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Trust-Aware Energy Optimization Techniques in Mobile Ad-hoc Networks: Current Trends and Future Directions

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Abstract: This systematic review paper provides a comprehensive analysis of recent advancements in energy optimization techniques for Mobile Ad-hoc Networks (MANETs). MANETs play a critical role in modern communication systems, enabling dynamic and decentralized networking in various applications, including disaster recovery, military operations, and remote sensing. However, energy consumption remains a significant challenge due to the limited power resources of mobile nodes, directly impacting network performance and lifespan. In recent years, optimization techniques such as metaheuristic algorithms, adaptive transmission power control, and machine learning models have shown remarkable potential in addressing these challenges by enhancing energy efficiency and prolonging network lifetime. This paper reviews the current trends in energy optimization for MANETs, including trust-aware routing protocols, clustering methods, and advanced mobility models like the Gauss-Markov model. Additionally, it provides a detailed analysis of the simulation parameters and metrics used in the studies, highlighting their applicability and limitations. The review also identifies key areas for future research, such as developing lightweight and scalable algorithms, integrating heterogeneous network technologies, and refining mobility and traffic models for more realistic simulations. The paper concludes by summarizing the key findings of the systematic review and emphasizing the importance of continuous innovation in energy optimization strategies to enhance the sustainability and reliability of MANETs. This review serves as a valuable resource for researchers and practitioners, guiding the development of robust and efficient networking solutions.

Keywords: Mobile Ad-hoc Networks, Energy optimization, Metaheuristic algorithms, Transmission power control, Trust-aware routing algorithm, Adaptive algorithms, Dynamic Source Routing Protocol

Introduction

Mobile Ad-hoc Networks (MANETs) are dynamic, self-configuring networks composed of mobile nodes that communicate wirelessly without the need for a fixed infrastructure. These networks are highly versatile, making them suitable for various critical applications, such as disaster relief operations, military communications, and sensor networks, where traditional network infrastructure may not be feasible or reliable [1]. However, the decentralized and dynamic nature of MANETs poses significant challenges, particularly in terms of energy consumption, security, and node reliability. As nodes in MANETs are typically battery-powered and move frequently, maintaining efficient communication while ensuring the longevity of the network is a key concern. Additionally, ensuring the security and trustworthiness of nodes is crucial to prevent malicious attacks or unreliable behavior, which could compromise the overall performance of the network [2]. A routing protocol specifies how routers communicate with each other to distribute information that enables them to select routes between nodes on a computer network.

In MANET, routing protocols are classified into three types: Proactive (Table-driven), Reactive (On-demand) and Hybrid routing protocol [3]. When a route is needed, a procedure is called to find a route to the destination node. The major goal of on demand protocols is to minimize the network traffic overhead. Examples of reactive protocols include the Dynamic Source Routing Protocol (DSR), Ad Hoc On-Demand Distance Vector Routing Protocol (AODV), Dynamic MANET on-Demand (DYMO) and Temporally-Ordered Routing Algorithm (TORA) [4].

Dynamic Source Routing (DSR) is one of the most widely used reactive routing protocols. With most other reactive routing protocols, has two basic mechanisms for its operation; route discovery and route maintenance [5]. The selection of a path is the source's responsibility. It does so by initiating a request packet and sending it to its neighbour's. The packet header will contain the information of all intermediate nodes or hops in the route until the destination is reached. The route that was recently discovered will be stored in the cache route of the node [6]. This protocol has limitations such as high in Packet Loss, low in Packet Delivery Ratio, high in Transmission Count or Routing Overhead and low in Throughput [7].

Energy efficiency is one of the primary challenges in MANETs due to the limited power resources of mobile nodes. Existing routing algorithms often fail to address the energy demands effectively, leading to premature node failures and reduced network lifespan. In high-demand scenarios where nodes are constantly transmitting and receiving data, the need for more energy-efficient routing algorithms becomes apparent. Traditional algorithms may not fully consider energy optimization in their routing decisions, resulting in faster depletion of node batteries and, consequently, network fragmentation [8, 9].

In addition to energy concerns, the reliability of nodes in a MANET is another critical factor. As the network lacks a central authority, it relies heavily on the cooperation of individual nodes for data transmission. Thus, the absence of trust mechanisms can lead to vulnerabilities, such as malicious nodes misbehaving or unreliable nodes disrupting communication. Ensuring that only trusted nodes are involved in routing decisions is essential for enhancing the network's security and overall performance [10]. Existing routing algorithms often lack robust mechanisms to evaluate node trustworthiness, which can leave the network exposed to attacks or failures.

Node failure is another challenge that impacts the stability and robustness of MANETs. Nodes in such networks are susceptible to various failures, including battery depletion, hardware malfunctions, or network partitioning due to mobility. When nodes fail, data transmission can be interrupted, leading to reduced packet delivery and an overall decline in network performance. Incorporating mechanisms to detect node failures and recover from them is essential to ensure continuous data transmission and prevent network disruptions. Hence, for this survey, we develop the following research questions:

i. How can energy consumption be optimized in Mobile Ad-hoc Networks (MANETs) to prolong network lifetime and enhance efficiency?
ii. What are the limitations of existing energy-efficient routing algorithms, such as those integrating the Cuckoo Search Algorithm (CSA), with Dynamic Source Routing (DSR), in terms of trust-aware routing and node failure recovery?
iii. How can trust metrics be effectively incorporated into routing algorithms to ensure secure and reliable communication within MANETs?
iv. What mechanisms can be developed to enable node failure recovery in MANETs to maintain continuous packet delivery and improve network robustness?

The key contributions of this systematic review can be summarized as follows:

1. First, the review provides a comprehensive survey of recent advancements in routing algorithms aimed at improving energy efficiency, trust-aware communication, and node failure recovery in Mobile Ad-hoc Networks (MANETs).
2. By synthesizing a wide range of literature, including journal articles, conference papers, and technical reports, the study offers a detailed overview of the current state of research. It highlights the progression of energy-efficient algorithms while emphasizing the importance of integrating trust metrics and fault-tolerant mechanisms to enhance overall network performance.
3. The study also identifies and analyzes critical challenges within existing MANET routing approaches. It brings attention to limitations such as the insufficient integration of trust-aware routing, the absence of robust mechanisms for detecting and recovering from node failures, and the inherent difficulties in achieving a balance between energy efficiency and secure communication. By addressing these gaps, the review provides valuable insights for researchers, outlining key areas that demand further investigation.
4. Additionally, this manuscript critically evaluates and compares the performance of various routing algorithms based on widely recognized benchmarks. Metrics such as energy efficiency, packet delivery ratio, trust management, and fault tolerance are analyzed to provide a nuanced understanding of the strengths and weaknesses of these algorithms. This analysis equips researchers and practitioners with the information needed to make informed decisions when designing or implementing routing solutions for MANETs.

The review concludes by proposing future research directions and potential solutions to bridge the identified gaps. It highlights the need for innovative frameworks that integrate trust metrics and fault recovery mechanisms into energy-efficient routing solutions. These recommendations aim to inspire the development of robust, secure, and efficient routing algorithms capable of addressing the internal and external challenges faced by MANETs.

The remainder of this study is structured to ensure a logical progression of ideas. The systematic literature review process, including the search strategy, inclusion criteria, and synthesis approach, is detailed in Section 2. Section 3 provides an overview of MANETs and their associated challenges, particularly in achieving energy efficiency, trust-aware communication, and fault tolerance. Section 4 energy efficiency in MANET, and Section 5 summarizes the key findings of the review. Finally, Section 6 concludes the study and outlines directions for future research.

Materials and Methods

To ensure the review comprehensively addresses the topic of the study, a systematic and structured methodology was adopted. This section details the processes and procedures followed to conduct the systematic literature review on advancements in routing algorithms for Mobile Ad-hoc Networks (MANETs), with a focus on energy efficiency, trust-aware communication, and node failure recovery. The methodology emphasizes the importance of adhering to established protocols for systematic literature reviews to ensure rigor and reproducibility.

Key elements of the methodology include discussions on the search strategies employed, the formulation of search terms, and the identification of relevant data sources. These components were carefully designed to capture a broad yet focused range of studies related to MANET routing challenges and solutions. Established guidelines for conducting systematic literature reviews in computer science [11], as outlined in prior works, provided the foundational framework for this study. By following these established protocols, the review ensures a comprehensive and unbiased synthesis of the existing body of knowledge. This approach not only validates the findings of the study but also provides a robust foundation for identifying research gaps and proposing future directions.

Search method

The search method employed in this study was designed to ensure adherence to established guidelines for systematic literature reviews and to comprehensively capture relevant research. The digital libraries IEEE Xplore, ScienceDirect, and Scopus were selected as primary sources due to their extensive repositories of high-quality and peer-reviewed studies. These platforms were instrumental in gathering literature on advanced routing algorithms for Mobile Ad-hoc Networks (MANETs), particularly those focused on energy efficiency, trust-aware communication, and node failure recovery mechanisms.

The search process was guided by clearly defined terms and methods, ensuring a targeted yet comprehensive exploration of the topic. Search terms were carefully formulated to encompass the critical aspects of the study, including energy-efficient routing, trust metrics, and fault-tolerant mechanisms. These terms were iteratively refined to maximize relevance and inclusivity while minimizing irrelevant results. The databases selected provided a wide range of articles, conference proceedings, and technical reports essential for achieving the study's objectives. This structured approach to the search process ensured that the review captured a holistic view of the current state of research while maintaining the methodological rigor required for systematic literature reviews. By utilizing these digital libraries and adhering to clearly defined search strategies, the study lays a solid foundation for synthesizing existing knowledge and identifying areas requiring further investigation.

Searching the articles

The article search was conducted in multiple phases, starting on April 15, 2024, and concluding on November 30, 2024, resulting in a total of 409 articles. Unrelated articles were excluded, and the search was restricted to publications from 2020 to 2024 to ensure relevance and currency. This systematic approach provided a focused and comprehensive foundation for the literature review.

Scholarly repositories

The scholarly repositories utilized for this study are summarized in Table 1, which lists the databases explored to gather relevant literature. These repositories were carefully selected to ensure access to high-quality, peer-reviewed articles that align with the study's focus.

Table 1: Scholarly repositories used and their links

Scholarly Repositories	Web links
Scopus	https://www.scopus.com/
IEEE Xplore	https://ieeexplore.ieee.org/
ScienceDirect	https://www.sciencedirect.com/

Overview of mobile ad-hoc networks (MANETs)

Mobile Ad-hoc Networks (MANETs) are a class of wireless networks characterized by their self-configuring, dynamic nature [12]. Unlike traditional networks that rely on a fixed infrastructure, MANETs consist of mobile nodes that communicate directly with one another. This unique architecture allows for flexible networking in scenarios where establishing physical connections is impractical, such as disaster recovery, military operations, and remote area communication [9].

Mobile Ad-hoc Networks (MANETs) represent a significant evolution in networking technologies, characterized by their ability to self-organize and operate without fixed infrastructure. These networks consist of mobile nodes that communicate wirelessly, forming a dynamic network topology that can change frequently due to node mobility and varying connection conditions [13]. The decentralized nature of MANETs makes them particularly suitable for applications in emergency response, military operations, and remote area communications, where traditional network infrastructure may be unavailable [14].

In a MANET, each node acts as both a host and a router, enabling it to transmit data to other nodes without the need for centralized management. This decentralization provides several advantages, including rapid deployment, scalability, and resilience against node failures. However, the mobile nature of the nodes presents significant challenges, such as variable connectivity, changing network topologies, and limited bandwidth. As nodes move, the network can become fragmented, leading to difficulties in maintaining consistent communication links [15]. The performance of MANETs relies heavily on efficient routing protocols, which are designed to facilitate communication by determining optimal paths for data transmission. These protocols must adapt to the dynamic nature of the network, accounting for factors such as node mobility, battery power, and network congestion. Various routing strategies have been developed, ranging from proactive approaches that maintain up-to-date routing information to reactive methods that establish routes on-demand [16].

The importance of MANETs has grown significantly in recent years due to their applicability in various real-world scenarios. As mobile devices become increasingly ubiquitous, the demand for flexible and reliable communication solutions has intensified. Research in MANETs continues to evolve, addressing challenges related to energy efficiency, security, and quality of service, ensuring their viability for future applications [17].
Routing protocols in MANETs are critical for facilitating communication among nodes, given the inherent challenges of variable topology and limited resources. They can be broadly classified into three categories: proactive, reactive, and hybrid protocols. Proactive protocols maintain up-to-date routing information regardless of traffic, while reactive protocols discover routes on-demand [4]. Hybrid protocols combine elements of both approaches to optimize performance under varying network conditions [18]. The choice of routing protocol significantly impacts the network's efficiency, scalability, and reliability.
Energy efficiency is a crucial concern in MANETs due to the reliance on battery-powered devices. The depletion of energy resources can lead to node failures, which adversely affects network performance [8]. As a result, many energy-efficient routing algorithms have been developed to minimize energy consumption while maintaining effective communication. For instance, the Energy-Aware Routing Protocol (EARP) dynamically adjusts the routing paths based on the energy levels of nodes, ensuring that messages are routed through nodes with sufficient energy reserves [19]. These approaches are vital for prolonging the operational lifespan of MANETs.
In addition to energy efficiency, trust management has emerged as a critical factor in ensuring secure and reliable communication in MANETs. The decentralized nature of these networks makes them susceptible to malicious nodesS that can disrupt communication or compromise data integrity [10]. Trust models play a fundamental role in assessing the reliability of nodes based on their behavior and interactions within the network. Recent studies have proposed various trust-based routing protocols that incorporate trust metrics to evaluate the trustworthiness of nodes, enhancing the overall security of MANETs. For example, the Trust-Based Secure Routing Protocol (TBSRP) utilizes historical data to compute trust scores, enabling nodes to make informed decisions when selecting routing paths [20].
Furthermore, the ability to detect node failures and recover from them is essential for maintaining network stability. Various mechanisms have been proposed to monitor node health and provide failover solutions in the event of a failure [21]. These mechanisms ensure that the network can adapt to changing conditions, minimizing the impact of node mobility and failures on overall performance.

Types of mobile ad-hoc networks (MANETs)
Mobile Ad-hoc Networks (MANETs) can be classified into several types based on various criteria, including their operational environments, applications, and protocols [22]. And this includes:

i. **Homogeneous MANETs:** In homogeneous MANETs, all nodes have similar capabilities, including processing power, energy resources, and communication ranges. This uniformity simplifies routing and network management, making it easier to implement algorithms and protocols across all nodes [23].
ii. **Heterogeneous MANETs:** Heterogeneous MANETs consist of nodes with varying capabilities and resources. This may include different hardware specifications, energy levels, and communication ranges. The diversity in node capabilities can enhance network resilience and performance but complicates routing and resource management [1].
iii. **Mobile sensor networks:** This type of MANET involves a collection of sensor nodes that gather environmental data and communicate wirelessly. Mobile sensor networks are often used in applications such as environmental monitoring, disaster management, and military surveillance. The mobility of sensor nodes adds complexity to data collection and routing [24].
iv. **Vehicular ad-hoc networks (VANETs):** VANETs are a specialized form of MANETs designed for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication. These networks enhance road safety, improve traffic management, and provide information services to drivers. The high mobility of vehicles poses unique challenges for routing and data transmission [25].
v. **Mobile mesh networks:** Mobile mesh networks consist of interconnected nodes that form a mesh topology. Each node can relay data for others, creating multiple paths for communication. This redundancy enhances reliability and can improve overall network performance, especially in dynamic environments [26].
vi. **Disaster recovery networks:** These MANETs are deployed in emergency situations, such as natural disasters, where traditional infrastructure is compromised. They enable first responders to communicate effectively in real time, facilitating coordination and resource allocation during crisis situations [27].
vii. **Military ad-hoc networks:** Military applications utilize MANETs for secure and robust communication in tactical operations. These networks must operate in challenging conditions, including variable terrain and dynamic threats, necessitating specialized routing protocols that prioritize security and reliability [1].
viii. **Community networks:** Community-based MANETs are established to provide connectivity in areas lacking traditional infrastructure. These networks often rely on local users to maintain and operate the network, promoting community engagement and self-sufficiency [1].

Importance of MANETs in modern communication

Mobile Ad-hoc Networks (MANETs) play a pivotal role in modern communication, addressing the need for flexible, reliable, and decentralized networking solutions [1]. This includes:

i. **Rapid deployment:** MANETs can be quickly established in areas lacking existing infrastructure, making them ideal for emergency situations, disaster recovery, and military operations. Their ability to form networks on-the-fly enables immediate communication, which is crucial in crisis management.
ii. **Flexibility and Scalability:** The self-configuring nature of MANETs allows them to adapt to changing conditions and varying numbers of nodes. This flexibility ensures that networks can grow or shrink as needed, accommodating fluctuating user demands and mobility patterns without requiring significant reconfiguration.
iii. **Cost-effectiveness:** By eliminating the need for fixed infrastructure, MANETs can significantly reduce deployment and operational costs. This aspect is particularly beneficial in rural or underserved areas where traditional networking solutions may be prohibitively expensive.
iv. **Support for mobile applications:** As mobile devices become ubiquitous, MANETs facilitate seamless communication among these devices. This support is vital for applications such as mobile gaming, social networking, and real-time data sharing, enhancing user experiences in various contexts.
v. **Enhanced connectivity:** MANETs provide connectivity in challenging environments where conventional networks struggle, such as remote locations, disaster zones, and densely populated urban areas. They can maintain communication links even when traditional infrastructure is compromised.
vi. **Improved network resilience:** The decentralized nature of MANETs enhances their resilience against failures. If one node fails or moves out of range, data can still be routed through alternative paths, ensuring continuous communication and reducing the likelihood of network disruption.
vii. **Support for emerging technologies:** MANETs are crucial for the development and deployment of emerging technologies, such as the Internet of Things (IoT) and smart city applications. They enable communication among diverse devices, facilitating data collection, sharing, and analysis in real time.

Routing protocols in MANET

Routing protocols in Mobile Ad-hoc Networks (MANETs) are designed to establish and maintain efficient communication paths between mobile nodes in a decentralized network, where each node can act as both a source and a relay [3]. Due to the highly dynamic and distributed nature of MANETs, routing protocols are essential for managing node mobility, handling limited resources, and ensuring reliable data transmission under constantly changing network topologies. Unlike traditional networks, which rely on fixed infrastructure, MANET routing protocols must adapt to frequent topology changes, manage power constraints, and address security challenges unique to ad hoc networks [7]. Routing protocols in MANETs can broadly be classified into three main categories which include Proactive (Table-Driven) Protocols, Reactive (On-Demand) Protocols, and Hybrid Protocols [3].

i. **Proactive (Table-driven) protocols**: These protocols maintain up-to-date routing information between all nodes in the network by periodically updating routing tables, regardless of the need for data transmission. Common examples include the Destination-Sequenced Distance-Vector (DSDV) and Optimized Link State Routing (OLSR) protocols. Proactive protocols are beneficial in terms of low latency for data transmission since routes are pre-established; however, they consume significant bandwidth and power due to regular updates, which may lead to inefficiencies in highly dynamic environments where topology changes frequently. Proactive protocols are generally better suited to small or medium-sized networks with relatively stable node positions [29].
ii. **Reactive (On-demand) protocols**: In contrast, reactive protocols discover routes only when required by initiating a route discovery process. When a source node needs to transmit data to a destination node, it broadcasts a route request throughout the network. Protocols such as Ad hoc On-Demand Distance Vector (AODV) and Dynamic Source Routing (DSR) fall under this category. Reactive protocols tend to conserve bandwidth and energy, as routes are created only when data transmission is necessary, which is advantageous in dynamic and large-scale networks. However, this approach introduces latency due to the time required for route discovery, which can delay data transmission [30].
iii. **Hybrid protocols**: Hybrid protocols combine the characteristics of both proactive and reactive protocols to optimize routing efficiency in MANETs. For example, the Zone Routing Protocol (ZRP) uses a proactive approach within a local zone around each node and a reactive approach for nodes outside the zone. This reduces the overhead of continuous updates while providing the benefit of immediate route availability within a node’s zone. Hybrid protocols are particularly advantageous in large networks with diverse mobility patterns, where the flexibility of both proactive and reactive strategies can be leveraged to balance overhead and latency [30].

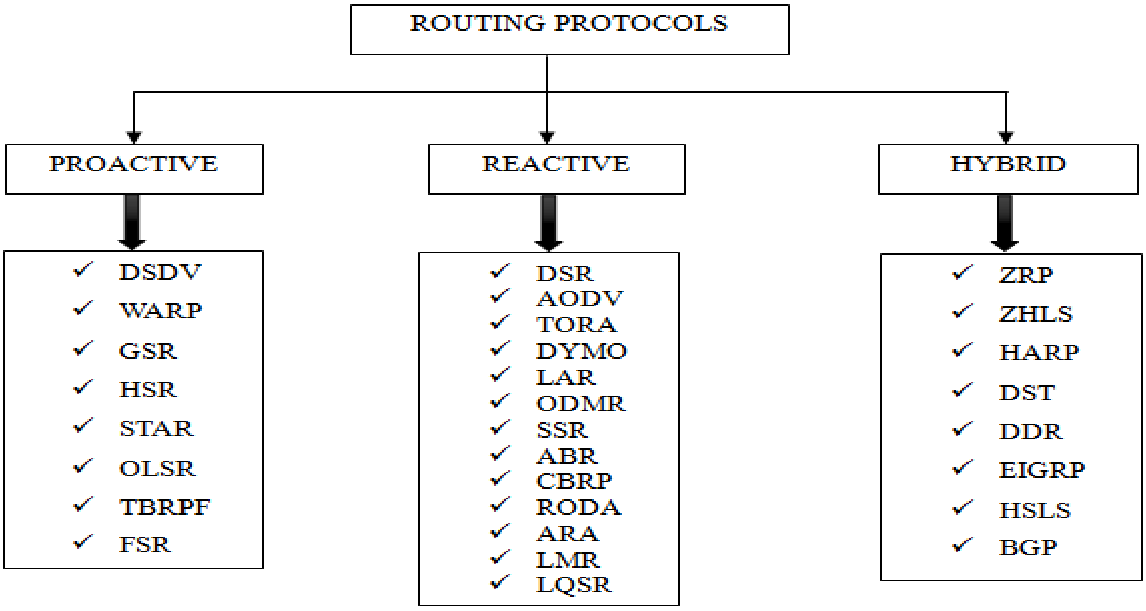

Figure 1: Classification of routing protocols for MANET [16]

Table 2: Comparison of routing protocols

Features	Proactive	Reactive	Hybrid
Bandwidth Requirement	High	Low	Medium
Structure	Flat/Hierarchical	Flat	Hierarchical
Power Consumption	High	Low	Medium
Storage Requirement	High	Low	Medium
Route Acquisition	Table-Driven	On-Demand	Both
Mobility	Periodic updates	Route maintenance	Both
Scalability	Low	Not For large network	For large networks
Routing Overhead	High	Low	Medium

Each of these types of routing protocols addresses specific challenges of MANETs and is chosen based on the network's unique characteristics, including size, node density, mobility rate, and energy constraints.

In addition to these traditional protocols, recent advances have introduced specialized routing protocols that incorporate QoS (Quality of Service) parameters, energy-efficient strategies, and trust-based routing to tackle the challenges posed by modern applications, particularly in resource-constrained and security-sensitive environments.

Limitations of DSR in MANET

A primary limitation of the Dynamic Source Routing (DSR) protocol is that its route maintenance mechanism lacks a local repair feature for broken links. This means that when a link breaks, the protocol requires a full route re-discovery instead of simply repairing the link locally, leading to increased latency. Additionally, DSR tends to have longer connection setup delays compared to table-driven protocols, which is especially noticeable in dynamic environments with frequent topology changes. While the protocol performs effectively in static or low-mobility scenarios, its performance declines significantly as mobility increases, largely because higher mobility leads to frequent route breakages that DSR does not handle efficiently.

Furthermore, the source-routing mechanism in DSR introduces substantial routing overhead, which grows with the length of the route. As each packet includes the complete source route, the header size increases with longer paths; leading to higher bandwidth consumption and decreased efficiency, especially in networks with numerous nodes or high levels of mobility. This routing overhead can contribute to packet collisions and congestion, impacting overall network performance, particularly in large or highly mobile networks.

Nature-inspired algorithms

Nature-inspired algorithms are optimization techniques and computational models that mimic processes and behaviors observed in the natural world. These algorithms draw inspiration from biological evolution, animal behaviors, physical laws, and ecological systems to solve complex problems that traditional methods find challenging. The primary advantage of nature-inspired algorithms lies in their adaptability, robustness, and efficiency, making them highly suitable for a wide range of optimization problems across disciplines, including engineering, data science, artificial intelligence, and network design [31].

Nature-inspired algorithms can be broadly categorized into several types based on the natural phenomena they emulate. Evolutionary Algorithms (EAs) are among the earliest and most established nature-inspired methods. These algorithms, including Genetic Algorithms (GA) and Differential Evolution (DE), are inspired by the process of natural selection, where a population of candidate solutions evolves over generations to optimize a given objective. In a GA, for example, each candidate solution is represented as a "chromosome" that undergoes genetic operations like selection, crossover, and mutation. Through these operations, the population evolves towards an optimal solution, allowing GAs to solve complex optimization problems, especially those with vast search spaces [31].

Agushaka *et al.* proposed a novel metaheuristic algorithm named the Dwarf Mongoose Optimization (DMO) Algorithm, designed to solve classical and CEC 2020 benchmark functions as well as 12 continuous/discrete engineering optimization problems [32]. The algorithm is inspired by the foraging behavior of dwarf mongooses and incorporates their unique social and ecological adaptations to optimize computational processes effectively. The DMO algorithm simulates the mongoose's restrictive prey capture strategies, which have shaped its social behaviors and ecological adaptations to maintain efficient family nutrition. These adaptations include considerations of prey size, space utilization, group size, and food provisioning.

Swarm Intelligence (SI) Algorithms are another prominent category, inspired by the collective behaviors of social animals, such as ant colonies, bee swarms, and bird flocks. In SI algorithms, simple agents interact with each other and their environment to perform complex tasks without central control. For instance, the Ant Colony Optimization (ACO) algorithm mimics the pheromone-laying behavior of ants to find the shortest path between food sources and their nest. Similarly, Particle Swarm Optimization (PSO) simulates the behavior of birds flocking to optimize a solution by adjusting individual particle positions based on their experiences and those of their neighbors. SI algorithms are highly effective for distributed problem-solving, where multiple agents can contribute to finding an optimal solution through collective intelligence [31].

Physics-Inspired Algorithms are motivated by natural physical processes and phenomena. Examples include Simulated Annealing (SA), which is based on the annealing process in metallurgy, where a material is heated and then slowly cooled to reduce defects and find a stable structure. In SA, candidate solutions move through a "cooling" process that gradually reduces the probability of accepting worse solutions, allowing the algorithm to escape local optima and move toward a global solution. Other physics-inspired algorithms, such as Gravitational Search Algorithms (GSA), draw from gravitational force principles, where particles with higher masses attract others, leading to a convergence towards an optimal solution [24].

Another category of nature-inspired algorithms is Ecosystem-Based Algorithms, which simulate interactions among species within ecosystems. These algorithms, such as the Artificial Bee Colony (ABC) and Cuckoo Search (CS), leverage ecological principles like competition, cooperation, and symbiosis [15]. In the ABC algorithm, for instance, artificial bees represent candidate solutions that explore the search space through behaviors similar to foraging and resource sharing, effectively balancing exploration and exploitation in the optimization process. Similarly, Cuckoo Search is inspired by the brood parasitism behavior of cuckoo birds, utilizing "nesting" strategies to locate optimal solutions within a search space [34]. Intelligence metaheuristics algorithms, like the DMOA, are widely valued in applications requiring efficient, decentralized decision-making, such as network routing in MANETs, where each node can adjust its route dynamically based on shared information from other nodes. This makes DMOA highly relevant in scenarios that require energy-efficient and trust-aware routing protocols, where collective intelligence and adaptive strategies are essential for optimal performance.

More recently, Hybrid and Adaptive Nature-Inspired Algorithms have emerged, combining features of multiple algorithms or adjusting parameters dynamically based on the problem's needs. These algorithms can achieve higher levels of flexibility and accuracy, especially when applied to real-world problems with changing conditions or complex, multi-objective functions [35]. For instance, the Hybrid Genetic-Simulated Annealing (HGSA) algorithm combines elements of GAs and SA, using genetic evolution to explore the solution space broadly while leveraging annealing to refine solutions locally [36].

The increasing popularity of nature-inspired algorithms is largely due to their versatility and effectiveness across numerous domains. In fields such as robotics, telecommunications, bioinformatics, and network routing, these algorithms have proven capable of handling nonlinear, high-dimensional, and dynamic problems. For example, in network design, algorithms like ACO and PSO are used to develop energy-efficient and trust-aware routing protocols in mobile ad hoc networks (MANETs), enhancing both performance and reliability. Similarly, nature-inspired algorithms are widely used in machine learning for feature selection, parameter optimization, and model training, where they help optimize complex models by balancing exploration of the search space with exploitation of promising solutions [36].

Nature-inspired algorithms represent a dynamic and rapidly evolving area of computational intelligence, offering an array of methods that draw on biological, physical, and ecological principles. Their ability to adapt, learn, and find near-optimal solutions in complex, uncertain, and changing environments makes them invaluable tools in modern problem-solving. As computational power continues to advance and new hybrid approaches emerge, the scope and capability of nature-inspired algorithms are expected to expand, providing even more sophisticated solutions to increasingly complex global challenges.

Limitations of nature-inspired optimization algorithms

Nature inspired algorithms have the following limitations:

i. They still lack a unified mathematical framework to analyze these algorithms. So, they lack in-depth understanding how such algorithms may converge and how quickly they can converge.

ii. There are many different algorithms and their comparison studies are mainly based on numerical experiments, and it is difficult to justify if such comparison is always fair.
iii. Most of the applications in the literature concern small-scale problems, and it is not clear if such approaches can be directly applied to large-scale problems.

Finally, it is not clear what are the conditions for the emergence of swarming and intelligence behaviour, even though the term ‘swarm intelligence is used widely [36].

1. Energy efficiency and trust management in MANET

In addition to energy efficiency, trust management has emerged as a critical factor in ensuring secure and reliable communication in MANETs. The decentralized nature of these networks makes them susceptible to malicious nodes that can disrupt communication or compromise data integrity. Trust models play a fundamental role in assessing the reliability of nodes based on their behavior and interactions within the network. Recent studies have proposed various trust-based routing protocols that incorporate trust metrics to evaluate the trustworthiness of nodes, enhancing the overall security of MANETs. For example, the Trust-Based Secure Routing Protocol (TBSRP) utilizes historical data to compute trust scores, enabling nodes to make informed decisions when selecting routing paths.

Research Question One: How can energy consumption be optimized in Mobile Ad-hoc Networks (MANETs) to prolong network lifetime and enhance efficiency?

Gulić and Žuškin addressed energy efficiency and security in MANETs, particularly vulnerabilities from limited energy resources and black hole attacks (BHAs). Introduced the Trust-Based Energy Aware Routing (TEAR) mechanism, which uses multiple detection routes to identify and mitigate BHAs, enhance trust-based data routing, and optimize energy consumption. Results showed improved network lifespan, reliability, and data transmission rates compared to earlier methods [37].

Adeyelu *et al.* proposed a hybrid routing algorithm combining the Cuckoo Search Algorithm (CSA) with Dynamic Source Routing (DSR) to optimize energy consumption in MANETs [9]. The approach improved energy efficiency, packet delivery, throughput, and reduced packet loss, demonstrating superior performance over traditional methods. This strategy effectively balanced energy use among nodes, extending network longevity.

Purushothaman *et al.* developed a Fuzzy C-Means Clustering-based Energy-Efficient Protected Optimal Path-Routing Protocol to optimize routing performance and enhance security in MANETs [38]. The protocol integrates advanced AES encryption and HMAC for secure key management. It achieved a 97% routing performance rate, outperforming established protocols, and demonstrated improved energy management and data security for MANETs.

Research Question Two: What are the limitations of existing energy-efficient routing algorithms, such as those integrating the Cuckoo Search Algorithm (CSA), with Dynamic Source Routing (DSR), in terms of trust-aware routing and node failure recovery?

Previous research conducted by Adeyelu *et al.* addressed the challenge of optimizing energy consumption in Mobile Ad-hoc Networks (MANETs) by introducing a novel approach that integrates an energy-efficient routing algorithm with the Cuckoo Search Algorithm (CSA) [9]. Also, Agor *et al.* proposed the Power-aware Intelligent Water Drops Routing Algorithm (PIWDRA) to address routing challenges in Mobile Ad hoc Networks (MANETs), by prioritizes energy efficiency by selecting paths based on a cost function that considers energy consumption, hop count, and time delay [35]. These approaches have demonstrated superior performance in terms of energy efficiency, packet delivery ratio, throughput, and maintaining energy balance across network nodes.

However, despite these advancements of the existing studies, the researchers, have largely overlooked critical aspects such as trust-aware routing and node failure recovery. Traditional energy-efficient routing algorithms do not account for the trustworthiness of nodes, which is essential for ensuring secure and reliable communication within MANETs. Moreover, the ability of nodes to recover from failures and continue packet delivery has not been adequately addressed, leaving networks vulnerable to disruptions and decreased performance in the event of node failures. Hence in order to bridge these gaps, there is a need to develop a comprehensive routing algorithm that not only optimizes energy consumption but also incorporates trust metrics to evaluate node reliability and mechanisms for node failure recovery to ensure continuous packet delivery.

Research Question three: How can trust metrics be effectively incorporated into routing algorithms to ensure secure and reliable communication within MANETs?

Incorporating trust metrics into routing algorithms for MANETs requires a robust framework to ensure secure and reliable communication. Trust metrics can be dynamically evaluated based on node behaviors such as packet forwarding reliability, response time, and cooperation history, offering a comprehensive assessment of node reliability. These metrics should be updated in real time to adapt to changing network conditions, with nodes below trust thresholds excluded from routing paths. The Dwarf Mongoose algorithm, known for its lightweight and adaptive capabilities, can be integrated to enhance trust-based routing by optimizing route selection through trustweighted metrics. By leveraging its ability to balance exploration and exploitation, the algorithm can identify energy-efficient and secure paths, minimizing reliance on potentially malicious nodes while maintaining network efficiency.

The Dwarf Mongoose algorithm also aids in detecting and isolating malicious nodes, such as those involved in black hole or grey hole attacks, by continuously refining trust assessments during the routing process. When combined with multi-path routing strategies, it enables the identification of inconsistencies caused by untrustworthy nodes, securing data transmission routes. Direct trust evaluations, based on firsthand interactions, and indirect trust derived from recommendations are further enhanced through the algorithm's adaptive nature. By integrating cryptographic techniques to safeguard the trust evaluation process, and optimizing trust-based routing across layers, MANETs can achieve enhanced resilience, energy efficiency, and security. Extensive simulations demonstrate that incorporating the Dwarf Mongoose algorithm into trust-aware routing significantly improves packet delivery ratios, reduces energy consumption, and ensures robust defense against adversarial activities.

Research question four: What mechanisms can be developed to enable node failure recovery in MANETs to maintain continuous packet delivery and improve network robustness?

To enable node failure recovery in MANETs and maintain continuous packet delivery, dynamic fault-tolerant routing protocols and adaptive mechanisms are essential. Proactive monitoring systems can detect node failures using metrics like energy levels and packet loss, while rerouting mechanisms ensure traffic is redirected to alternative paths in real time. The Dwarf Mongoose algorithm enhances this process by dynamically identifying reliable and energy-efficient backup routes, minimizing disruptions.

Additional strategies like data replication and cooperative node recovery further improve network robustness by ensuring redundancy and enabling nearby nodes to temporarily handle failed node functions. Integrating these approaches with the Dwarf Mongoose algorithm optimizes resource allocation and accelerates recovery. Predictive analytics and cross-layer optimization can pre-emptively mitigate potential failures, ensuring sustained network performance. Together, these mechanisms significantly enhance packet delivery, minimize downtime, and strengthen MANET resilience.

To provide a solid foundation for examining the study's objectives, an empirical review is essential for understanding prior research, methodologies, and outcomes in the area of mobile ad hoc networks (MANETs) and routing protocol optimization. The empirical review will cover studies that focus on the performance, efficiency, and limitations of MANET routing protocols, particularly reactive protocols like the Dynamic Source Routing (DSR) protocol, the Ad hoc On-Demand Distance Vector (AODV), and others enhanced by nature-inspired algorithms, including the novel Dwarf Mongoose Optimization Algorithm. The purpose of this review is to identify the strengths and weaknesses of existing protocols and to illustrate how new algorithms can enhance their adaptability and efficiency in dynamic network conditions.

The first segment of the empirical review will explore existing literature on the challenges MANETs face, including high mobility, limited bandwidth, frequent topology changes, and energy constraints. These factors make efficient routing critical, as they impact network stability, data throughput, and overall communication quality. Many studies underscore the performance limitations of traditional MANET routing protocols in handling these challenges, especially when mobility increases or when nodes operate with restricted resources. For example, researchers have highlighted issues such as excessive routing overhead in DSR and increased delay in AODV, emphasizing the need for more adaptive and efficient routing strategies.

Subsequent sections will focus on empirical studies that have implemented various algorithms and techniques to address the limitations of conventional routing protocols. For instance, nature-inspired algorithms like Cuckoo Search algorithm, Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), and Genetic Algorithms (GA) have been widely adopted to enhance route discovery and maintenance in MANETs. These algorithms draw on principles from nature, such as the collective intelligence of ants or the flocking behavior of birds, to find optimized paths in complex networks. Empirical studies reveal that these algorithms often improve routing performance by reducing overhead, minimizing latency, and increasing packet delivery rates, especially under high mobility scenarios.

Additionally, the review will cover recent advancements in the application of novel algorithms like the Dwarf Mongoose Optimization Algorithm to optimize MANET routing. Empirical research on such algorithms demonstrates their effectiveness in adapting to dynamic network topologies, balancing load distribution, and reducing energy consumption among nodes. These studies will provide insights into how nature-inspired and hybrid algorithms have achieved notable improvements in MANET routing efficiency compared to traditional protocols.

Hence, the empirical review will highlight the gaps in current literature, specifically the limitations of conventional MANET routing protocols under varying mobility and resource constraints, as well as the benefits and performance enhancements introduced by nature-inspired and novel algorithms. This review will form the basis for developing a routing protocol solution that is both efficient and resilient in managing the challenges typical of MANET environments.

Adeyelu *et al.* addressed the challenge of optimizing energy consumption in Mobile Ad-hoc Networks (MANETs) by introducing a novel approach that integrates an energy-efficient routing algorithm with the Cuckoo Search

Algorithm (CSA) [9]. This hybrid algorithm aims to enhance the routing paths of Dynamic Source Routing (DSR) by leveraging the CSA's ability to explore solution spaces based on metrics like energy consumption, distance, and link stability. Through simulations and comparative analysis, the study demonstrates that the proposed algorithm significantly outperforms traditional routing methods in terms of energy efficiency, packet delivery ratio, throughput, packet loss, and transmission count. The results show that the hybrid algorithm effectively maintains energy balance across nodes and extends the network's operational lifespan, contributing to the advancement of sustainable and efficient MANET routing strategies.

Yaqoob and Shamas examined the challenges faced in Mobile Ad Hoc Networks (MANETs) due to the lack of fixed infrastructure and frequent topology changes, which complicate the design of efficient routing algorithms [3]. Their study reviewed three primary categories of MANET routing protocols: Proactive (such as DSDV), Reactive (such as AODV, DSR, and TORA), and Hybrid (such as ZRP), comparing their performance across varying network conditions, including dynamic network size, node mobility, and density. The research analyzed each protocol under scenarios of high and low mobility and evaluated their performance based on key metrics like Throughput, Packet Delivery Ratio (PDR), Normalized Routing Load (NRL), and End-to-End Delay (ETE). Additionally, the study addressed the security challenges posed by network layer attacks in MANETs, discussing detection mechanisms and assessing the impact of these attacks on metrics such as Routing Overhead, Transmission Delay, and Packet Drop Rates. Through this comprehensive analysis, they highlighted the strengths and weaknesses of each protocol type in dynamic network environments, contributing valuable insights for optimizing MANET routing protocols under diverse and challenging conditions.

Pari and Sudharson explored the security challenges in ad-hoc networks, which lack a central authority, making them vulnerable to attacks that can lead to significant losses in data, power, or capacity [10]. To address these vulnerabilities, the authors proposed an Enhanced Trust-Based Secure Route Protocol (ETBSRP), leveraging feature extraction to improve trust-based routing. Their approach involves retrieving primary and secondary trust characteristics and calculating an integrated trust value for each node based on logical and physical trust factors. ETBSRP assesses the trustworthiness of intermediate nodes by calculating each mobile node's reputation using four trust characteristics: connection, honesty, power, and capacity. Nodes are classified as either trustworthy or untrustworthy based on their reputation scores; untrustworthy (or compromised) nodes are excluded from the routing path. Additionally, cryptographic functions are applied to secure data transmission, effectively safeguarding datagrams from origin to destination. This protocol demonstrated a significant improvement in network performance, increasing throughput by 93.4% and reducing transmission delay, showcasing its effectiveness in maintaining secure and efficient data flow in ad-hoc networks.

Purushothaman *et al.* addressed the challenge of optimizing data flow and routing efficiency in Mobile Ad Hoc Networks (MANETs), focusing on maximizing throughput and network lifespan [38]. Recognizing the limitations of existing energy-efficient algorithms, such as inadequate security, low packet delivery ratios, and high energy consumption, the authors proposed a novel Fuzzy C-Means Clustering-based Energy-Efficient Protected Optimal Path-Routing Protocol. This system is designed to improve routing performance while minimizing energy use and error rates, thereby enhancing the network's overall longevity. The proposed protocol integrates the TACIT technique, which leverages advanced AES-based encryption along with a random key generation approach and HMAC algorithm for secure key authentication and verification [38]. The protocol's security enhancements contribute to more efficient encryption and decryption processes, addressing MANET's unique demands for robust data protection. In a performance comparison, the protocol demonstrated superior routing optimization, achieving a 97% routing performance rate for a 50-node setup, outperforming existing protocols like AODV (69%), OLSR (72%), BTSNADS (82%), and DSR (92%). This study demonstrates that the Fuzzy C-Means clustering-based approach provides a substantial improvement in routing efficiency, data security, and energy management, making it a promising solution for secure, energy-efficient MANET communication.

Merlin and Ravi tackled the dual challenges of energy efficiency and security in Mobile Ad Hoc Networks (MANETs), specifically addressing vulnerabilities caused by limited energy resources and the open nature of wireless transmission [37]. Noting the prevalent threat of black hole attacks (BHAs) which disrupt data collection and amplify resource constraints by monopolizing network linksthe authors introduced the Trust-Based Energy Aware Routing (TEAR) mechanism to mitigate these risks. The TEAR mechanism is designed to counter BHAs by dynamically generating multiple detection routes, enabling rapid identification of malicious nodes and enhancing data route security through nodal trust assessment. This approach ensures energy-efficient route generation by utilizing energy from non-hotspot areas, thus optimizing network lifespan without draining critical energy resources. The multi-detection routes in TEAR help secure data paths and prevent potential interruptions from black hole nodes, leading to a more stable and secure network environment. Theoretical and experimental analyses confirmed that TEAR outperformed previous methods, significantly enhancing network lifespan and reliability by preventing BHAs and increasing successful data transmission rates.

Rahman *et al.* focused on enhancing secure data transmission within Mobile Ad Hoc Networks (MANETs) by proposing a Quality of Service (QoS)-dependent secured multipath routing system [19]. Given the decentralized and dynamic nature of MANETs, they addressed the challenge of maintaining secure communication while managing the mobility of nodes, which often leads to network vulnerabilities due to self-centered or malicious nodes. Their proposed system ensures data reliability, privacy, authentication, and non-repudiation through a secure routing mechanism. The study introduced an innovative multipath routing process using the AODV-BR protocol integrated with Optimal Fuzzy Logic to strengthen route security. For optimal path selection, the researchers employed the Adaptive Grey Wolf Optimization approach, which effectively identified the most secure and efficient paths from available routes. Additionally, they incorporated Homomorphic Encryption for robust key management to protect data integrity and confidentiality. The proposed routing system was assessed through simulation, showing improved performance in terms of energy efficiency, packet delivery ratio, and network lifespan compared to traditional methods, highlighting its potential for more resilient and energy-efficient MANET communication.

Khudayer *et al.* conducted a comparative analysis of Mobile Ad Hoc Network (MANET) routing protocols, identifying critical strengths and weaknesses across proactive, reactive, and hybrid routing types [16]. MANETs, characterized by mobile wireless nodes that communicate over multiple hops without centralized management, have seen applications in both commercial sectors (such as intelligent shipping, gaming, and agriculture) and non-commercial sectors (such as military, disaster response, and wildlife monitoring). Despite MANETs' versatility, routing mobility management remains a significant challenge impacting network performance. The study systematically compared the functional characteristics of proactive, reactive, and hybrid routing protocols based on metrics like routing overhead, scalability, and delay. Proactive protocols, while ensuring route availability and rapid access, are limited by scalability and high routing overhead. Reactive protocols, on the other hand, initiate route discovery only when data needs to be transmitted, which reduces overhead but leads to increased delay due to the time taken for route establishment, impacting performance. Hybrid protocols attempt to blend the advantages of both approaches, maintaining up-to-date routing information and supporting larger networks, yet they add complexity to network operations. The researchers concluded that enhancing MANET routing protocols remains essential to meet evolving performance requirements, given each protocol's limitations under varying conditions. The study’s insights highlight the ongoing need for protocol improvements that address scalability, delay, and routing efficiency in diverse MANET environments.

Gulić and Žuškin introduced a hybrid metaheuristic algorithm combining the Genetic Algorithm (GA) with the African Buffalo Optimization (ABO) to tackle complex optimization challenges, specifically focusing on the NP-hard Container Relocation Problem [36]. This hybrid approach adaptively switches between GA and ABO throughout the optimization process, utilizing the unique advantages of each to enhance solution accuracy and convergence speed. To bolster randomness and reduce issues like premature convergence, the authors implemented high-quality pseudorandom number generators – both 64-bit and 32-bit versions of the SIMD-Oriented Fast Mersenne Twister. Evaluations of the hybrid algorithm demonstrated that it significantly outperformed standalone applications of GA and ABO using standard pseudorandom generators, especially on more complex test sets of the Container Relocation Problem. The adaptive switching mechanism enabled the hybrid model to better address challenges such as premature convergence and local optima by dynamically adjusting to the problem’s specific requirements during the optimization process. Moreover, the study underscored the critical role of pseudorandom number generator selection in metaheuristic algorithms, as high-quality generators improved the robustness of the optimization results by reducing the likelihood of convergence issues. Their study highlights the potential of hybrid metaheuristic algorithms in solving intricate optimization problems, marking them as valuable tools for both scientific research and practical applications that require adaptive and resilient solutions.

Agor *et al.* address the challenge of routing in Mobile Ad Hoc Networks (MANETs), where issues such as the absence of a central control, frequent topology changes, limited resources, and distributed structure make efficient routing a critical concern [35]. The authors propose the Power-aware Intelligent Water Drops Routing Algorithm (PIWDRA), a routing mechanism that draws inspiration from the physics-based Intelligent Water Drops (IWD) metaheuristic. PIWDRA selects optimal paths by employing a cost function that prioritizes minimum energy, hop count, and time delay, with the minimum energy criterion assigned the highest weight. The PIWDRA algorithm incorporates various factors in path selection, including link cost, Heuristic Undesirability (HUD), local and global soil updates, which collectively consider metrics like time delay, energy, and hop count. Simulation results from Network Simulator 3 (NS-3), with variations in pause times and active source numbers, show that PIWDRA outperforms several existing algorithms: the original IWDRA, IWDHocNet, the Ad-hoc On-Demand Distance Vector (AODV) protocol, and the Destination Sequence Distance Vector (DSDV) protocol. Performance metrics evaluated include packet delivery ratio, average end-to-end delay, energy consumption, and network lifetime. The researchers suggest that future work could enhance the algorithm by incorporating congestion control mechanisms, such as cross-layer design, queue management, and rate control. Additionally, a hybrid metaheuristic routing approach may further improve routing efficiency in MANETs.

Goyal *et al.* focused on the Wireless Body Area Network (WBAN), a specialized subset of Wireless Sensor Networks (WSNs) that monitors and transmits patients' physiological data to a coordinator. WBANs, like WSNs, encounter significant routing challenges [7]. However, the unique constraints of WBANs, such as the limited battery life of body-worn sensor nodes, make efficient routing even more challenging. This survey article categorizes and analyzes a range of contemporary routing protocols developed for WBANs, highlighting their importance in ensuring efficient and reliable network performance. The study provides an overview of the WBAN architecture and explores the main challenges associated with effective routing, emphasizing the critical role of routing protocols in managing energy consumption and maintaining quality of service (QoS). Several WBAN routing strategies are classified by factors such as network structure, energy efficiency, QoS, node temperature, patient posture, and node transmission range [10]. Protocol types include cross-layered, cluster-based, QoS-aware, postural movement-based, and temperature-aware approaches. A comparative analysis of these protocols examines strengths and limitations across parameters like delay, packet delivery ratio, and energy usage.

Rahamat Basha *et al.* address packet loss and communication interference challenges in Mobile Ad Hoc Networks (MANETs), which arise due to the absence of backup information from previous routing processes [28]. This lack of backup prevents effective identification of communication failures, ultimately reducing node protection and network reliability. To mitigate these issues, the authors propose the Reliability Antecedent Packet Forwarding (RAF) technique, designed to ensure reliable routing from source to destination by avoiding "flooding" nodes and backing up prior routing information. In cases of interference during communication, the RAF technique retrieves this backup data, helping maintain the continuity of data transmission. Additionally, the Straddling Path Recovery Algorithm is introduced to monitor packet flow rates for each node and establish an interference-free routing path. This path comprises nodes with high resource levels, which serve both as primary routes and as backups for forwarding data if a routing failure occurs. By using backup nodes effectively, the proposed technique enhances network lifetime and decreases packet loss rates, addressing critical reliability issues in MANETs. This approach is particularly significant for improving MANET resilience and reliability through its proactive interference management and data recovery strategies.

Pari and Sudharson explored the security challenges in Mobile Ad Hoc Networks (MANETs), where nodes interact dynamically in a decentralized, infrastructure-less environment [20]. Due to the inherent vulnerabilities in MANETs, traditional security methods often fall short in ensuring secure communication. To address this, the authors introduce the Hybrid Trust-Based Reputation Mechanism (HTRM), a system designed to establish secure, trust-based communication by evaluating each node's trust level. This mechanism supports reliable routing, secure computations, and detection of misbehaving nodes. The researchers also design a Public Key Infrastructure (PKI) system that integrates trust evaluation into key generation, essential for MANET cryptosystems. The PKI is reinforced with a robust pre-authentication process for solid node verification, enhancing edge-to-edge security by assessing safe and trustworthy routes. To account for uncertainties, the HTRM incorporates a flexible trust management approach, allowing for adaptive trust evaluations in dynamic network conditions. In simulations, the proposed HTRM approach demonstrated significant improvements over other protocols. Results showed reduced end-to-end delay, increased packet delivery ratio, improved overall performance, reduced power consumption, and decreased key-computing time by 3.47, 3.152, 2.169, 3.527, and 3.762%, respectively. These findings underscore HTRM's potential to bolster MANET security and efficiency through trust-based routing and robust authentication.

Rajeshkumar *et al.* focus on enhancing the resilience of Mobile Ad Hoc Networks (MANETs), self-organizing wireless networks that operate without centralized infrastructure, where nodes collaborate to establish network connectivity [15]. Due to the decentralized nature of MANETs, they are vulnerable to various security threats, particularly blackhole attacks, where malicious nodes can disrupt data transmission. To counter these threats, the authors propose a hybrid approach combining Cluster Trust Adaptive Acknowledgement (CTAA) and Multi-Objective Particle Swarm Optimization (MOPSO), named CTAA-MPSO, to improve security, efficiency, and trust in the network.

In this study, an Intrusion Detection System (IDS) is implemented to monitor and detect malicious behavior within the network, raising alerts when policy violations occur. Dynamic Source Routing (DSR) protocol is leveraged to investigate blackhole attacks within the network, while CTAA is applied to identify unauthorized and malfunctioning nodes. To forecast node reliability, Kalman Filters (KF) are used, which help in reducing synchronization errors during data transmission, contributing to the network's stability. For optimized routing and energy efficiency, the MOPSO technique is utilized, which determines the optimal number of clusters in the MANET, balancing network traffic and energy consumption across nodes. The results indicate that the CTAA-MPSO method enhances the Packet Delivery Ratio (PDR), achieving a 3.3% PDR increase. Specifically, CTAA-MPSO outperforms the CTAA-PSO approach by an additional 3.5% when facing 30% malware presence. These improvements demonstrate the efficacy of combining CTAA and MOPSO in reinforcing MANET security and performance through optimized routing and proactive threat detection.

Rahamat Basha *et al.* addressed energy efficiency challenges in Mobile Ad Hoc Networks (MANETs), which are decentralized wireless networks made up of mobile nodes without a fixed infrastructure [28]. Due to the dynamic topology and the limited transmission range of nodes, MANETs rely on multi-hop communication for routing, making efficient route planning crucial. The Location-Aided Routing (LAR) protocol is one established routing method in MANETs, but it suffers from high energy consumption, which has remained a persistent challenge even after some improvements. To tackle this issue, the researchers propose an Energy Aware Metaheuristic Optimization with LAR (EAMO-LAR) protocol, which integrates the Manta Ray Foraging Optimization (MRFO) algorithm into LAR. MRFO, inspired by the foraging behaviors of manta rays, assists in searching for optimal routing solutions by selecting nodes with the best "fitness" values to reduce energy consumption in the network. By combining MRFO with LAR, EAMO-LAR aims to enhance energy efficiency while maintaining the protocol's effectiveness in route discovery. Extensive simulations were conducted to test the EAMO-LAR protocol against other recent energy-

efficient techniques. Results indicate that EAMO-LAR achieves superior performance, particularly in terms of energy utilization and routing efficiency. The protocol outperformed existing approaches, demonstrating its potential as a robust solution for energy-efficient routing in MANETs.
Table 3 gives the analogy of existing literature surveyed to compare various authors' scope of work, simulation tool, research problems, and the proposed solution. Despite numerous researchers' contributions to the improvement of dynamic source routing, there is still much room for further improvement.

Table 3: Analogy of existing literature surveyed

S/N	Ref.	Objective	Problem Identified	Proposed Solution	Simulation Tool Used
1	[9]	To enhance routing efficiency in MANETs by minimizing energy consumption and maximizing network lifetime	High energy consumption and poor routing performance in MANETs	Cuckoo search optimization algorithm	MATLAB
2	[35]	To develop an energy-efficient routing algorithm for MANETs	Energy inefficiency, high delay, packet loss in existing protocols	Power-aware Intelligent Water Drops Routing Algorithm (PIWDRA)	Network Simulator 3 (NS-3)
3	[36]	To improve optimization in the Container Relocation Problem	Premature convergence and local optima in metaheuristic algorithms	Hybrid Genetic Algorithm and African Buffalo Optimization with advanced random generators	-
4	[7]	To categorize routing protocols in Wireless Body Area Networks (WBANs)	Energy limitations and high delay in body sensor nodes	Survey of existing routing protocols categorized by energy, QoS, node temp., etc.	-
5	[28]	To enhance reliability in MANETs	acket loss due to interference and lack of backup information	Reliability Antecedent Packet Forwarding (RAF) with backup route information	-
6	[22]	To improve secure communication in MANETs	Security vulnerabilities due to lack of infrastructure	Hybrid Trust-based Reputation Mechanism (HTRM) with PKI and trust management	-
7	[15]	To secure MANETs against blackhole attacks	Vulnerability to blackhole attacks in dynamic MANETs	Cluster Trust Adaptive Acknowledgment (CTAA) with Kalman Filters and Multi-Objective PSO	-
8	[24]	To enhance routing reliability in MANETs	Packet loss due to interference and inefficient communication failure detection	Reliability Antecedent Packet Forwarding (RAF) with backup routes and straddling path recovery algorithm	-
9	[39]	To improve routing performance in MANETs using swarm intelligence	Inefficient energy use, long delays, and poor reliability in MANET routing	Ant Colony Optimization (ACO) based routing with energy-aware mechanisms	NS-3
10	[7]	To improve energy efficiency and routing in MANETs	High energy consumption and inefficient routing in MANETs	Energy-efficient routing with an optimization algorithm based on Particle Swarm Optimization (PSO)	NS-2, MATLAB
11	[23]	To develop a routing protocol for MANETs that minimizes delay and packet loss	High latency, packet loss, and insufficient throughput in MANETs	Hybrid routing algorithm using a combination of genetic and particle swarm optimization (GA-PSO)	NS-3, MATLAB
12	[38]	To propose a reliable energy-efficient routing algorithm for MANETs	Inefficient resource usage, high energy consumption, and poor reliability	Trust-based energy-efficient routing using fuzzy logic for MANETs	NS-3
13	[22]	To analyze and optimize energy consumption in MANETs	High energy consumption and inefficient routing due to node mobility	A hybrid routing algorithm combining fuzzy logic and machine learning for energy optimization	NS-2, MATLAB
14	[3]	To enhance energy efficiency and security in mobile ad hoc networks (MANETs).	MANETs face challenges in terms of high energy consumption, security vulnerabilities, and unreliable communication.	Proposes a Hybrid Energy-Efficient Secure Routing Protocol (HEESRP) that combines energy-efficient routing with security mechanisms to address both energy and security issues.	NS-2 (Network Simulator 2)
15	[38]	To propose a new routing protocol for MANETs with enhanced security and energy efficiency.	MANETs face security vulnerabilities, high energy consumption, and poor routing reliability.	Introduces a Secure and Energy-efficient Routing Protocol (S-ERP) that improves security and reduces energy usage by incorporating trust and encryption mechanisms.	NS-3 (Network Simulator 3)
16	[37]	To address energy efficiency and security challenges in MANETs, particularly focusing on mitigating black hole attacks (BHAs).	Energy constraints in MANETs and vulnerabilities due to BHAs disrupting data paths and amplifying resource limitations.	Introduced the Trust-Based Energy Aware Routing (TEAR) mechanism to dynamically generate multiple detection routes, assess node trust, and enhance energy-efficient route generation.	-
17	[36]	To address complex optimization challenges, specifically focusing on the NP-hard Container Relocation Problem.	Optimization difficulties, such as premature convergence and local optima, in the Container Relocation Problem.	Introduced a hybrid metaheuristic algorithm combining the Genetic Algorithm (GA) with African Buffalo Optimization (ABO) and used high-quality pseudorandom number generators to improve solution accuracy and convergence.	Not specified (The study mentioned the use of high-quality pseudorandom number generators).
18	[39]	To address energy efficiency challenges in Mobile Ad Hoc Networks (MANETs) using a more energy-efficient routing protocol.	High energy consumption in the Location-Aided Routing (LAR) protocol in MANETs.	Proposed the Energy Aware Metaheuristic Optimization with LAR (EAMO-LAR) protocol, integrating the Manta Ray Foraging Optimization (MRFO) algorithm into LAR to reduce energy consumption.	Extensive simulations (simulation tool not specified).

Summary
This systematic literature review analyzed recent advancements in optimizing energy consumption in Mobile Ad-hoc Networks (MANETs) to prolong network lifetime and enhance efficiency. The studies reviewed primarily focused on innovative routing algorithms, energy-efficient protocols, and optimization techniques such as machine learning and metaheuristic algorithms. A variety of approaches were evaluated, including adaptive transmission power control, clustering mechanisms, and trust-aware routing strategies. Table 3 provides a comparative summary of these techniques, highlighting their unique features, strengths, and limitations in addressing energy efficiency challenges in MANETs.

Conclusion

This review thoroughly examined state-of-the-art methodologies for optimizing energy consumption in MANETs, emphasizing their potential to enhance network lifetime and operational efficiency. Among the approaches discussed, metaheuristic algorithms and machine learning techniques emerged as particularly promising due to their ability to dynamically adapt to the network's changing conditions and mobility patterns. The review identified several innovative algorithms, such as the Cuckoo Search and Intelligent water drop algorithm, which demonstrated high effectiveness in addressing energy consumption challenges through efficient routing and power control mechanisms.

Despite these advancements, the field faces unresolved challenges, including scalability issues, real-time adaptability, and the complexity of integrating heterogeneous devices. Future research should prioritize the development of lightweight and scalable algorithms, leveraging hybrid approaches that combine machine learning with metaheuristic techniques. Additionally, enhancing simulation models to better reflect real-world scenarios and refining mobility models such as the Gauss-Markov framework will further advance this area. This study serves as a comprehensive reference for researchers and practitioners in the field of MANETs, providing insights into the current state of energy optimization strategies and paving the way for future innovations to sustain and improve network performance.

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