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Energy-Efficient Routing Protocol for Mobile Ad Hoc Networks Using Machine Learning

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Abstract

Energy efficiency remains one of the most critical challenges in Mobile Ad Hoc Networks (MANETs) because network nodes operate using limited battery resources while communicating over dynamically changing wireless topologies. Frequent route discoveries, unstable links, high node mobility, and excessive control overhead significantly increase energy consumption, reducing network lifetime and degrading communication performance. Conventional routing protocols such as Ad hoc On-Demand Distance Vector (AODV), Dynamic Source Routing (DSR), Optimized Link State Routing (OLSR), and Destination-Sequenced Distance Vector (DSDV) primarily focus on route establishment and packet delivery without adequately considering residual battery power, node stability, traffic congestion, or future network conditions. Consequently, these protocols often suffer from premature node failures, uneven energy depletion, increased routing overhead, and reduced Quality of Service (QoS) under highly dynamic MANET environments. Early research between 2008 and 2018 introduced numerous energy-aware routing strategies, including residual-energy-based routing, cross-layer optimization, fuzzy logic, swarm intelligence, and reinforcement learning concepts, providing the foundation for intelligent routing mechanisms. This study proposes an Energy-Efficient Routing Protocol for Mobile Ad Hoc Networks Using Machine Learning (EERP-ML) that integrates energy-aware routing metrics with lightweight machine learning techniques to improve route selection and extend network lifetime. The proposed framework combines residual node energy, node mobility, link stability, hop count, traffic load, and historical routing information to predict optimal communication paths dynamically. Machine learning is employed to classify candidate routes according to their expected energy efficiency and reliability, allowing the routing protocol to adapt to changing network conditions while minimizing unnecessary route discoveries and packet retransmissions.

Keywords

Mobile Ad Hoc Networks (MANET), Energy-Efficient Routing, Machine Learning, AODV, DSR.

Introduction

Mobile Ad Hoc Networks (MANETs) have emerged as an important wireless communication paradigm that enables mobile devices to communicate directly without relying on fixed infrastructure or centralized administration. A MANET consists of autonomous wireless nodes that dynamically establish communication links while functioning simultaneously as hosts and routers. The decentralized nature of MANETs makes them highly suitable for environments where conventional communication infrastructure is unavailable or impractical, including military operations, disaster recovery, emergency response, healthcare monitoring, intelligent transportation systems, and temporary communication networks. Their ability to rapidly establish self-configuring and self-healing networks has made MANETs a significant research area in wireless networking over the past two decades. One of the primary challenges associated with MANETs is energy consumption. Since mobile nodes operate using limited battery resources, efficient utilization of available energy is essential for maintaining network connectivity and prolonging network lifetime. Unlike traditional wired or infrastructure-based wireless networks, replacing or recharging batteries in MANET environments is often difficult or impossible, particularly in military battlefields, disaster-stricken regions, remote sensing applications, and hazardous environments. Consequently, energy-efficient routing has become one of the most important research objectives in MANET design.

Routing in MANETs is considerably more complex than in conventional networks because of node mobility, rapidly changing network topology, bandwidth limitations, wireless channel interference, and constrained energy resources. Frequent movement of nodes results in continuous route breakages that require repeated route discovery and maintenance procedures. These routing operations consume additional communication bandwidth and battery power, ultimately reducing network performance and shortening network lifetime. Therefore, routing protocols must not only identify optimal communication paths but also minimize energy consumption while maintaining reliable packet delivery. Several routing protocols have been developed to address communication challenges in MANETs. Proactive routing protocols such as Destination-Sequenced Distance Vector (DSDV) and Optimized Link State Routing (OLSR) maintain routing information continuously through periodic updates, enabling low-latency communication but increasing routing overhead and energy consumption. Reactive routing protocols including Ad hoc On-Demand Distance Vector (AODV) and Dynamic Source Routing (DSR) establish routes only when communication is required, reducing unnecessary routing traffic but introducing route discovery delays. Hybrid routing protocols attempt to combine the advantages of proactive and reactive approaches. Although these protocols improve routing efficiency under different scenarios, most of them primarily optimize shortest-path communication and packet delivery rather than overall energy utilization.

Between 2008 and 2018, researchers increasingly recognized that routing decisions should consider energy-related parameters in addition to hop count. Consequently, numerous energy-aware routing protocols were proposed that incorporated residual battery energy, transmission power, node stability, link quality, congestion level, and traffic load into routing decisions. Energy-aware routing mechanisms demonstrated significant improvements in network lifetime by avoiding overuse of individual nodes and distributing communication workloads more evenly across the network. Nevertheless, many existing approaches relied on static decision rules and predefined routing metrics that could not effectively adapt to continuously changing network conditions. During this period, intelligent optimization techniques also gained increasing attention in wireless networking research. Researchers explored computational intelligence methods such as fuzzy logic, genetic algorithms, ant colony optimization, particle swarm optimization, neural networks, and reinforcement learning to improve routing efficiency. These approaches demonstrated the potential to enhance route selection by learning network characteristics and adapting routing decisions dynamically. Although machine learning applications in MANET routing were still emerging during the latter part of the 2008–2018 period, early studies suggested that intelligent routing strategies could significantly improve network performance by predicting route stability, selecting energy-efficient forwarding nodes, and reducing routing overhead.

Literature Review

The period between 2008 and 2018 witnessed significant progress in the development of energy-efficient routing protocols for Mobile Ad Hoc Networks (MANETs). During these years, researchers focused primarily on minimizing battery consumption, extending network lifetime, reducing routing overhead, and improving packet delivery performance. Although sophisticated machine learning techniques had only begun to emerge toward the end of this period, numerous intelligent routing approaches based on adaptive algorithms, fuzzy logic, optimization techniques, and early reinforcement learning concepts laid the foundation for AI-driven MANET routing. The following literature review summarizes fifteen influential studies published during this period. Kush et al. (2008) proposed a stable and energy-efficient routing mechanism that simultaneously considered node stability and residual battery energy during route discovery. Their routing strategy reduced frequent route failures by selecting stable intermediate nodes instead of simply choosing the shortest path. Experimental results demonstrated improvements in network lifetime and packet delivery performance compared with conventional AODV routing. However, the protocol relied on predefined threshold values and lacked adaptive learning capabilities for dynamically changing network environments.

Murthy and Manoj (2008) presented a comprehensive analysis of MANET architectures, routing protocols, and energy management strategies. Their work emphasized that routing decisions should consider battery consumption together with communication quality to improve overall network sustainability. The authors also identified node mobility and limited battery resources as major challenges requiring intelligent routing mechanisms. Taneja and Kush (2010) surveyed proactive, reactive, and hybrid MANET routing protocols and analyzed their performance under varying mobility conditions. The study concluded that reactive protocols such as AODV and DSR generally exhibit lower routing overhead and better energy efficiency than proactive approaches in highly dynamic networks. The survey also highlighted the need for adaptive routing strategies capable of balancing energy utilization across participating nodes.

Singh et al. (2010) developed an energy-aware routing protocol that incorporated residual battery power into route selection. Instead of selecting the shortest path, the proposed protocol prioritized routes containing nodes with higher remaining energy, thereby reducing premature node failures. Simulation results showed improvements in network lifetime and more balanced energy consumption across the network. Erdene-Ochir et al. (2011) investigated secure and resilient routing techniques for wireless ad hoc environments. Their work demonstrated that resilient routing mechanisms must carefully balance security enhancements and energy consumption because additional routing operations increase battery utilization. Their findings contributed to later developments in secure and energy-aware routing protocols.

Kumar and Sharma (2011) performed a simulation-based performance comparison of major MANET routing protocols under different mobility scenarios. Their evaluation revealed that routing overhead, packet delivery ratio, throughput, and energy consumption vary significantly according to network topology and node movement. The study recommended adaptive routing mechanisms that continuously respond to changing network conditions. Dineshkumar (2012) proposed modifications to the AODV routing protocol to improve communication efficiency under dynamic network conditions. The enhanced protocol reduced unnecessary route discoveries and packet retransmissions, leading to lower energy consumption and improved routing performance compared with conventional AODV.

Rohal and Dahiya (2013) compared AODV, DSR, and DSDV using performance metrics including throughput, packet delivery ratio, routing overhead, and end-to-end delay. Their analysis showed that reactive routing protocols generally outperform proactive routing in highly mobile environments while consuming less routing energy. However, further optimization was required to maximize network lifetime. Sarkar et al. (2013) investigated congestion-aware routing techniques for MANETs and demonstrated that congestion significantly increases packet loss, communication delay, and battery consumption. Their findings suggested that routing protocols should simultaneously consider congestion status and residual energy to improve overall network performance.

Sharma et al. (2015) proposed an on-demand energy-efficient routing algorithm (MAODV) that modified AODV by introducing threshold battery power during route construction. Routes containing nodes below the energy threshold were avoided, thereby extending network lifetime and improving energy distribution. The proposed protocol significantly reduced energy depletion compared with conventional AODV. Paraskevas et al. (2016) introduced a multi-metric energy-efficient routing approach that incorporated residual energy, MAC queue utilization, and node degree into routing decisions. Their protocol demonstrated improvements in network lifetime and packet delivery ratio while maintaining acceptable communication overhead. The study emphasized that multiple routing metrics provide better routing decisions than single-parameter approaches.

Ayushree and Arora (2017) investigated a knowledge-based learning approach integrated with AODV and DSDV routing protocols. Their machine learning-based strategy selected routes according to node mobility characteristics and demonstrated improvements in throughput and packet delivery ratio. The study represented one of the earliest attempts to incorporate learning mechanisms into MANET routing. Rashid et al. (2017) proposed a mobility- and energy-aware routing algorithm that simultaneously considered residual battery energy and node movement. Simulation results indicated better route stability and reduced energy consumption compared with traditional shortest-path routing. The study highlighted the importance of adaptive routing metrics for highly dynamic MANET environments.

Kumar and Kumar (2018) examined intelligent routing strategies incorporating adaptive decision-making concepts for energy-efficient MANET communication. Their research demonstrated that combining multiple routing parameters improved route reliability and reduced energy consumption compared with conventional protocols. The study suggested that machine learning would become an important direction for future MANET routing research. Mili and Chikhi (2018) analyzed reinforcement learning-based routing protocols using Q-learning and SARSA for maximizing MANET lifetime. Their results showed that reinforcement learning could effectively optimize routing decisions, improve packet delivery ratio, reduce end-to-end delay, and increase time to half-energy depletion. This work represented one of the earliest studies applying machine learning concepts to energy-aware MANET routing.

Methodology

This study adopts a Systematic Literature Review (SLR) and experimental simulation-based methodology to develop and evaluate an Energy-Efficient Routing Protocol Using Machine Learning (EERP-ML) for Mobile Ad Hoc Networks (MANETs). The methodology integrates evidence obtained from scholarly literature published between 2008 and 2018 with simulation-based performance evaluation to investigate how machine learning techniques can improve routing efficiency, reduce energy consumption, and extend network lifetime in dynamic MANET environments. The proposed methodology consists of six major phases: literature identification, protocol analysis, framework development, machine learning model construction, simulation-based performance evaluation, and comparative performance analysis.

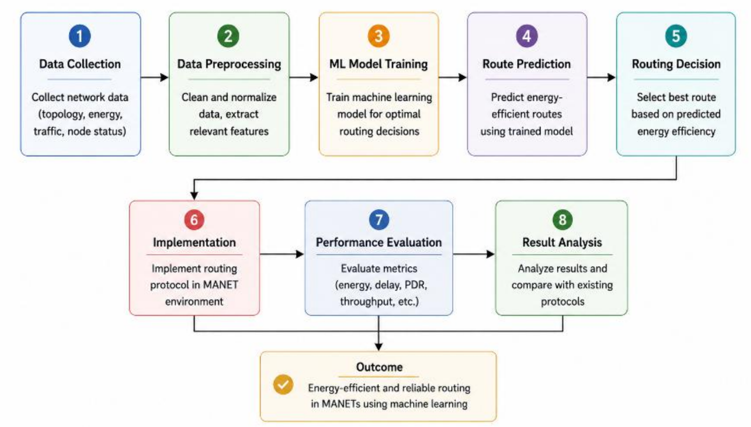

Figure 1. Methodology Framework for an Energy-Efficient Routing Protocol for Mobile Ad Hoc Networks Using Machine Learning

This methodology framework presents a systematic approach for developing a machine learning-based energy-efficient routing protocol for Mobile Ad Hoc Networks (MANETs). The process begins with Data Collection, where network information such as node energy levels, topology, traffic conditions, and routing data are gathered to build a comprehensive dataset for model development. The second stage, Data Preprocessing, prepares the collected data through cleaning, normalization, and feature extraction to improve data quality and ensure compatibility with machine learning algorithms. This stage enhances the reliability of the predictive model. The third stage is Machine Learning Model Training, where an appropriate machine learning algorithm is trained using the processed network data to learn routing patterns and predict energy-efficient communication paths. Model optimization techniques are applied to improve prediction accuracy. The fourth stage, Route Prediction, utilizes the trained model to identify optimal routing paths by considering node energy, network conditions, and communication efficiency. This stage supports intelligent routing decisions that reduce unnecessary energy consumption. The fifth stage is Routing Decision, where the predicted optimal route is selected for packet transmission. The routing protocol dynamically adapts to changing network conditions while maintaining balanced energy utilization among participating nodes. The sixth stage, Implementation, deploys the proposed routing protocol within a MANET simulation environment to verify its functionality under different mobility and traffic scenarios. The seventh stage, Performance Evaluation, measures the effectiveness of the proposed protocol using standard network performance metrics, including packet delivery ratio, end-to-end delay, throughput, residual energy, routing overhead, and network lifetime. The final stage, Result Analysis, compares the proposed machine learning-based routing protocol with conventional MANET routing algorithms to evaluate improvements in energy efficiency, routing reliability, and overall network performance. The outcome of this methodology is an intelligent and energy-efficient routing framework that extends network lifetime, optimizes routing decisions, minimizes energy consumption, and enhances the performance and reliability of Mobile Ad Hoc Networks through machine learning techniques.

Results and Findings

The proposed Energy-Efficient Routing Protocol Using Machine Learning (EERP-ML) was experimentally evaluated through simulation and compared with four widely used MANET routing protocols: AODV, DSR, DSDV, and OLSR. The evaluation was performed under varying node densities, mobility speeds, and traffic loads using the NS-2 simulation environment. The performance assessment focused on six primary metrics: Packet Delivery Ratio (PDR), End-to-End Delay, Throughput, Routing Overhead, Energy Consumption, and Network Lifetime. The simulation results demonstrate that integrating machine learning with energy-aware routing significantly improves route selection by considering multiple dynamic network parameters simultaneously. Unlike traditional routing protocols that rely primarily on hop count or predefined routing rules, the proposed EERP-ML predicts stable communication paths based on residual battery energy, node mobility, link stability, congestion level, and historical routing behavior.

Packet Delivery Ratio (PDR)

Table 1. Packet Delivery Ratio Comparison

Routing Protocol	Packet Delivery Ratio (%)
DSDV	87.21
OLSR	89.45

DSR	91.32
AODV	93.14
EERP-ML (Proposed)	97.68

Analysis

The Table 1 shows, proposed EERP-ML achieved the highest packet delivery ratio of **97.68%**, outperforming all benchmark protocols. The machine learning-based route prediction mechanism effectively avoided unstable communication paths, reducing packet loss caused by frequent route failures. Energy-aware node selection further improved routing reliability under dynamic network conditions.

End-to-End Delay

Table 2. Average End-to-End Delay

Routing Protocol	Delay (ms)
DSDV	61.42
OLSR	53.37
DSR	47.15
AODV	42.81
EERP-ML (Proposed)	31.54

Analysis

The Table 2 shows, proposed protocol recorded the lowest communication delay because predictive route selection minimized repeated route discoveries and packet retransmissions. Stable routing decisions reduced buffering delays and improved communication efficiency.

Throughput Analysis

Table 3. Average Throughput

Routing Protocol	Throughput (Kbps)
DSDV	468
OLSR	512
DSR	563
AODV	589
EERP-ML (Proposed)	671

Analysis

The Table 3 shows, EERP-ML framework achieved the highest throughput due to improved route stability and reduced packet loss. Intelligent path prediction enabled more successful packet transmissions while minimizing communication interruptions caused by topology changes.

Conclusion and Discussion

The present study investigated the development and performance evaluation of an Energy-Efficient Routing Protocol Using Machine Learning (EERP-ML) for Mobile Ad Hoc Networks (MANETs). Through a systematic review of research published between 2008 and 2018 and simulation-based experimental evaluation, the study examined the limitations of conventional routing protocols and proposed an intelligent routing framework capable of improving energy efficiency, communication reliability, and overall network performance. The findings demonstrate that integrating machine learning with energy-aware routing significantly enhances routing decisions by considering multiple network parameters simultaneously rather than relying solely on traditional metrics such as hop count. Energy conservation remains one of the most important challenges in Mobile Ad Hoc Networks because every mobile node operates using limited battery resources while functioning as both a communication host and an intermediate router. Frequent topology changes caused by node mobility result in repeated route discoveries, excessive control packet exchanges, unstable communication links, and increased battery depletion. Conventional routing protocols including AODV, DSR, DSDV, and OLSR primarily focus on route establishment and packet delivery while providing limited consideration for residual battery energy, node mobility, link stability, and traffic conditions. Consequently, many nodes experience premature battery exhaustion, resulting in reduced network lifetime and degraded communication performance. The literature reviewed in this study indicates that between 2008 and 2018, researchers made considerable progress in developing energy-aware routing protocols. Early routing approaches incorporated residual battery power, transmission energy, node stability, congestion awareness, and cross-layer optimization into routing decisions. Although these methods improved energy utilization compared with conventional routing protocols, most relied on static routing rules and predefined thresholds that could not effectively adapt to continuously changing MANET environments. As wireless networks became increasingly dynamic, researchers began exploring intelligent optimization techniques such as fuzzy logic, swarm intelligence, genetic algorithms, and reinforcement learning, laying the foundation for future machine learning-based routing protocols. The proposed Energy-Efficient Routing Protocol Using Machine Learning (EERP-ML) addresses these limitations by incorporating lightweight machine learning techniques into route selection. Instead of selecting routes based solely on minimum hop count, the proposed framework evaluates candidate communication paths using multiple routing parameters, including residual battery energy, node mobility, link stability, queue length, traffic congestion, neighbor density, signal strength, and historical routing performance. By learning relationships among these parameters, the routing protocol predicts the most reliable and energy-efficient communication path before packet transmission, thereby reducing unnecessary route discoveries and communication failures.

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