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A Comprehensive Review of Load and Energy-Efficient Geographic Routing Protocols in MANETs

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Abstract

Mobile ad hoc networks (MANETs) are wireless networks that do not have any self-configuring infrastructure. Routing in MANETs is a challenging task because of frequent topology changes, limited bandwidth, and power-limited mobile nodes. Geographic routing protocols offer a promising path towards scalability and location-based communication. Nevertheless, the performance of the protocols often degrades under high mobility and power constraints. This review paper presents a comprehensive overview of energy-efficient and load-balanced geographic routing protocols for MANETs, such as AODV, EAODV, ELGR, LAR, DREAM, and ZRP. We classify the protocols according to their routing strategy and test their ability to ensure balanced energy consumption and load distribution. Additionally, we outline the limitations of previous protocols and introduce the motivation behind developing the load and energy-aware geographic routing (LEGR) protocol. Finally, directions for future work to optimize routing performance in dynamic and energy-constrained networks are presented.

Keywords: MANETs, Geographic Routing, Energy Efficiency, Load Balancing, AODV, EAODV, ELGR, Routing Protocols, LEGR

1. Introduction

Mobile Ad Hoc Networks (MANETs) are self-configuring wireless networks composed of mobile nodes that communicate with each other without relying on any pre-existing infrastructure, such as routers or base stations[1]. Each device in a MANET is free to move independently, leading to frequent changes in network topology. Due to their decentralized nature, MANETs have become increasingly important in scenarios where fixed infrastructure is unavailable or impractical, such as in military battlefield communications, emergency response and disaster recovery, intelligent transportation systems, and remote sensing environments[2]. Figure 1 illustrates the general structure of various mobile nodes in a MANET.

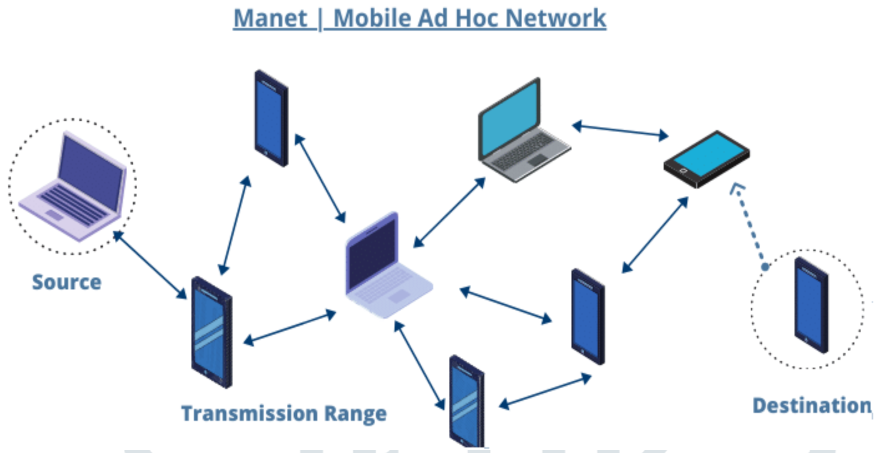

Figure 1: MANET architecture and components.

Routing in MANETs presents a significant challenge because of the highly dynamic topology, limited transmission range, variable wireless link quality, and constrained energy resources of the participating nodes[3]. Traditional routing protocols used in wired or infrastructure-based networks are generally unsuitable for MANETs due to their assumptions of stable paths and continuous power availability[4]. To address these challenges, several routing protocols have been developed specifically for MANETs, broadly classified into proactive, reactive, hybrid, and geographic routing categories[5]. Figure 2 illustrates the main categories of routing protocols in MANETs.

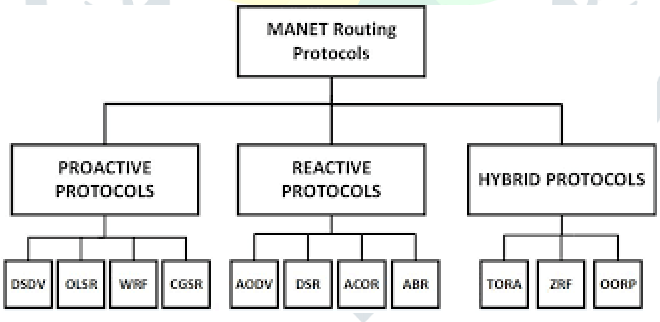

Figure 2: Types of MANET routing protocols.

Among these, **geographic routing protocols** have attracted considerable attention due to their scalability and efficiency in dynamic environments[6, 7]. These protocols utilize the geographical position of nodes—obtained through GPS or other localization techniques—to make localized forwarding decisions, often without maintaining complete route information[8]. This reduces routing overhead and enables the protocol to scale better in large networks. Notable geographic routing protocols include Location-Aided Routing (LAR), Distance Routing Effect Algorithm for Mobility (DREAM), and Energy-efficient Load-balanced Geographic Routing (ELGR)[9].

However, despite the advantages of geographic routing, many existing protocols suffer from critical limitations. Most notably, they often overlook the **trade-off between energy efficiency and load balancing**. As mobile nodes in MANETs operate on limited battery power, excessive or uneven packet forwarding responsibilities can lead to premature energy depletion in some nodes, resulting in **network partitioning**, **increased packet loss**, and **reduced network lifetime**. Similarly, failure to distribute load efficiently can cause congestion, increased delays, and lower throughput[10].

Consequently, **designing routing protocols that simultaneously address energy consumption and load distribution** has become a vital area of research in MANETs. Efficient load balancing ensures fair usage of network resources, while energy-aware mechanisms prolong the operational life of nodes and the overall network. A combined approach that considers **residual energy, node connectivity, queue status, and mobility patterns** can help in making smarter routing decisions that enhance the robustness and longevity of MANETs[11].

This review paper focuses on analysing existing geographic routing protocols with an emphasis on their energy and load balancing capabilities[12]. It highlights their strengths and limitations, identifies critical research gaps, and proposes the need for an integrated solution such as the **Load and Energy-efficient Geographic Routing (LEGR)** protocol. The subsequent sections discuss the routing challenges, existing literature, comparative evaluations, and directions for future research aimed at achieving more sustainable and efficient communication in MANETs.

2. Routing Challenges in MANETs

Routing in Mobile Ad Hoc Networks (MANETs) is a complex task due to the absence of centralized control, dynamic network conditions, and resource constraints. Several intrinsic characteristics of MANETs pose significant challenges to the design and implementation of efficient and reliable routing protocols. These challenges must be carefully addressed to maintain optimal network performance, ensure scalability, and prolong network lifetime. The major routing challenges in MANETs include:

- **Dynamic Topology:** One of the most critical challenges in MANETs is their highly dynamic topology. Since nodes are mobile, the network structure can change unpredictably and frequently. Routes established at one moment may become invalid moments later due to node movement or link breakages. This requires routing protocols to be adaptive, capable of quickly discovering new routes and maintaining communication even in the presence of frequent topology changes[13].
- **Limited Energy Resources:** Most nodes in MANETs are powered by batteries with limited capacity[14]. Energy is consumed during data transmission, reception, and processing. If some nodes deplete their batteries faster than others—especially those that frequently participate in routing—network partitions may occur, resulting in degraded performance or complete communication failure. Therefore, energy-aware routing is essential to prolong the operational lifespan of both individual nodes and the network as a whole.
- **Scalability:** As the number of nodes in a MANET increase, the complexity of route discovery and maintenance also grows[5]. A routing protocol must scale efficiently to accommodate networks ranging from a few nodes to potentially hundreds or thousands. Scalability involves minimizing control overhead, maintaining reasonable route accuracy, and avoiding excessive flooding of control messages that could congest the network and waste resources.
- **Load Balancing:** In many routing protocols, certain nodes may become overloaded due to repeated use in multiple paths, leading to congestion, increased packet delays, and faster energy depletion[15]. Uneven traffic distribution can significantly impact network stability and fairness. Effective load balancing ensures that routing responsibilities are evenly distributed among nodes based on parameters like energy level, buffer status, and node degree, thereby enhancing reliability and performance.
- **Quality of Service (QoS) Requirements:** Many applications deployed over MANETs—such as real-time video transmission, VoIP, and emergency alerts—demand guaranteed levels of service. Routing protocols must therefore account for Quality of Service (QoS) parameters such as low latency, minimal packet loss, high throughput, and guaranteed bandwidth. Achieving QoS in a dynamic and resource-constrained environment like MANET is inherently difficult, especially when combined with energy and load balancing requirements.

In summary, designing routing protocols for MANETs requires careful consideration of these diverse and interdependent challenges. Protocols must not only establish and maintain routes effectively but also optimize resource usage, ensure fairness, and adapt to changing network conditions. Addressing these challenges is crucial to developing robust, energy-efficient, and scalable routing strategies for MANET environments.

3. Existing Geographic Routing Protocols

To address the unique challenges of routing in Mobile Ad Hoc Networks (MANETs), numerous geographic and energy-aware routing protocols have been developed[16, 17]. These protocols aim to leverage the physical location of nodes to improve routing decisions while optimizing performance metrics such as energy consumption, delay, and packet delivery. Below is an overview of some widely adopted and researched protocols:

- **AODV (Ad hoc On-Demand Distance Vector):** AODV is a widely used reactive routing protocol that establishes routes only when required by a source node[18]. It uses Route Request (RREQ) and Route Reply (RREP) messages to discover paths between nodes. While AODV is efficient in terms of control overhead during idle periods, it does not incorporate any geographic or energy-awareness in its design, which can limit its performance in highly dynamic or resource-constrained environments[2].
- **EAODV (Energy-Aware AODV):** EAODV is an enhancement of the standard AODV protocol, introducing residual energy awareness into the route discovery process[19]. It selects routes not only based on hop count but also by considering the energy levels of participating nodes. This approach helps extend network lifetime by avoiding nodes with low energy, thus preventing early node failures and potential network partitioning.
- **ELGR (Energy-efficient Load-balanced Geographic Routing):** ELGR is a geographic routing protocol that combines both energy efficiency and local load balancing strategies[20]. It introduces two significant spatial concepts—Destination Area (DA) and Forwarding Area (FA)—to guide the routing process. DA refers to the region where the destination node is expected to reside, while FA represents the zone from which the forwarding node is selected. By integrating energy and load metrics into geographic routing decisions, ELGR attempts to balance traffic and reduce premature energy exhaustion of critical nodes.
- **LAR (Location-Aided Routing):** LAR reduces the overhead associated with route discovery by using location information to define a "request zone" where RREQ messages are propagated[21]. This limits unnecessary flooding across the entire network. However, LAR assumes accurate and timely availability of location data, which may not always be feasible in highly mobile or obstructed environments.
- **DREAM (Distance Routing Effect Algorithm for Mobility):** DREAM is designed to utilize the mobility pattern of nodes by predicting their direction and speed[22]. It attempts to forward packets in the direction of the destination based on these predictions. While DREAM is efficient in theory, in practice it suffers from excessive control overhead due to frequent beaconing and location updates, especially in dense or fast-moving networks.
- **ZRP (Zone Routing Protocol):** ZRP is a hybrid routing protocol that combines proactive and reactive strategies[11, 23]. Within a defined local zone, routing is proactive, meaning routing tables are maintained regularly. For communication beyond the local zone, ZRP uses reactive routing to reduce overhead. This balance allows ZRP to adapt to varying node densities and mobility levels but requires careful tuning of zone radius for optimal performance[24].

In conclusion, while each of these protocols addresses specific limitations in MANET routing, they also bring their own set of trade-offs. AODV and its variants focus on simplicity and energy awareness, while ELGR, LAR, and DREAM emphasize geographic information and load balancing. However, no single protocol optimally satisfies all requirements, highlighting the need for more comprehensive routing solutions that jointly consider energy efficiency, geographic awareness, load balancing, and adaptability to dynamic topologies.

4. Energy and Load Balancing Techniques in Literature

Efficient energy utilization and effective load balancing are critical for ensuring the prolonged operation and reliability of Mobile Ad Hoc Networks (MANETs)[15, 25, 26]. To address these challenges, researchers have proposed a variety of mechanisms that integrate energy-aware and load-aware strategies into routing protocols. These techniques are often used in isolation or in combination to enhance overall network performance. Some of the prominent strategies discussed in the literature include:

- **Residual Energy Monitoring:** This technique involves each node periodically monitoring and broadcasting its remaining battery level to neighboring nodes. Routing decisions are then influenced by this information to avoid low-energy nodes, thereby extending the overall network lifetime. Residual energy thresholds are often used to determine whether a node should participate in forwarding packets or enter a sleep mode to conserve power.
- **Load Estimation Mechanisms:** Load balancing in MANETs often relies on measuring the workload of nodes by tracking parameters such as queue length, number of active flows, or the rate of packet processing. Nodes with high queue lengths are considered heavily loaded and may be bypassed in favor of less burdened alternatives. This approach prevents congestion and ensures more equitable use of network resources.

- **Geographic Constraints for Forwarding Control:** Several routing protocols introduce spatial constraints to limit the number of nodes involved in packet forwarding. For instance, the use of a **Destination Area (DA)**—where the destination node is expected to reside—and a **Forwarding Area (FA)**—the region through which packets are relayed—helps narrow the candidate nodes for routing. This not only reduces routing overhead but also minimizes unnecessary energy consumption caused by redundant transmissions.
- **Adaptive Delay-Based Forwarding:** In this approach, nodes introduce controlled delays in forwarding control packets such as Route Requests (RREQs) or Route Replies (RREPs) based on their residual energy levels. Nodes with higher energy respond faster, whereas nodes with lower energy introduce longer delays or remain silent. This prioritization mechanism ensures that more energy-efficient routes are discovered without completely excluding low-energy nodes from the routing process.
- **Multipath Routing Strategies:** To further enhance load distribution and fault tolerance, multipath routing techniques are employed. These strategies establish multiple disjoint or partially disjoint paths between source and destination nodes. By distributing data across these paths, the network prevents overutilization of a single route and reduces the chance of congestion and early node failures. Multipath routing also improves reliability in dynamic topologies where links may frequently break.

Collectively, these techniques contribute to improving the robustness, scalability, and longevity of MANETs[25, 26]. However, each technique comes with its trade-offs in terms of overhead, complexity, and adaptability, thereby highlighting the importance of designing hybrid approaches that can dynamically adapt to varying network conditions.

Comparative Analysis Table

Protocol	**Type**	**Energy Aware**	**Load Balancing**	**Geographic Info**	**Advantages**	**Limitations**
AODV[27]	Reactive	No	No	No	Simple, widely used	Not energy efficient
EAODV[28]	Reactive	Yes	Partial	No	Prolongs network lifetime	Limited load balancing
ELGR[29]	Geographic	Yes	Yes	Yes	Region-based, scalable	Moderate improvement
LAR[21]	Geographic	No	No	Yes	Reduced search space	Inefficient flooding
DREAM[30]	Geographic	No	No	Yes	Predictive forwarding	High overhead
ZRP[23]	Hybrid	No	No	No	Efficient zone-based routing	Not energy-aware

5. Research Gaps Identified

Although significant progress has been made in the development of geographic routing protocols for Mobile Ad Hoc Networks (MANETs), a detailed review of the existing literature reveals several unresolved issues that continue to hinder optimal network performance. The following key gaps have been identified:

- **Lack of Integrated Optimization for Energy and Load Balancing:** Most existing protocols tend to focus exclusively on either energy efficiency or load balancing. Very few provide a unified framework that simultaneously optimizes both, which is critical for achieving sustainable performance in resource-constrained MANET environments.
- **Absence of Intelligent Adaptation to Node Mobility and Residual Energy:** MANETs are characterized by dynamic topologies due to frequent node movement. However, current protocols often fail to incorporate real-time mobility patterns and residual battery levels into routing decisions. This leads to suboptimal path selection and increased risk of communication failure.
- **Underutilization of Spatial Forwarding Region Constraints:** While some protocols employ concepts such as Forwarding Area (FA) and Destination Area (DA), these spatial constraints are not always fully exploited. Limited use of such mechanisms results in higher control overhead and less efficient forwarding decisions, particularly in dense or rapidly changing networks.

- **High Overhead in Maintaining Accurate Node State Information:** Maintaining up-to-date information on node location and energy status is crucial for geographic routing but introduces considerable control overhead. Existing methods often lack lightweight strategies to manage this trade-off, thereby affecting the scalability of the network.
- **Inadequate Response to Energy-Depleted Nodes:** Many protocols do not include proactive mechanisms to prevent the use of nodes that are critically low on energy. As a result, these nodes continue to be used in routing paths until failure occurs, leading to disruptions in communication and reduced overall network reliability.

These limitations underline the need for a more adaptive and comprehensive routing solution. To address these gaps, a novel protocol—**LEGR (Load and Energy-aware Geographic Routing)**—is proposed. LEGR aims to integrate energy and load awareness into geographic routing through intelligent region-based forwarding, adaptive energy thresholds, and control packet mechanisms. This approach is envisioned to enhance both network longevity and data delivery performance under varying mobility and density conditions.

Conclusion and Future Directions

This paper presented a comprehensive review of geographic routing protocols in Mobile Ad Hoc Networks (MANETs), with particular emphasis on energy efficiency and load balancing. Through a detailed comparative analysis of established protocols such as AODV, EAODV, ELGR, LAR, DREAM, and ZRP, it has been demonstrated that although these protocols offer significant advantages in specific scenarios, none of them provide a holistic solution to the challenges posed by node mobility, constrained energy resources, and dynamic network topologies. The study identified several critical gaps, including the lack of integrated optimization strategies for both energy conservation and traffic load balancing, inadequate adaptability to real-time node status and mobility, and high control overhead due to inefficient management of location and energy data.

To address these issues, the paper proposes the development of a new routing framework—**LEGR (Load and Energy-aware Geographic Routing)**—which seeks to intelligently combine spatial awareness, residual energy estimation, and adaptive load distribution mechanisms for more efficient and reliable routing in MANETs. LEGR is designed to enhance packet delivery rates, extend network lifetime, and reduce energy wastage through region-based forwarding and dynamic control packet management.

Looking forward, future research should focus on augmenting LEGR with **machine learning and artificial intelligence techniques** to enable predictive route selection and real-time decision-making. Additionally, incorporating **energy harvesting models** could transform nodes into more sustainable communication entities, reducing dependency on finite battery resources. Research should also explore **cross-layer optimization** and **security enhancements** to protect against routing attacks in hostile or mission-critical environments. The integration of such intelligent, adaptive, and secure mechanisms will be key to realizing the full potential of MANETs in next-generation wireless communication systems.

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