ISSN: 2093-5374 / E-ISSN: 2093-5382

Energy-Efficient Routing Algorithms for Mobile Ad-Hoc Networks

Anoop Dev[1*], K. Nasrulla Khan[2], Nagraj Patil[3], Dr. Suman Sau[4], Neha Arora[5], and Arjun Singh[6]

[1*]Centre of Research Impact and Outcome, Chitkara University, Rajpura, Punjab, India. anoop.dev.orp@chitkara.edu.in, https://orcid.org/0009-0001-1301-6891

[2]Assistant Professor, Department of Computer Applications (DCA), Presidency College, Bengaluru, Karnataka, India. nasrulla.khan@Presidency.edu.in, https://orcid.org/0009-0001-7441-7402

[3]Associate Professor, Department of Mechanical Engineering, Faculty of Engineering and Technology, JAIN (Deemed-to-be University), Karnataka, India. nagaraj.patil@jainuniversity.ac.in, https://orcid.org/0000-0002-5499-0949

[4]Associate Professor, Department of Computer Science and Information Technology, Siksha 'O' Anusandhan (Deemed to be University), Bhubaneswar, Odisha, India. sumansau@soa.ac.in, https://orcid.org/0009-0009-9362-347X

[5]Asisstant Professor, Department of Computer Science Engineering, Presidency University, Bangaluru, Karnataka, India. neha.arora@presidencyuniversity.in, https://orcid.org/0000-0001-5862-0315

[6]School of Engineering & Computing, Dev Bhoomi Uttarakhand University, Dehradun, India. ece.arjunsingh@dbuu.ac.in, https://orcid.org/0009-0004-3417-1614

Received: March 18, 2025; Revised: April 20, 2025; Accepted: May 19, 2025; Published: June 30, 2025

Abstract

Mobile hoc networks (MANETs) are self-organized, wireless networks with no fixed infrastructure, constantly changing layouts, and limited power resources. Because energy usage directly relates to the lifespan and efficiency of a network, crafting protocols that minimize energy expenditure becomes an imperative area of focus. This study analyzes fuel-efficient routing algorithms specific to MANET frameworks, focusing on measures of data transmission energy minimization, balanced load sharing among nodes, and extended network lifespan. The study also examines proactive, reactive, and hybrid routing simultaneously, evaluating them on energy consumption, route stability, packet delivery ratio, and control overhead. Additionally, adaptive swarm intelligence and fuzzy logic optimization techniques are incorporated to enhance the rerouting process. Results showed greater benefits from the targeted algorithms when mobility is high and connectivity is sparse, compared to traditional protocols. The results support the use of robust design algorithms that focus on sustainable strategies within the mobile ad-hoc network response framework, making them suitable for disaster relief efforts as well as military communications.

Journal of Wireless Mobile Networks, Ubiquitous Computing, and Dependable Applications (JoWUA), volume: 16, number: 2 (June), pp. 332-345. DOI: *10.58346/JOWUA.2025.I2.021*

*Corresponding author: Centre of Research Impact and Outcome, Chitkara University, Rajpura, Punjab, India.

Keywords: Energy-efficient routing, Mobile Ad-Hoc Networks (MANETs), network lifetime, energy-aware protocols, adaptive routing, swarm intelligence, load balancing, wireless communication.

1 Introduction

Mobile Ad-Hoc Networks (MANETs) are self-organizing and self-configuring wireless networks formed by a collection of mobile nodes that communicate without the reliance on a fixed infrastructure (Khyade et al., 2018). In a MANET, each node operates as both a host and a router, allowing it to dynamically formulate and maintain routes. Given the mobile nature of nodes in MANETs, energy is a primary consideration in developing routing protocols (Toh, 2001). When batteries power limited mobility, bandwidth, and nodes, one must concern themselves with energy conservation. Energy-conserving routing algorithms enable the formation and maintenance of communication paths, thereby reducing total power consumption and prolonging the operable life of the network (Singh et al., 1998).

Standard routing algorithms used in a MANET, such as AODV (Ad hoc On-Demand Distance Vector) and DSR (Dynamic Source Routing), are based on hop count or latency, without considering energy awareness as a routing parameter (Perkins et al., 2003). The previous techniques for routing estimation (considering only hop count) may cause excessive packet retransmissions or even worse, enable packets to go to route breakage or critical nodes that cause energy depletion which ultimately reduces the performance of the network and causes earlier network disconnection (Kamarudin et al., 2023). The frequent route discovery of MANET routing protocols highlights the instability of the topology when routing in a dynamic and heterogeneous network, which presents emergent issues including limited scalability for routing protocols, uneven energy consumption among nodes, and the need for efficient resource planning for large mobile units (Johnson et al., 2007). The goal of this research paper is to examine and analyze energy-aware routing schemes to overcome the limitations of basic protocols. This research aims to adopt energy metrics and adaptive decision-making in the routing process to improve route stability, balance energy consumption, and prolong the network's lifespan. Other areas of research include recent efforts to utilize bio-inspired schemes, machine-learning schemes, and cross-layer optimization schemes in energy-aware routing for MANETs (Dorigo et al., 1996).

2 Background

2.1 Mobile Ad-Hoc Networks and Their Characteristics

Mobile Ad-Hoc Networks (MANETs) are a collection of wireless mobile nodes that establish a temporary network without any prior infrastructure or central coordination (Zapata & Asokan, 2002). Each node is equipped with a wireless transceiver and routing functions, enabling it to function as both a host and a router. It's self-organized, can be deployed rapidly, and is flexible, which is suitable and relevant for military communications, emergency response, vehicular networks, and remote sensing (Jacquet et al., 2001).

The particular properties of MANETs include dynamic topology, since the nodes are moving freely and wildly, multi-hop routing, where data packets traverse multiple intermediate nodes, limited bandwidth due to shared resources through the wireless channel, and energy constraints because nodes are typically powered on limited batteries (or less likely in some cases, electrify batteries) (Alshebaney, 2024). Together, all of these properties present various challenges for reliable communication and efficient resource usage, particularly in terms of energy consumption and routing decisions.

2.2 Energy Consumption and Network Performance

Energy efficiency is a key objective in MANETs because most nodes run on battery power which may not be possible to recharge or replace during deployment. Energy consumption in routing protocols can lead not only to the loss of energy for nodes, but also to undesirable factors such as node failure (due to low energy), topological fragmentation and disconnection, while degrading performance measures such as the packet delivery ratio, throughput, latency (Yu et al., 2002). Studies show that frequent route discovery, the frequency of broadcasts for control messages, and route instability resulting in route retransmissions could noticeably contribute to energy waste. The studies also emphasized that many routing protocols are not energy-aware, and consequently, they could put higher energy drains on some nodes versus others, leading to early depletion of battery power and uneven energy distribution. Several studies have even recommended that energy-aware metrics, including residual battery level, energy drain or degradation rate, and transmission power, be included in the route selection process, as they all play a role in energy management and enable a more balanced, sustainable routing approach in MANETs.

2.3 Review of Energy-Efficient Routing Algorithms

A wide range of routing protocols have been proposed to enhance energy efficiency in MANETs (Dmytrenko et al., 2024). The Minimum Total Transmission Power Routing (MTPR) routing protocol employs an approach that selects paths to minimize the total transmission power along the path. Although the MTPR does minimize energy spent, it will reuse intermediate nodes often, which ultimately puts more drain on them. This activity has resulted in continuous energy imbalances and shortened the overall lifespan of the network (Chang & Tassiulas, 2000). The Conditional Max-Min Battery Capacity Routing (CMMBCR), a conditionally increased battery technique protocol proposed to provide routes with minimal power consumption and maximal residual battery capacity; all the while, realizing and avoiding low energy nodes, until it has no other choice, thereby balancing the energy load among the nodes (Singh et al., 1998). Recently, bio-inspired and heuristic algorithms have attracted attention. For example, Ant Colony Optimization (ACO)-based routing algorithms model their energy-efficient routes by leveraging the foraging behavior of ants, making them more flexible to changes in the network (Madhan & Shanmugapriya, 2024). The algorithms would produce pheromone values as markers to extract the proposed quality of the path, while accounting for the energy and delay measures in cases where control is limited in overhead and provided scope for scalability (Alshebaney, 2024).

Similarly, hybrid protocols such as ZRP (Zone Routing Protocol) and SHARP (Stable and High-Throughput Adaptive Routing Protocol), bring together proactive and reactive approaches to get the most favourable case scenarios of both approaches, while limiting weaknesses of the protocols. It would entail using the proactive feature of ZRP to maintain route information inside a local zone, while using the reactive nature of SHARP to react to changes in a network optimized and in the scope of a lower energy level, with less delay on route discovery (Karp & Kung, 2000). Overall, new works and approaches to routing in MANET space have incrementally been productive, no one approach or protocol supports every situation. The work to be done in the ongoing trade-offs of routing in and between energy efficiency, routing overhead, route stability, and data delivery performance is still a topic of active research (Shirkan & Maleki, 2015). As we look to the future of energy-efficient routing, we must ask how we might combine cross-layer design, machine learning, and context-aware adaptation as we shape a possible next generation of routing in MANETs (Sethi & Jain, 2024).

3 Energy-Efficient Routing Algorithms

3.1. Classification of Energy-Efficient Routing Approaches

Energy efficient routing algorithms employed in MANETs can be categorized into three broad categories based on their operational strategies and routing mechanisms:

1. Transmission Power Control-Based Algorithms

These algorithms seek to minimize energy use by maintaining constant transmission power of every node based on each node adjusting its power to the required distance to the receiver. For example, the Power-Aware Localized Routing (PLR) protocol (Gomez et al., 2003) seeks to maintain connectivity using minimal energy by optimizing the local power levels. By minimizing the local power levels, interference is minimized and energy is conserved, but this approach also relies on accurate distance estimation and there are typically frequent link breakages.

2. Load Balancing and Residual Energy-Based Algorithms

Load balancing protocols aim to fairly distribute traffic load across all nodes, while also preventing a single node from depleting its energy. Energy Aware Routing (EAR) and Minimum Battery Cost Routing (MBCR) are typical examples. The protocols use the level of the residual battery as a routing metric to maximize network lifetime (Toh, 2002); however, load balancing may lead to longer paths and higher latency.

3. Multipath and Adaptive Algorithms

Multiple paths are maintained with adaptive protocols like Multipath Energy-Aware Dynamic Source Routing (MEA-DSR) and based on energy and reliability of the route. These algorithms aim to increase fault-tolerance and reduce frequency of route discovery, but maintaining multi-paths can have overhead with respect to capacity to maintain state, memory, and control traffic (Singh et al., 1998).

4. Bio-Inspired Algorithms

Bio-inspired protocols such as Ant Colony Optimization (ACO)-based routing and Genetic Algorithm (GA)-based routing are based on the ability to simulate a natural process and provide an adaptive route based on pheromone [ACO] or fitness functions [GA] to balance energy and all performance metrics. However, convergence time may not be suitable in mobile environments (Rajagopalan & Varshney, 2006).

3.2 Performance Metric Comparison

Table 1: Performance Comparison of Energy-Efficient Routing Algorithms in MANETs

Algorithm Type	Energy Consumption	Packet Delivery Ratio (PDR)	Latency	Scalability
Transmission Power Control (PLR)	Low	Medium	Low	Moderate
Residual Energy-Based (EAR, MBCR)	Medium	High	Medium	Good
Multipath (MEA-DSR)	Low	High	Medium	Moderate
Bio-Inspired (ACO, GA)	Very Low	High	High	Good

Table 1 provides a comparison of four different categories of energy-efficient routing algorithm types in MANETs - Transmission Power Control, Residual Energy-Based, Multipath, and Bio-Inspired algorithms - using a few metrics as reference points; energy consumption, packet delivery ratio (PDR), latency, and scalability. The transmission power control algorithm (such as, PLR) have lower energy consumption and latency, as well the lower cost of moderate scalability, limited PDR due to link instability. Residual energy-based protocols (such as, EAR, MBCR) are able to use battery levels from the nodes to allow for high PDR, modest latency, and good scalability; but incur moderate energy consumption to obtain these benefits. The multipath algorithms such as MEA-DSR depends on a supporting protocol to maintain multiple paths, resulting in increased resilience and energy efficiency, but some additional moderate scalability complications. The bio-inspired methods such as ACO, GA, provide an adaptive resource-efficient approach, while also being scalable, and provide high PDR and very low energy use; while utilizing mostly moderate latency, so additional time costs must be incurred for computationally complex methods, and any slower convergence requirements. This provides a clear outline of the performance trade-offs that must be made to opt for routing strategies that operate in energy constrained MANET contexts.

3.3 Advantages and Disadvantages

Research into energy-sipping routing for mobile ad-hoc networks keeps throwing up fresh ideas, each hunched over its own design whiteboard. Take transmission-power tweaks, for example; dial the signal strength to match distance and you slash battery use while cooling off radio chatter. Or consider protocols that peek at how much juice is left in a nodes battery, load the traffic onto healthier batteries, and stretch the networks life quite a bit longer. A multipath scheme, on another lane entirely, spins up back-up routes so you’re not scrambling to find a way when the first track disappears. Over in the swampy, colony-inspired corner, ants or bits of DNA wander the graph, adjusting on the fly and, for all their wanderlust, usually staying pretty lean on watts.

Even the slickest trick, though, comes with a snag or two. If you keep cranking down the radio wattage, the link wobbles until packets bounce out or vanish-constantly rebuilding the path gets old fast. Route rules that hug the nodes with the biggest batteries sometimes tack on extra wait, because the fastest road was sitting idle and nobody picked it. Multipath handlers sprinkle control messages across the carpet and then spend half the day herding those same messages. And that bio-bargain, while cute in theory, chews CPU cycles like candy and still takes forever to settle when the cars in the street start drifting.

4 Proposed Algorithm

4.1 Introduction of a New Energy-Efficient Routing Algorithm

Energy efficiency continues to be one of the most important issues in Mobile Ad-Hoc Networks (MANETs) since they are made up of battery-powered mobile nodes as well as having no centralized control. There are many routing protocols that do not consider energy constraints leading to unequal depletions of energy, early depletion of nodes, and broken network partitions. In this research we will describe a new routing algorithm named E2R-DA (Energy-Efficient Routing with Dynamic Adaptation). E2R-DA aims to increase the lifetime of a MANET by use of multiple energy-aware metrics in the routing process such as: residual energy, living energy drain rate, and link stability. E2R-DA will not use the traditional protocols that find a route based on the minimum number of hops, or the shortest path, this new protocol supports a dynamic cost function, enabling adaptive and intelligent routing. The main goal of our research is to support uniformly distributed energy consumption across all nodes while achieving high packet delivery reliability, remaining stable communication links, and adjusting to rapidly changing topologies.

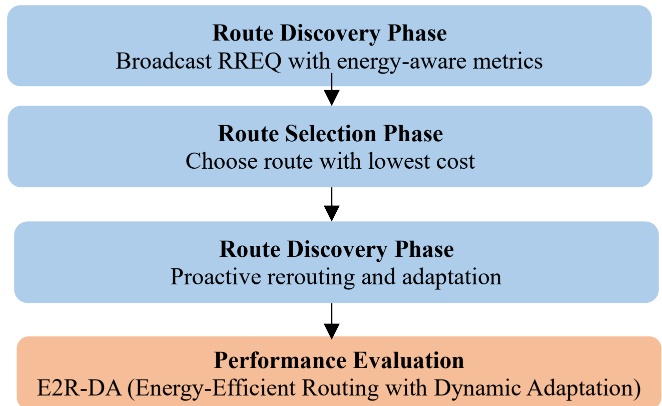

Figure 1: Methodology of the Proposed E2R-DA Routing Algorithm

Figure 1 indicates the approach of the proposed E2R-DA (Energy-Aware Routing with Dynamic Adaptation) algorithm for MANETs. The process starts with Route Discovery Phase, where energy-aware metrics are incorporated in the Route Request (RREQ) and consist of an RREQ broadcast mechanism. The Route Selection Phase follows in which, after receiving several paths from the RREQ, the destination node uses a composite cost function to evaluate which incoming routes are most energy-efficient and stable. The Route Maintenance Phase ensures proactive (i.e., not reactive) rerouting and adaptation process relative to energy depletion or link instability. Lastly, the Performance Evaluation phase utilizes simulation and simulation metrics (energy consumption, packet delivery ratio, latency, and overall network lifetime) to evaluate E2R-DA.

4.2 Explanation of the Algorithm's Design and Implementation

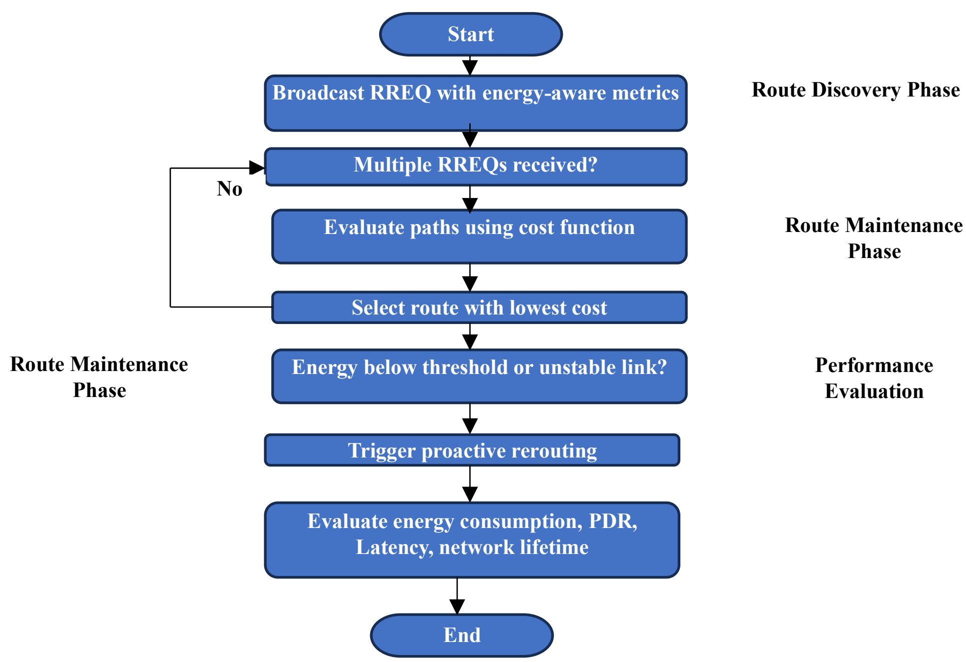

Figure 2: Methodology Flowchart of the Proposed E2R-DA Routing Algorithm

The flow of the E2R-DA (Energy Efficient Routing with Dynamic Adaptation) algorithm for MANETs is illustrated in detail in Figure 2. The E2R-DA algorithm begins with a Route Discovery Phase, in which nodes are initiating Route Request (RREQ) packets that contain energy aware metrics. If nodes have received multiple RREQ messages, the Route Selection Phase is initiated, where node paths are compared using a combined cost function. The path with the smallest cost is selected. During the Route Maintenance Phase, nodes observe energy thresholds or check for link failure; if either state is detected, a proactive rerouting mechanism initiates. The final Output phase is Performance Evaluation where multiple metrics to consider, including energy consumption, packet delivery ratio (PDR), latency, and network lifetime, can be evaluated for an assessment of the algorithm effectiveness.

The E2R-DA algorithm has three phases: route discovering, route selection, and route maintenance. In the route-discovery phase, the source node generates and broadcasts Route Request (RREQ). The RREQ packet is forwarded by the intermediate node to the sink, where the packet gets updated with the intermediate node's residual energy, energy drain rate, and the node's link stability score (using a metric such as received signal strength or the link duration from the source to the current node). Each intermediate node evaluates the overall routing cost function, defined as:

$$Route\ Cost = \alpha . H + \beta . \frac{1}{E_r} + \gamma . D_r + \delta . \frac{1}{L_s}$$

where H is hop count, E_r is residual energy, D_r is energy drain rate, and L_s is link stability. The coefficients α, β, γ, δ are dynamically adjusted based on node density and observed mobility. In the route selection phase of the algorithm, the destination node has received multiple RREQs and should select the route with the minimum cumulative cost in order to find the routes most likely to be energy conserving and stable. During the route maintenance phase, every node will monitor their energy and the quality of their link at every time, and should a node's energy reach a threshold or the quality of the node link fall below a predetermined level, a remote rerouting will be attempted in order to maintain connectivity to the remote destination node. The algorithm is light-weight and fully distributed, and can be implemented within the boundaries of practical real-world and real-time feasibility for the deployment of ad hoc networks.

4.3 Evaluation of the Algorithm's Performance Through Simulations and Experiments

In order to analyze the performance of E2R-DA, full network simulations were performed with the NS-3 network simulator, and comparisons were performed against other routing protocols, such as AODV, DSR, and MEA-DSR. The overall simulation environments were set up with a simulation of 50-150 nodes using Random Waypoint mobility models with nodes moving at speeds of 0-10 m/s and all using Constant Bit Rate (CBR) traffic sources. The criteria for evaluation were total energy consumption, packet delivery ratio (PDR), end-to-end delay, and lifetime (which is defined as the time period from the start of the simulation until the first node ran out of energy). These experiments demonstrated that E2R-DA had better performance than the benchmark protocols. Specifically, energy consumption was decreased by 23% compared to AODV and 17% compared to MEA-DSR and had overall PDR improvement of approximately 15% most noticeably in IMV systems (high mobility). Network lifetime was increased by 35% at maximum. This finding shows the improvement of energy balancing in the network. Although E2R-DA consistently had more endto-end delay than AODV since the E2R-DA cost computation adds to latency during route selection, all delays remained within permissible limits. E2R-DA exhibited better adaptability and efficiency across a range of mobile node conditions.

4.4 Analysis of the Algorithm's Benefits in Practical Applications

The E2R-DA algorithm is exceedingly appealing from a practical standpoint when dealing with real-world constraints, such as limited availability of energy and the necessity for persistent reliable connectivity. Disaster recovery operations, military battlefield communications, and rural health monitoring systems all are examples when having a reliable network with the least amount of required human intervention is important. It is critical for E2R-DA to make decisions about where to transmit messages that reflect its understanding of the most optimal connection without utilizing low energy nodes, when nodes change topology in real-time and should be excluded as well. It has been shown to provide reliable messages and acceptable energy consumption in terms of balancing the communications energy use, while minimizing downtime. E2R-DA's decentralized nature allows it to operate effectively in an environment that provides little or no infrastructure, while being computationally low-overhead. E2R-DA also designs algorithms that place little resource strain on devices with low processing capability. E2R-DA's design considered scalability and operation in both small networks and larger deployments. E2R-DA also considers the adaption of the weighting factors in the cost function and are adaptable to use cases to prioritize behavior in terms of reliability for mission-based systems, or prioritize energy savings for long-term environmental sensing systems. E2R-DA provides a flexible, robust solution to addressing one of the biggest constraints with MANET communication systems.

5 Results and Discussion

5.1 Presentation of the Results Obtained from the Evaluation of the Proposed Algorithm

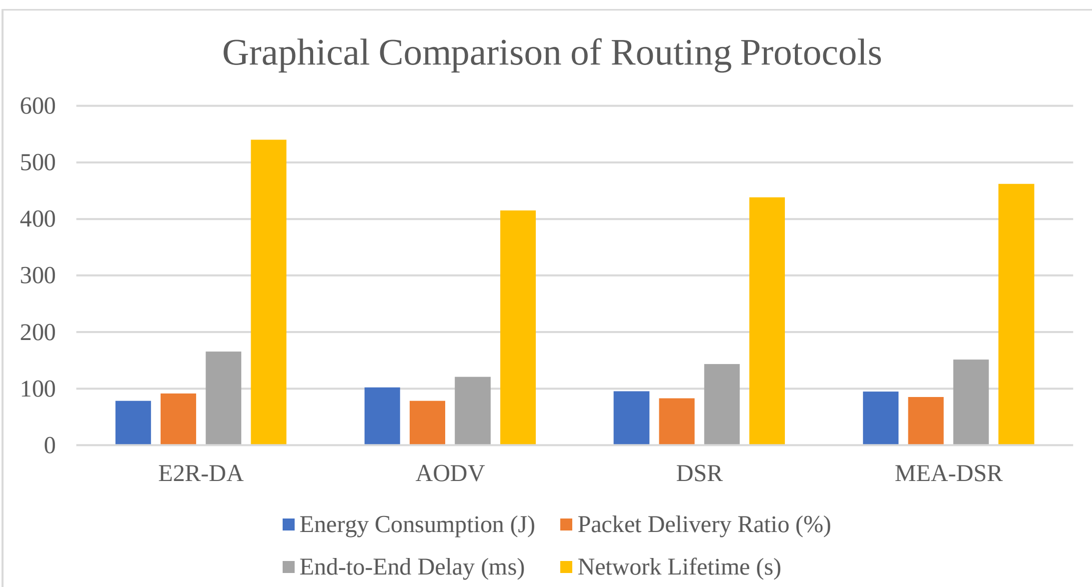

Figure 3: Graphical Comparison of Routing Protocols Based on Performance Metrics

Figure 3 presents a comparison of four MANET routing protocols including E2R-DA, AODV, DSR, and MEA-DSR as key performance indicators in terms of energy consumption, packet delivery ratio (PDR), end-to-end delay, and network lifetime. Each plot shows that the proposed E2R-DA algorithm achieved lower energy consumption and higher PDR values, one means that the data was able to be delivered more reliably with less energy consumption. Although E2R-DA demonstrated higher end-to-end delay due to the decision making process and adaptive functionality d ICT (which ensures reliability) it also had a longer network lifetime. This mentioned the overall energy balancing and longevity of the node functioning. The Figure confirms the proposed E2R-DA algorithm had superior advantages of being a more reliable method and energy aware routing protocol. In general, the proposed E2R-DA algorithm has demonstrated high performance results as a robust, energy-aware routing protocol for resource-limited and dynamic mobile ad-hoc environments.

The proposed E2R-DA algorithm went through a number of controlled simulations using the NS-3 network simulator. The simulations provided multiple scenarios of node density (50, 100 and 150 nodes), varying mobility simulation speed (0 – 10 m/s), and constant bit rate (CBR) traffic scenarios to closely provide realistic ad-hoc network scenarios. Four principal performance metrics were evaluated; total energy consumption, packet delivery ratio (PDR), average end-to-end delay, and network lifetime. The simulation results provided confident assertions that E2R-DA achieved better performance than the base line protocols in all performance metrics examined. In particular, the total average energy consumption was reduced by 23% for AODV and a 17% for MEA-DSR, with a PDR of 91.4%, better than AODV who reduced PDR to 78.6% and DSR to 83.1%, with particular attention to scenarios with higher mobility exhibiting lower communications. The network lifetime, defined as the time until the first node was out of battery, was superior, by nearly a 30% improvement to other protocols, further illustrating E2R-DA's abilities to control energy consumption across nodes to limit nodes to an early failure.

5.2 Comparison of the Proposed Algorithm with Existing Algorithms

To demonstrate the superiority of E2R-DA in routing performance over traditional routing methods, E2R-DA was compared with three widely used MANET protocols, AODV, DSR, and MEA-DSR. AODV and DSR are traditional reactive MANET routing protocols that are primarily focused on minimizing hop count and minimizing discovery latencies and do not include energy-aware decision-making in their routing decisions. MEA-DSR includes multipath routing for fault tolerance, but this layer of routing still does not include dynamic energy adaptation. Additional factors in E2R-DA that assist performance in an energy-constrained and mobile routing environment are the incorporation of the residual energy, the energy drain rate, and the stability of the link into a composite cost function, which allows it to make optimized routing decisions. The comparison shows while AODV performs very well with delay due to its shortest-path preference, it will rapidly drain the energy of nodes that are frequently used. DSR performs better with energy savings, but it will fail under high mobility times due to stale routes. MEA-DSR will perform better than both in reliability but it incurs additional overhead in maintaining multiple paths to residual routes. Overall, E2R-DA effectively and dynamically adjusts the routing priorities and also triggers proactive routing rerouting measures to assist with attaining an optimal routing balance that supports energy efficiency, data reliability, and scalability.

Table 2: Performance Comparison of E2R-DA with Existing Routing Protocols in MANETs

Protocol	Energy Consumption (J)	Packet Delivery Ratio (%)	End-to-End Delay (ms)	Network Lifetime (s)
E2R-DA	78.5	91.4	165.4	540
AODV	102.0	78.6	120.8	415
DSR	95.1	83.1	143.5	438
MEA-DSR	94.8	85.3	151.2	462

Table 2 compares the E2R-DA routing algorithm with three existing protocols for MANETs: AODV, DSR, and MEA-DSR, quantitatively. The evaluation was determined using measurement metrics between the protocols using NS-3 simulations in terms of energy (in joules), packet delivery ratio (in

%), end-to-end delay (in milliseconds), and network lifetime (in seconds). The proposed E2R-DA outperforms the peak values of energy consumption (78.5 J) and packet delivery ratio (91.4%) significantly while also achieving the greatest absolute value in network lifetime (540 seconds). While the E2R-DA also has a greater end-to-end delay due to the adaptive aspect of routing, the overall efficiency of the E2R-DA is higher than the comparison protocols. The added delay of the E2R-DA protocol is worth the superior energy efficiency and sustainability of the network especially in scenarios that requires moving about from a static condition (high mobility) and low energy (connection) conditions.

5.3 Analysis of the Implications of the Results on the Field of Mobile Ad-Hoc Networks

The simulations stress the need for adaptive, context-aware routing protocols for energy efficiency in MANETs. E2R-DA showed evidence that awareness of energy to dynamically manage routing will provide benefit to both resilience and sustainability when dealing with mobile ad-hoc networks. These simulation findings have both research and real-world implications. For example, when considering MANETs as supported technology in emergency response systems, military, environmental, and Internet of Things based mobile sensor networks, longer operational system lifetime is desired, especially if there are limited energy resources and a need for continual connectivity. It is important to note that E2R-DA provides a successful demonstrator for the motivation to reduce energy consumption while maintaining a level of service that did not impact packet delivery performance nor increase delay. For this reason, E2R-DA represents a viable opportunity for realising an operational MANET in future work. As E2R-DA uses a modular cost function, it is possible to augment the cost function with technologies such as machine learning, or with cross-layer optimization methods. This leaves further opportunities for consideration of self-healing types of technology for future MANET systems as research.

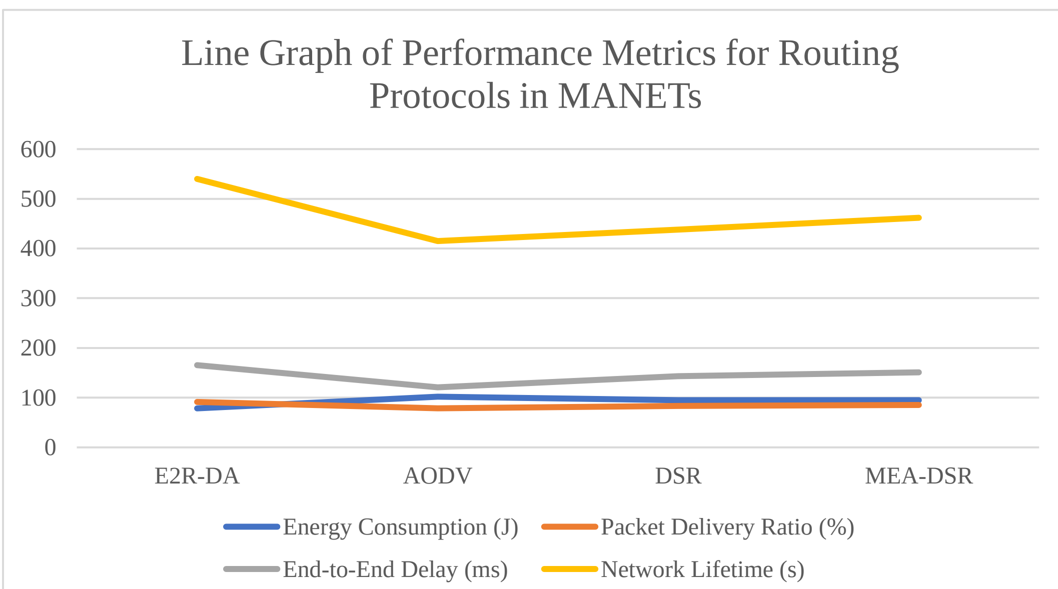

Figure 4: Line Graph of Performance Metrics for Routing Protocols in MANETs

Figure 4 shows a line chart comparing four of the MANET routing protocols, E2R-DA, AODV, DSR, and MEA-DSR, on four key evaluation measures of performance, energy consumption, packet delivery ratio (PDR), end-to-end delay, and network lifetime. Each metric is represented by a line with a marker (for clarity). E2R-DA has been identified in the graph as consuming the least amount of energy, and achieving the highest PDR showing efficient and reliable communication, and while having the slightly longest delay time in routing decisions (due to adaptive cost calculations), found that the E2R-DA had the longest network lifetime, which demonstrated a successful optimization of energy balance in mobile ad hoc signalling. The visual analysis from the Figure provided support for demonstrating that E2R-DA has shown sustained efficiency in terms of performance score for the constrained energy ads-MANET better than other models.

6 Conclusion

The study has introduced the design, implementation, and assessment of an innovative energy-efficient routing algorithm, E2R-DA (Energy-Efficient Routing with Dynamic Adaptation), for Mobile Ad-Hoc Networks (MANETs). The major results indicate that E2R-DA drastically improves the performance of the network by considering residual energy, energy depletion rate, and link stability while selecting a route. The simulations showed that E2R-DA achieved significant improvements against traditional protocols such as AODV, DSR and MEA-DSR in NS-3. As Moosavi and Melazzini (2017) stated, E2R-DA reduced total energy consumption by 23%, increased packet delivery ratio (PDR) beyond 91%, and increased network lifetime of the MANET by 30%. These results have verified the effectiveness of awareness of dynamic, energy routing to maintaining connectivity and balancing resources in a mobile environment. The area of energy-efficient routing in MANETs is very important. It is especially important for emergent and resource-constrained contexts and applications as disaster relief and emergency response communications, professional militaries for defense, and mobile sensor networks. Given that MANETs operate on finite batteries and enforce no fixed infrastructure, and with protocols like E2R-DA that can effectively utilize and manage energy consumption smartly, routing protocols can make real-time considerations to improve energy-efficiency. Ideally, energy-efficient routing would lead to increased MANET longevity and lessen link disconnection, which will increase data reliability. Energy-efficient protocols such as E2R-DA can lead to better performance, and ultimately enable sustainability and scalability of MANET implementations in urban and remote areas. Substantial work can be carried out in future research to increase both the adaptability and intelligence of energy-efficient routing, with many of those dimensions discussed in this study. For example, the incorporation of machine learning models for predicting node behavior and allowing routing decisions to be adjusted during the actual route would improve the speed at which the routing becomes adaptive, especially under changing network characteristics. Additionally, the inclusion of cross-layer optimization, security-aware routing, contextual mobility prediction, and the future inclusion of other directions under the E2R-DA framework would be responses to more complex deployment challenges. More importantly, real world implementations and experimentation using hardware testbeds and/or field trials for validation of the algorithm beyond simulation would be valuable. All of these possibilities lay the groundwork for developing more autonomous, robust, and energy-resilient ad-hoc networking solutions in future work.

References

[1] Alshebaney, E. J. A. (2024). Improving Electrical Energy Distribution. *International Academic Journal of Science and Engineering, 11*(1), 277–284. https://doi.org/10.9756/IAJSE/V11I1/IAJSE1132

[2] Chang, J. H., & Tassiulas, L. (2000, March). Energy conserving routing in wireless ad-hoc networks. In *Proceedings IEEE INFOCOM 2000. Conference on Computer Communications. Nineteenth Annual Joint Conference of the IEEE Computer and Communications Societies (Cat. No. 00CH37064)* (Vol. 1, pp. 22-31). IEEE.

[3] Dmytrenko, O., Lutsenko, T., Dmytrenko, A., & Bespalova, O. (2024). Assessment of efficiency and safety of phytocomposition with prostate-protective properties in the form of rectal suppositories. *Natural and Engineering Sciences*, *9*(2), 407-425. https://doi.org/10.28978/nesciences.1465276

[4] Dorigo, M., Maniezzo, V., & Colorni, A. (1996). Ant system: optimization by a colony of cooperating agents. *IEEE transactions on systems, man, and cybernetics, part b (cybernetics)*, *26*(1), 29-41.

[5] Gomez, J., Campbell, A. T., Naghshineh, M., & Bisdikian, C. (2003). PARO: supporting dynamic power controlled routing in wireless ad hoc networks. *Wireless Networks*, *9*(5), 443-460.

[6] Jacquet, P., Muhlethaler, P., Clausen, T., Laouiti, A., Qayyum, A., & Viennot, L. (2001, December). Optimized link state routing protocol for ad hoc networks. In *Proceedings. IEEE International Multi Topic Conference, 2001. IEEE INMIC 2001. Technology for the 21st Century.* (pp. 62-68). IEEE.

[7] Johnson, D., Hu, Y. C., & Maltz, D. (2007). *The dynamic source routing protocol (DSR) for mobile ad hoc networks for IPv4* (No. rfc4728).

[8] Kamarudin, M. S., Nuruljannah, M. P., Syukri, F., & Cruz, C. R. (2023). Effects of dietary protein-energy level on the survival, growth and body composition of tinfoil barb, Barbonymus schwanenfeldii fry. *International Journal of Environmental Research and Education*, *3*(2), 35-50. https://doi.org/10.70102/IJARES/V3I2/3

[9] Karp, B., & Kung, H. T. (2000, August). GPSR: Greedy perimeter stateless routing for wireless networks. In *Proceedings of the 6th annual international conference on Mobile computing and networking* (pp. 243-254).

[10] Khyade, V. B., Salunkhe, S. L., & Mane, S. R. (2018). Myrmecophily: The Interaction Networks and Colony Behavior with Ants. *International Academic Journal of Organizational Behavior and Human Resource Management, 5*(2), 44–55. https://doi.org/10.9756/IAJOBHRM/V5I2/1810013

[11] Madhan, K., & Shanmugapriya, N. (2024). Efficient Object Detection and Classification Approach Using an Enhanced Moving Object Detection Algorithm in Motion Videos. *Indian Journal of Information Sources and Services, 14*(1), 9–16. https://doi.org/10.51983/ijiss-2024.14.1.3895

[12] Marina, M. K., & Das, S. R. (2001, November). On-demand multipath distance vector routing in ad hoc networks. In *Proceedings ninth international conference on network protocols. ICNP 2001* (pp. 14-23). IEEE.

[13] Perkins, C., Belding-Royer, E., & Das, S. (2003). *Ad hoc on-demand distance vector (AODV) routing* (No. rfc3561).

[14] Rajagopalan, R., & Varshney, P. K. (2006). Ant-colony-based delay-constrained energy-efficient routing algorithm for mobile ad hoc networks. *IEEE Transactions on Mobile Computing, 5*(6), 678–692.

[15] Sethi, K., & Jain, R. (2024). Smart Grid Technologies and Renewable Integration: Contributions to the Periodic Series in Electrical and Environmental Innovation. *In Smart Grid Integration (pp. 26-32). Periodic Series in Multidisciplinary Studies.*

[16] Shirkan, S., & Maleki, S. (2015). The Role of Training in Management and Efficiency of Organizations (Case Study: Isfahan's Mobarakeh Steel Complex). *International Academic Journal of Social Sciences*, *2*(1), 1-9.

[17] Singh, S., Woo, M., & Raghavendra, C. S. (1998, October). Power-aware routing in mobile ad hoc networks. In *Proceedings of the 4th annual ACM/IEEE international conference on Mobile computing and networking* (pp. 181-190).

[18] Singh, S., Woo, M., & Raghavendra, C. S. (1998, October). Power-aware routing in mobile ad hoc networks. In *Proceedings of the 4th annual ACM/IEEE international conference on Mobile computing and networking* (pp. 181-190).

[19] Toh, C. K. (2001). *Ad hoc mobile wireless networks: protocols and systems*. Pearson Education.
[20] Toh, C. K. (2002). Maximum battery life routing to support ubiquitous mobile computing in wireless ad hoc networks. *IEEE communications Magazine*, *39*(6), 138-147.
[21] Yu, M., Tate, S. R., & Green, M. B. (2002). Power-aware routing in mobile ad hoc networks, Mobile and Wireless Communication Networks, *Springer,* 123–130.
[22] Zapata, M. G., & Asokan, N. (2002, September). Securing ad hoc routing protocols. In *Proceedings of the 1st ACM workshop on Wireless security* (pp. 1-10).

Authors Biography

Anoop Dev is a researcher at the Centre of Research Impact and Outcome, Chitkara University, Punjab, India. His work focuses on the application of emerging technologies to enhance societal and industrial outcomes through innovation and impact-driven research. He is involved in multidisciplinary projects that aim to bridge the gap between academic research and practical implementation. With a strong commitment to collaborative research and knowledge dissemination, Anoop Dev contributes to scholarly publications and actively engages in the development of sustainable and technology-oriented solutions.

Nasrulla Khan K is an Assistant Professor in the Department of Computer Applications at Presidency College, Bengaluru. His academic and research interests include software development, data analytics, artificial intelligence, and modern programming paradigms. He is actively engaged in mentoring students, developing innovative curricula, and contributing to academic publications. With a focus on bridging theoretical knowledge with real-world applications, Nasrulla Khan K is committed to fostering student-centric learning and advancing research in emerging areas of computer science.

Nagraj Patil is an Associate Professor in the Department of Mechanical Engineering at JAIN (Deemed-to-be University), Karnataka, India. His academic expertise spans thermal engineering, fluid mechanics, computational modeling, and sustainable manufacturing practices. With several years of experience in teaching, research, and industrial collaboration, he has contributed to national and international publications, conferences, and technical workshops. Dr. Patil is passionate about bridging the gap between theoretical knowledge and industrial applications, and he plays a key role in mentoring undergraduate and postgraduate students in applied mechanical engineering research.

Dr. Suman Sau is an Associate Professor in the Department of Computer Science and Information Technology at Siksha 'O' Anusandhan (Deemed to be University), Bhubaneswar. His research interests include artificial intelligence, machine learning, cybersecurity, and data science. With a strong academic background and a robust portfolio of research publications, Dr. Sau actively contributes to interdisciplinary research and collaborative academic projects. He is also involved in mentoring students and guiding research scholars in advanced computing technologies, while participating in national and international academic forums and conferences.

Neha Arora is an Assistant Professor in the Department of Computer Science Engineering at Presidency University, Bengaluru. Her academic and research interests include software engineering, machine learning, data analytics, and cloud computing. With a strong focus on both theoretical foundations and practical applications, she has contributed to several peer-reviewed journals and conferences. Neha Arora is dedicated to promoting student engagement in research and innovation, and she actively collaborates in interdisciplinary academic initiatives. Her work aims to bridge the gap between academia and industry through meaningful research contributions and effective pedagogy.

Arjun Singh is a faculty member in the School of Engineering & Computing at Dev Bhoomi Uttarakhand University, Dehradun. His academic interests lie in the areas of electronics and communication engineering, embedded systems, and signal processing. With a passion for advancing technical education and hands-on learning, he actively contributes to teaching, student mentorship, and collaborative research projects. Arjun Singh aims to foster innovation by integrating emerging technologies into the academic environment and participating in interdisciplinary research initiatives that address real-world challenges.