and optimizing path selection, yet shorter or more energy-efficient paths may suffer from congestion or increased latency [10]. Balancing these trade-offs is particularly challenging in scenarios with high node mobility, such as disaster relief operations or military communications, where both timely delivery and prolonged network availability are critical.

Addressing these challenges requires the integration of advanced techniques such as artificial intelligence, machine learning, and bio-inspired algorithms, which can adapt dynamically to changing network conditions. However, these solutions often involve high computational overhead, creating additional barriers to implementation in resource-constrained environments. This underscores the need for innovative approaches that holistically optimize routing and energy management in MANETs while ensuring scalability and fault tolerance.

2 Related Works

MANETs have been extensively studied, with research primarily addressing challenges related to performance, stability, and efficiency. One early breakthrough in this area was the introduction of the Robust Cooperative Routing Protocol (RCRP) [11]. Designed for mobile wireless sensor networks, RCRP improves energy efficiency by utilizing cooperative relays and selecting robust links to minimize retransmissions. However, as node mobility increases, energy consumption rises, necessitating frequent path updates—a trade-off that subsequent research sought to address. Building on these efforts, [12] incorporated Artificial Immune Systems (AIS) into MANETs for secure routing and fault detection. While AIS effectively detected anomalies, its high computational cost posed a significant drawback. Similarly, [13] proposed a cattle monitoring system using a delay-tolerant store-and-forward architecture to handle high mobility and disconnections, though their findings were limited to data from only two animals. [14] introduced the Quality of Service-enabled Ant Colony-Based Multiple Routing (QAMR) algorithm, which enhanced routing under high-mobility conditions by mimicking ant colony behaviour. Meanwhile, [15] proposed a bacteria noise-based mobility algorithm that optimized sensing but restricted communication to nodes near the highest cost function.

The Power-Efficient Reliable Routing Algorithm (PERRA), proposed by [16], emphasized energy efficiency and reliability, particularly in underwater WSNs (UWSNs). While it extended network lifespan and reduced energy waste by prioritizing power-efficient routes, its design for underwater environments presented challenges when adapted to terrestrial or aerial sensor networks, where dynamic topologies and unpredictable node behaviour may reduce performance.

[17] advanced energy-efficient tracking by using GPS and wireless nodes to monitor cattle movement and network connectivity. Their system, however, evaluated only two metrics, leaving potential for broader applications. [18] furthered energy-saving efforts with the Ant Colony Optimization-based Energy Saving Routing (A-ESR) algorithm, though it faced parameter selection challenges. [19] introduced a hierarchical mobile sensor network inspired by kangaroo behaviour, offering flexible deployment but suffering from reduced efficiency with high node counts. [20] combined Particle Swarm Optimization (PSO) and Genetic Algorithms (GA) for fault-tolerant routing, showcasing resilience to topology changes despite parameter tuning difficulties. [21] introduced the Link-stAbility and Energy-aware Routing (LAER) protocol, balancing link stability and energy consumption to improve scalability, network performance, and lifespan. Bio-inspired algorithms continued to gain traction. [22] merged ACO and GA for multicast routing and QoS optimization, although slow convergence persisted in dynamic settings. [23] integrated AIS and ACO for secure routing, demonstrating reliability in hostile environments at the cost of high computational demands. [24] applied the Artificial Bee Colony (ABC) algorithm for load balancing, but latency issues arose in dense networks. Other significant contributions included blue crab-inspired strategies for mobile sensor networks by [25] and hormone-based protocols for sink node relocation by [26], which balance networks at the cost of additional node expenses. [27] developed the Immune Orthogonal Learning Particle Swarm Optimization algorithm (IOLPSOA), which enabled rapid route recovery but required high computational power.

Recent advances include QoS-based protocols like QSDN-WISE by [28], which improved adaptability using software-defined network architectures, and the Weighted Energy and Temperature-Aware Routing Protocol (WETRP) by [29], which optimized energy and thermal considerations for body sensor networks. Despite progress, challenges such as scalability, fault tolerance, and network delay persist. Newer protocols, such as the Deep

Reinforcement Learning for Energy-Efficient Routing (DRLER) [30] and the Trust-based Secure Routing Protocol (TSRP) [31], focus on optimizing energy consumption and enhancing security. However, issues like computational overhead and scalability remain barriers. The integration of AI and software-defined networking (SDN), explored by [32] and [26], has shown promise in reducing latency and improving resource utilization, although specialized infrastructure requirements and SDN control plane overhead pose challenges that must be addressed to ensure widespread adoption and long-term reliability. Additionally, the integration of these technologies requires careful consideration of interoperability standards and robust error-handling mechanisms to ensure seamless functionality in diverse network environments. A comparison of the studies reviewed is presented in Table 1.

Study	**Approach**	**Group**	**Key contributions**	**Gaps**
[22]	Hybrid ACO-GA	Bio-Inspired	Optimized multicast routing and QoS	Scalability and high node density affect performance, requiring further studies
[23]	Hybrid AIS-ACO	Bio-Inspired	Secure routing in MANETs	High computational overhead
[24]	Artificial Bee Colony (ABC)	Bio-Inspired	Load balancing in MANETs	Latency issues in dense networks
[25]	Blue Crab-Inspired Algorithm	Bio-Inspired	Mobile sensor network optimization	Limited scalability in dynamic networks
[33]	Ant Colony Optimization (ACO)	Bio-Inspired	QAMR algorithm enhanced routing under high mobility conditions	Limited exploration of energy efficiency
[46]	GA and Neural Networks	Bio-Inspired	developing a hybrid technique that leverages the global search capabilities of GAs and the learning abilities of neural networks	The performance of GAs and neural networks is often sensitive to parameter settings, The paper does not give a detailed analysis of how these parameters influence the outcomes.
[30]	Deep Reinforcement Learning (DRL)	AI-Based	DRLER protocol for energy-efficient routing	Computational overhead and scalability remain barriers
[31]	Trust-Based AI Model	AI-Based	TSRP blockchain-integrated trust-based secure routing	Requires specialized infrastructure
[41]	Machine Learning-Based HEGR	AI-Based	Hybrid energy-aware geographic routing	Performance variation with changing node densities
[20]	PSO-GA Hybrid	Heuristic Optimization	Fault-tolerant routing	Sensitive to improper parameter selection
[38]	Butterfly Optimization + ACO	Heuristic Optimization	Cluster head selection for WSN	Computational overhead
[43]	Hybrid Optimization	Heuristic Optimization	Dynamic cluster head selection	Struggles with scalability in high mobility scenarios
[21]	LAER	Network-Based	Link-stability and energy-aware routing	Parameter tuning complexity
[26]	Hormone-Based Protocol	Network-Based	Sink node relocation	High node expenses
[44]	Zero-Knowledge Proof (ZKP)	Network-Based	Privacy-preserving route discovery	Scalability issues in high-mobility settings
[51]	DTN (Delay Tolerant Networks)	Network-Based	Hybrid Routing Flexibility .	High Overhead Ratio as Increased message replication leads to a higher overhead, which may be problematic for energy-constrained devices.
[52]	Adaptive Congestion and Energy Aware Multipath	Network-Based	Adaptive feedback for congestion	The study does not extensively discuss ACEAMR's performs in larger networks. Scalability

	Routing Scheme (ACEAMR) to enhance Quality of Service (QoS)		detection and the incorporation of a fitness function for energy-aware routing.	is crucial for practical applications, and future research should evaluate ACEAMR's performance in more extensive network scenarios.
[48]	An enhancement to the Ad-hoc On-Demand Distance Vector (AODV) routing protocol, termed F_AODV+	Network-Based	Incorporates factors such as node energy, path queue length, and a "frozen factor" to improve gateway discovery and selection	The term 'frozen factor' is introduced as a key component of the proposed algorithm. However, the article lacks a clear definition and explanation of this term. Providing a detailed description and rationale for its inclusion would enhance understanding and reproducibility.
[49]	Distributed nonconvex optimization for energy efficiency in mobile ad hoc networks.	Network-Based	The proposed model addresses the complexity of nonconvex optimization problems and offers a solution to reduce computational overhead.	The study is heavily theoretical, with limited experimental validation, making it difficult to assess the feasibility of the approach in practical MANET environments.
[42]	Energy saving optimization technique-based routing protocol in mobile ad-hoc networks	Network-Based	introduces an optimized routing protocol with extensive performance analysis, demonstrating improvements in energy conservation	The study does not sufficiently address the impact of node mobility and network density on its proposed solution, raising concerns about scalability in real-world applications.

The studies reviewed underscore the ongoing efforts to develop adaptive solutions that address the unique challenges of MANETs, focusing on enhancing energy efficiency, scalability, optimizing routing protocols, and ensuring fault tolerance. However, their performance varies significantly depending on environmental conditions and network scenarios.

3 Conclusion

Overall, while the studies presented show significant advancements in optimizing MANETs for energy efficiency, scalability, and security, they also underscore the persistent challenges such as high computational overhead, scalability in dynamic environments, and limitations in mobile or complex scenarios.

The reviewed studies demonstrate that AI-based routing, bio-inspired optimization, and heuristic approaches have made significant advancements in improving energy efficiency and network performance in MANETs. Among these, AI-based methods such as deep reinforcement learning (DRL) and trust-based models show the most promise in dynamically adapting to network conditions and optimizing resource utilization. However, high computational costs and scalability remain key challenges. While bio-inspired algorithms have shown promise in extending network lifetime, their effectiveness decreases in highly mobile scenarios.

4 Direction for future work

Future research should focus on developing lightweight AI implementations, integrating edge computing, optimizing across network layers, improving scalability through hierarchical routing, and enhancing security with resource-efficient protocols. Success will depend on balancing performance requirements with energy efficiency and resource constraints, particularly through practical implementations like pruned neural networks and distributed learning approaches as the future of MANETs lies in continued innovation and the integration of emerging technologies.

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