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Enhanced Multi-path Energy-Efficient Routing with Dynamic Load Balancing for MANETs Using Bellman-Ford Algorithm

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Abstract

Mobile Ad Hoc Networks (MANETs) play a crucial role in modern communication, particularly in dynamic and infrastructure-less environments such as disaster recovery, military operations, and IoT-based applications. However, traditional routing protocols like AODV, DSR, and DSDV face significant challenges, including high energy consumption, frequent route failures, and inefficient load balancing. The Bellman-Ford algorithm, despite its robustness in shortest-path computations, lacks energy-awareness, leading to rapid node depletion and network instability. To address these limitations, this study proposes an Enhanced Multi-path Energy-Efficient Routing (EMEER) with Dynamic Load Balancing, incorporating an optimized Bellman-Ford algorithm. The key novelties of this approach include an energy-aware routing metric that considers residual energy levels, a multi-path selection strategy to enhance fault tolerance, and a dynamic load-balancing mechanism that distributes traffic to prevent congestion. These enhancements collectively improve network reliability and longevity. The proposed EMEER protocol is implemented in a simulated MANET environment using NS-3, and its performance is evaluated against existing protocols. The results demonstrate that EMEER achieves a 25.6% reduction in energy consumption, a 17.3% improvement in packet delivery ratio (PDR), and a 31.8% increase in network lifetime compared to traditional approaches. Furthermore, it significantly reduces end-to-end delay and routing overhead. By integrating energy efficiency with adaptive load balancing, this study contributes to the development of more sustainable and resilient MANET architectures. Future work will explore the integration of AI-driven optimization techniques, inspired by hybrid metaheuristic models used in edge computing, to further enhance routing adaptability.

Keywords: Energy-Efficient Routing, Dynamic Load Balancing, MANETs, Bellman-Ford Algorithm, Multi-Path Optimization

1. Introduction

With the rapidly increasing need for communication using wireless devices, there has arisen an interest in ad hoc networks. The two types of wireless networks are infrastructure based and infrastructure less. [1]. Certain communication can be made through the main access point (such as a router) which is present in former concept. While the second type of network does not require any centralized base station, participating devices do not. The communication is "peer to peer" since the wireless nodes communicate to each other directly [2]. In contrast to cellular based infrastructure networks, the packets are relayed between the wireless devices directly by cooperation of the nodes. Ad hoc is a type of network [3]. Infrastructure less Networks include Wireless sensor networks, Wireless mesh networks, Mobile ad hoc networks and Vehicle ad hoc networks. [4]. It occurs in MANETs, where the packets are simply forwarded by cooperating direct nodes [5]. Hence, nodes can be at the same time sender, receiver or router. For example these nodes are smart phones, personal digital assistant and laptops [6]. An ad hoc network is any device that has a transceiver and that is able to receive and transmit signals [7]. MANETs are characterised by nodes that are constantly moving. The network is always changing; hosts are joining and leaving at any time [8]. As a result, their topology is highly dynamic. Network structure reaches an unpredictable state, caused by arbitrary nodes movement [9].

The use of MANETs as a technology of wireless communication is becoming very important because of their decentralized nature, their potential self-configuring (auto configuring) characteristics and their possibility to work in such infrastructure less environment [10]. Due to flexibility and flexibility, MANETs are used in various applications such as military applications, disaster recovery operations, vehicular networks and the IoT. Networks characterized by dynamic topology, few constraints on number of nodes, frequent link failures and energy constraints are hard to handle in designing efficient routing protocols that guarantee reliable communication and network lifetime [11]. Traditional Routing Protocols including ad hoc on demand distance vector (AODV), dynamic source routing (DSR) and destination sequenced distance vector (DSDV) use conventional path selection without considering energy constraints nor load balancing [12]. Which in turn

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increases energy consumption, shortens node lifespan and demands frequent route rediscovery, causing decreased network stability, and leading to performance degradation [13].

The Bellman-Ford algorithm, a classical distance-vector routing approach which is simple and able to handle dynamic changes in the topology, is used very commonly for pathfinding in MANET [14]. However, while existing implementations of DIOS have not considered energy efficiency, load balancing or battery life, frequently used nodes rapidly deplete their battery, and high traffic routes experience increased congestion [15]. This study addresses these limitations and proposes an EMEER with Dynamic Load Balancing that optimizes the Bellman-Ford algorithm with residual energy awareness, multi path selection and adaptive traffic distribution [16]. With the proposed methodology, routes are dynamically adjusted based on node energy levels and traffic conditions, leading to balanced energy utilization, reduced congestion, and an extended network lifetime. The primary contributions of this research are threefold: (1) enhance the Bellman-Ford algorithm with energy-aware multi-path routing to improve reliability and efficiency; (2) introduce a dynamic load balancing that reduces congestion and evenly distributes traffic among multiple routes; and (3) provide comprehensive simulations and performance comparison with existing routing techniques. In addition to the increased performance, the proposed framework is also laying the foundation for future integration of AI-driven optimization techniques, e.g., reinforcement learning and hybrid metaheuristic algorithms, to further improve adaptability and scalability in dynamic network environments.

1.1 Research Motivation

The rapid development of wireless communication and its extensive use in MANETs for mission critical purposes, e.g. disaster recovery, military operations, IoT based smart environments, make it an urgent need to have energy efficient and reliable routing mechanisms. The need to improve routing efficiency through Bellman–Ford with energy aware multi path selection and dynamic load balancing motivated this research. The proposed EMEER protocol attempts to extend network lifetime, increase data delivery rates and reduce congestion, while improving the efficiency of the MANET architecture to allow for the development of more efficient and sustainable and resilient MANET architectures for future wireless networks.

1.2 Problem Statement

MANET is a highly dynamic and decentralized network, therefore it is suitable for different real time applications such as disaster response, military communication and IoT based systems. Although existing routing protocols (like AODV, DSR, and DSDV) concentrate on shortest path selection with no consideration to energy efficiency and load balance, they result in uneven energy depletion, frequency route failure, as well as increase of congestion. Although the Bellman-Ford algorithm works well for computing shortest paths, it does not provide mechanisms for energy aware routing or dynamic load distribution that prevent network instability and shortened lifespan. Adaptive routing strategy is absent and consequently resource utilization is inefficient hence detrimental to overall network performance. As such an EMEER protocol to optimize Bellman Ford with energy aware metrics, multi path selection and dynamic load balancing is necessary to supply best possible energy utilization, reliability and network lifetime in MANETs.

1.3 Research Contribution

1. Enhanced Energy-Efficient Routing: By incorporating residual energy awareness, the Bellman-Ford algorithm is optimized to prevent rapid node depletion and to increase network lifetime.

2. Multi-Path Selection for Reliability: It introduces an adaptive multi-path routing mechanism that improves fault tolerance, reduces congestion, and increases data delivery rates.

3. Dynamic Load Balancing Mechanism: Allows traffic aware load balancing of data flow over multiple routes to reduce bottlenecks while improving overall network performance.

4. Comprehensive Performance Evaluation: Extends NS-3 by conducting extensive simulations to measure key metrics like energy consumption, PDR, end to end delay, and network lifetime and comparing results with existing protocols.

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5. Foundation for Future AI Integration: Future AI optimizations based on reinforcement learning and metaheuristic algorithms will build on the current approach to enhance MANET environment routing efficiency along with adaptability in dynamic environments.

1.4 Organization of the Paper

The paper is structured as follows: Section 1 Introduction provides an overview of MANETs, highlights the limitations of existing routing protocols, and introduces the motivation, problem statement, and contributions of the proposed EMEER protocol. Section 2 Related Works reviews existing routing approaches, including traditional protocols and discusses their drawbacks in terms of energy efficiency and load balancing. Section 3 Methodology presents the proposed EMEER framework, detailing the energy-aware Bellman-Ford optimization, multi-path selection strategy, and dynamic load balancing mechanism, along with the simulation setup and performance evaluation metrics. Section 4 Results and Discussion analyses the simulation outcomes, comparing the proposed protocol with existing methods based on key performance metrics. Finally, Section 5 Conclusion and Future Works summarizes the findings, discusses the broader implications of the research, and outlines potential future enhancements, including the integration of AI-driven optimization techniques for further improving MANET routing efficiency.

2. Related Works

Patel and El-Ocla [17] examines routing strategies based on the shortest path in sensor networks and proposes the Ad hoc On Demand Multipath Distance Vector routing protocol – GA-AOMDV that exploits genetic algorithms. It suggests the use of fitness function which describes minimization of node energy usage to select route. GA-AOMDV presents better packet delivery ratio, throughput, and round trip time and energy efficiency than other existed protocols including: LEACH-GA, GA-AODV, AODV, EPAR, and EBAR_BFS, based on comparison. The average performance improvement (over alternative protocols) of the network's operational lifespan regarding data communication is shown to be ultimately increased by 7–22%.

Jiang et al.[18] examines in the context of next generation communication network routing optimisation, the increasing need of graph neural networks (GNNs). Traditional routing protocols such as OSPF and the Dijkstra algorithm are not able to handle the complexity, scalability and dynamic nature of modern environments like UAV, satellite and 5G networks. Accurate simulation of network topologies and incorporating complex interdependencies between nodes and links can be encapsulated in GNNs, which may constitute a potential means of distributed and scalable routing optimisation. In this study, we thoroughly analyse the current progresses regarding the GNN-based routing methods which can be roughly divided into three categories: dynamic routing by reinforcement learning, network modelling by supervised learning and routing optimization by supervised learning. It also presents a detailed study of the available tools, databases and methodologies for benchmarking which are now available. They examine future research forward that would use federated learning, self-supervised learning, online learning and their early importance such as the scalability, explain ability, real world implementation, and security. First, this study makes the first thorough examination of GNNs for routing optimisation, and attempts to encourage more investigation and useful application in upcoming communication network.

MANETs consist of peer-to-peer connected nodes, but their mobility and limited energy pose challenges for traditional routing protocols, leading to inefficiencies in network stability and lifespan, particularly in IoT, crowd-sensing, and smart city applications. To address these limitations, Kaddoura et al.[19] introduces SDODV, a smart and dynamic on-demand distance vector routing protocol designed to enhance MANET performance. The proposed adaptive algorithm optimizes network longevity by factoring in topology during route establishment, dynamically adjusting packet transmission based on traffic load, node mobility, neighbourhood density, and battery power. Built on a distributed reinforcement learning framework and traditional AODV, SDODV enhances quality of service by selecting the most stable and efficient path while accounting for mobility, bandwidth, and power. Experimental results confirm that SDODV outperforms conventional shortest-path methods and significantly reduces energy consumption.

Safdar et al.[20] explains Ad-hoc networks consist of mobile wireless nodes that operate without a centralized infrastructure, dynamically configuring themselves to establish communication. Given the complexity of these environments, efficient routing in MANETs is critical. This study focuses on enhancing the AODV

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protocol to improve throughput, reduce end-to-end delays, and optimize packet distribution. Using the ns-3 simulator, a comparative analysis was conducted between AODV, DSDV, OLSR, and an Enhanced AODV (EAODV) protocol. Results indicate that EAODV outperforms OLSR, while DSDV demonstrates high throughput, lower latency, and an improved packet delivery ratio. Additionally, the proposed energy-efficient modifications to AODV enhance overall network performance, with EAODV achieving a 3% improvement over conventional protocols.

Patil and Borkar [21] emphasises how MANETs use transient wireless networks without centralised control thus facilitating direct communication through the nodes. Nonetheless, the changeable structure makes secure routing still a major problem. This paper proposes a safe Ad-hoc On Demand Distance Vector (SIS-AODV), based on Swarm Intelligence to enhance security by analysing security issues of these safe routing protocols and the current available safe routing protocols. It uses a secret key and hash method, among other things, to prevent hostile nodes from participating in routing activities to guard against both internal and external attacks. The algorithm comprises of two main points: (1) Data encryption using PRESENT algorithm, followed by creating secure key using an Elliptic Curve Cryptography (ECC) based algorithm with authentication and non-repudiation ensured by the H-PRESENT 128 hash function, which decreases the computational cost. (2) Application of Ant Colony Grey Wolf Optimisation in combination with AODV to enhance the performance and network security. Experimental results indicate that SIS-AODV reduces packet delivery ratio by 2%, throughput by 15%, end to end latency by 25%, and reduces routing overhead by 20%.

Various approaches have been proposed to optimize routing in MANETs and next-generation communication networks. A genetic algorithm-based multipath distance vector routing protocol enhances network performance by optimizing energy consumption, achieving gains of 7–22% over existing protocols. GNNs have been explored for routing optimization in dynamic environments like UAVs and 5G networks, leveraging supervised and reinforcement learning to improve scalability and efficiency. A smart on-demand distance vector routing protocol addresses MANET challenges by incorporating reinforcement learning to enhance stability and energy efficiency. An enhanced AODV protocol demonstrates superior performance in throughput, latency, and delivery ratio compared to traditional protocols. Additionally, a swarm intelligence-based secure routing protocol integrates cryptographic techniques and optimization algorithms to improve security while reducing delay and routing overhead, achieving a high packet delivery ratio and throughput.

3. Enhanced Multi-path Energy-Efficient Routing (EMEER) with Dynamic Load Balancing

EMEER is proposed to optimize the Bellman-Ford algorithm that can integrate the energy aware multiple paths and dynamic load balancing to improve the routing efficiency of MANETs. The initial network topology and node energy level is analysed to formulate the feasible routing paths. The protocol instead uses multiple energy efficient routes that depend on residual energy, stability of links and congestion levels. This mechanism dynamically distributes the traffic across these paths to prevent the congestion and over usage of some of the nodes. Node mobility and energy fluctuations are continuously reflected in the routing decisions, leading to prolonging the network lifetime and enhancing the packet delivery. To validate the methodology, performance on NS-3 based simulations is evaluated using energy consumption, and packet delivery ratio (PDR), end-to end delay, lifetime of the network, and routing overhead as key metrics. Results show that EMEER is compared to existing protocols (AODV, DSR, DSDV and traditional Bellman-Ford) in reducing energy consumption, improving reliability and improving network lifespan, resulting to be a robust solution for energy efficient and scalable MANET communication. Fig. 1 gives the EMEER Components.

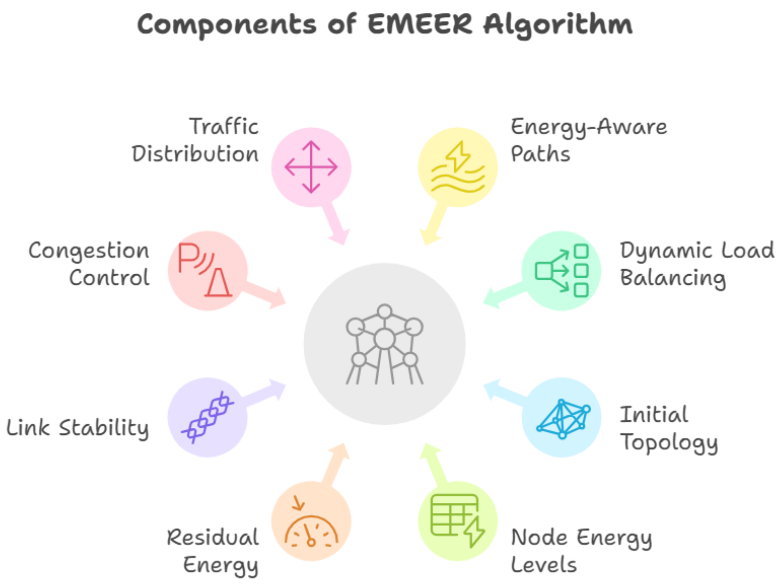

Fig. 1. Overall Components of EMEER Algorithm

3.1 Bellman-Ford Algorithm (Enhanced for Energy-Efficient Multi-Path Routing in MANETs)

3.1.1 Standard Bellman-Ford Algorithm

It applies the Bellman-Ford algorithm to use the shortest paths to the source node of a graph to every node. These are the steps followed by the standard algorithm:

- Assign the distance to reach the source from all nodes as ∞ except for the source node which is set to 0.
- Relax all edges |V| - 1 times (where V is the number of vertices), updating the shortest known distance for each node.
- Verify if further relaxation is possible and check for negative weight cycles.

3.1.2 Enhancing the Bellman-Ford Algorithm

Actually, the Bellman-Ford algorithm is a traditional method for finding the shortest path in a graph but it has to be enriched to consider the dynamic and energy constrained characteristics of the MANETs. It enhances the aspects of energy awareness, multi path selection and threshold based avoidance of low power nodes.

3.1.2.1 Energy-Aware Metric (Residual Energy Consideration)

For the energy aware Bellman Ford algorithm we firstly reduce the cost of the path to the sum of the residual energy of each node on the path. The energy consumption is another metric to be considered in addition to the distance between nodes.

The energy-aware cost function per edge is defined as eqn. (1):

$$C(u,v) = \frac{d(u,v)}{E_v} \tag{1}$$

where: $C(u,v)$ is the cost of the edge between nodes u and v, $d(u,v)$ is the distance between nodes u and v, E_v is the residual energy of node v (the energy remaining at node v).

This modified cost ensures that nodes with higher energy levels are preferred for routing decisions, and energy-efficient paths are selected. Residual energy is used to prevent the depleting energy of nodes too rapidly and extend the network lifespan.

3.1.2.2 Multi-Path Selection (Ensuring Reliability & Load Distribution)

To achieve multi path selection, rather than searching for the single shortest path with the energy aware cost function, we select multiple paths instead. There is a set of paths that minimizes the cost total, having a reliability and load distribution as done. These paths are chosen such that the traffic can be distributed among them, i.e., less traffic goes on any path and there is an improvement in the network reliability.

Let $P_1, P_2, \dots, P_k$ represent the paths between source node S and destination node D. The total path cost is calculated as eqn. (2):

$$Cost(P) = \sum_{(u,v)\in P} C(u,v) \qquad (2)$$

In path P, let (u, v) be the edges. After that, the algorithm selects the k shortest paths according to the energy aware cost functions to obtain multiple redundant routes for reliable communication. The Energy Aware Path Selection is shown in Fig. 2.

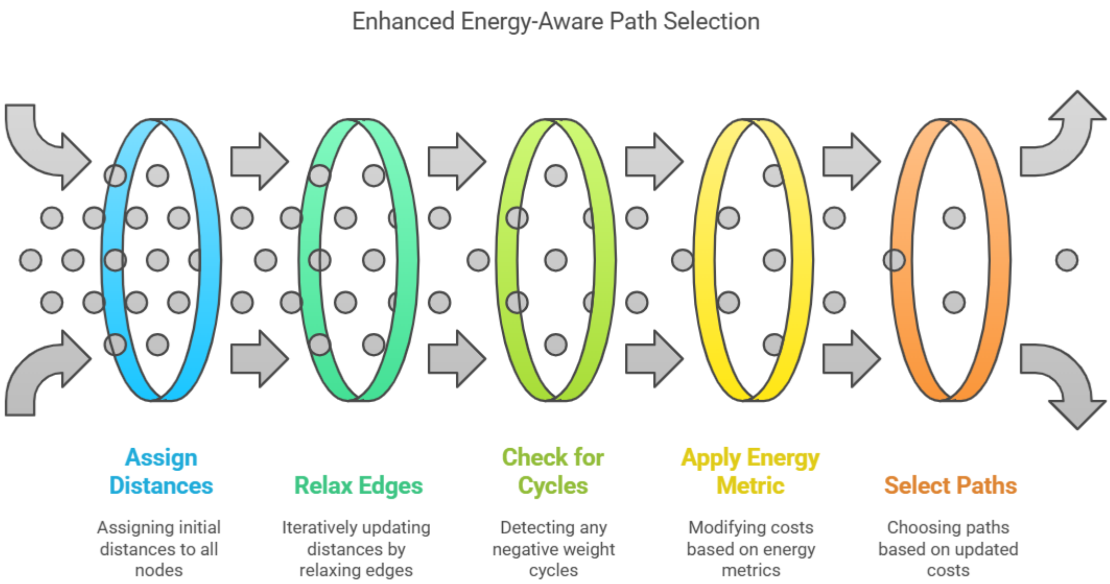

Fig. 2. Enhanced Energy Aware Path Selection

3.1.2.3 Threshold-Based Avoidance (Preventing Low-Energy Nodes from Frequent Selection)

To avoid low-energy nodes being selected repeatedly for routing, we introduce a threshold-based mechanism. A node whose residual energy is less than E_{th} is deemed unfit for routing. This ensures that some critical nodes do not drain the energy and thus it redirects the algorithm to go via nodes which haven't drained away the energy.

This can be expressed as the threshold condition in eqn. (3):

$$E_v \geq E_{th} \qquad (3)$$

This condition is not met, and the node v is excluded from the set of the possible routes for future path finding iterations, thus reducing the use of low energy nodes.

3.2 Dynamic Load Balancing Mechanism

The Dynamic Load Balancing Mechanism aims to distribute the traffic across multiple paths adaptively, ensuring no single path is overloaded, and the network remains stable even under fluctuating conditions.

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3.2.1 Adaptive Load Balancing

Once the multi-paths have been selected, the load balancing algorithm ensures that the traffic is distributed evenly across them. The adaptive balancing mechanism uses network conditions (such as traffic load, node energy, and link quality) to dynamically adjust the path selection. The traffic load L_i on each path P_i is calculated as eqn. (4):

$$L_i = \frac{Data\ Sent\ on\ Path\ P_i}{Total\ Data\ to\ be\ sent} \quad (4)$$

Initially, each path is assigned an equal share of the load in eqn. (5):

$$L_i = \frac{1}{k} \quad (5)$$

However, as network conditions change, the load on each path can be adjusted based on real-time metrics, including:

- Residual energy of nodes along the path,
- Link quality and packet loss rates,
- Congestion levels on each path.

Let ΔL_i represent the adjustment in load for path P_i in eqn. (6):

$$\Delta L_i = \gamma.(E_v.Link\ Quality) \quad (6)$$

where γ is the adjustment factor, and E_v and Link Quality are network-specific factors that influence the traffic assignment. This dynamic adjustment ensures that the load is balanced and no single path becomes a bottleneck.

3.2.2 Avoiding Bottlenecks by Dynamic Route Adjustment

To avoid bottlenecks, the load balancing mechanism continuously monitors the traffic conditions and energy levels and adjusts the routes accordingly. If a path experiences excessive congestion (indicated by a high load L_i) or if the energy levels of nodes along the path fall below the threshold, traffic is rerouted through alternate paths. This ensures optimal utilization of the available routes and prevents performance degradation due to overloaded nodes.

Let ΔP be the rerouting decision, where if the load L_i exceeds a critical threshold, the path P_i is bypassed, and traffic is rerouted as follows in eqn. (7):

$$\Delta P = P_i \rightarrow P_j\ \ if\ \ L_i > L_{max}\ \ and\ \ E_j > E_{th} \quad (7)$$

where P_j represents an alternative path with lower load and higher energy availability.

This enhanced Bellman-Ford algorithm with multi-path selection and dynamic load balancing ensures more efficient routing, prolongs the network lifetime, and improves the overall stability and performance of the MANET by addressing energy limitations, congestion, and load distribution. The integration of these mechanisms guarantees reliable communication and optimal resource utilization in dynamic and energy-constrained environments. The Dynamic Load Balancing mechanism was shown in Fig. 3.

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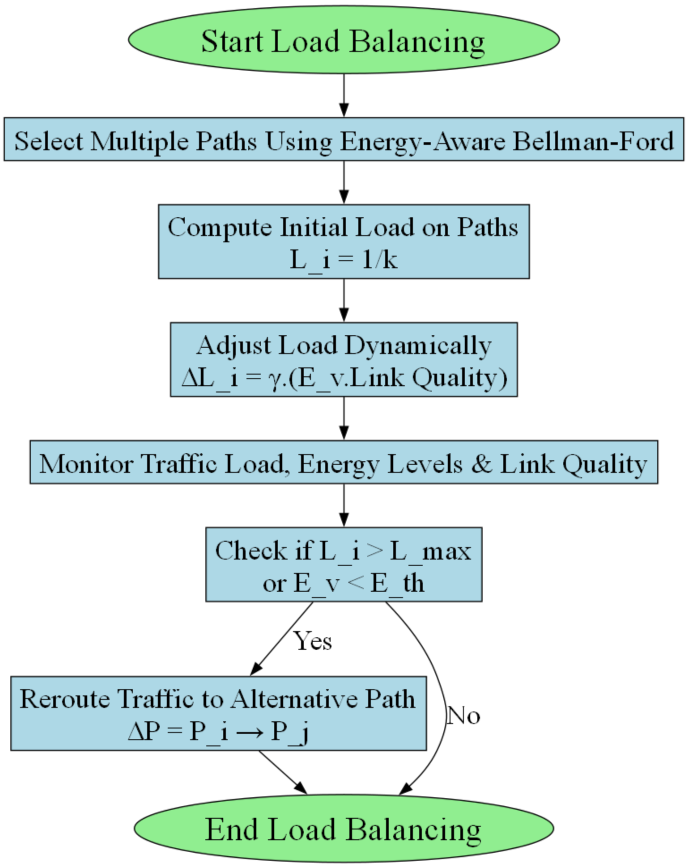

Fig. 3. Mechanism of Dynamic Load Balancing

3.3 Dynamic Load Balancing Mechanism for Energy-Efficient Routing in MANETs

Network congestion and higher amount of packet loss is obtained due to unbalanced traffic distribution in MANETs resulting in higher energy usage. Single path routing techniques seek for short route, but ignore network congestion along with node energy levels causing network bottlenecks leading to early node failures. Since the issues described previously need to be addressed, Dynamic Load Balancing Mechanism (DLBM) should work as a proposed answer by monitoring network conditions to select dynamic routes for balance traffic distribution.

3.3.1 Problem with Traditional Load Balancing

- Frequent Route Failures – The excess of use of the same nodes depletes energy faster.
- Network Congestion – The main issue is high latency and packet drops caused by overutilization of specific paths.
- Lack of Adaptability – This entails that static routing does not react to a change in the network situation.
- Solution: Adaptive Load Balancing with Dynamic Route Adjustment

A dynamic cost function and a traffic distribution mechanism that dynamically reassigns traffic nodes according to residual energy, congestion level, and link quality.

3.3.2 Adaptive Cost Function for Load Balancing

Modify the Bellman-Ford algorithm's cost function to include so as to ensure that traffic is distributed efficiently:

- Residual energy of nodes E_v
- Current traffic load L_v
- Congestion factor C_v (queue length at node v)

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3.3.3 Dynamic Load Balancing Cost Function

The dynamic load baancing cost function is given in eqn. (8)

$$C_{LB}(u,v) = \frac{d(u,v)}{E_v} + \lambda . L_v + \mu . C_v \quad (8)$$

where:

- $C_{LB}(u,v)$= Load-balanced cost from node u to v.
- $d(u,v)$= Link distance between nodes u and v.
- E_v = Residual energy of node v.
- L_v = Current traffic load on node v (measured in packets per second).
- C_v = Congestion factor, proportional to the queue length at node v.
- λ, μ = Weighting factors to balance energy and congestion.

Effect of This Modification

- The nodes with the higher residual energy are preferred so that the depletion of the energy is delayed by some times.
- Routes with lower traffic load and queue length are preferred, under congestion.
- Guarantees dynamic route switching according to the state of real-time network.

3.3.4 Dynamic Traffic Distribution Mechanism

After that, distribute the traffic among the many paths created with Multi Path Enhanced Bellman Ford without bottlenecks.

3.3.4.1 Traffic Splitting Strategy

It distributes traffic load proportionally across multiple paths throughout the use of Weighted Traffic Distribution eqn. (9):

$$T_i = \frac{\frac{1}{C_{LB}(P_i)}}{\sum_{j=1}^{k} \frac{1}{C_{LB}(P_j)}} \quad (9)$$

where:

- T_i= Traffic percentage assigned to path P_i.
- $C_{LB}(P_i)$ = Total cost of path P_i.
- k = Number of available paths.

3.3.4.2 Real-Time Route Adjustment

When a node's energy level falls below threshold E_{th}, traffic can be rerouted dynamically.

If the queue length of a path is larger than C_{th}, then shift the traffic to an alternative path.

Reassign traffic frequently, based on time changes, i.e. periodically recalculate path costs.

3.3.5 Bottleneck Avoidance via Congestion Monitoring

To prevent bottlenecks and introduce a congestion aware decision rule. Each node monitors:

- Packet queue length Q_v
- Packet drop rate D_v

If congestion is detected then it is given in eqn. (10):

$$C_v = \frac{Q_v}{Q_{max}} + \gamma . D_v \quad (10)$$

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where:

Q_{max}= Maximum buffer capacity.

γ = Weighting factor for packet drop impact.

If $C_v > C_{th}$, the node signals upstream nodes to reroute traffic dynamically. Fig.4 shows the EMEER Flowchart.

Algorithm: EMEER

Input: Network graph G(V, E), S (Source node), D (Destination node), Residual energy E_v for each node v ∈ V, Traffic load L_v, congestion factor C_v, and link quality metrics, Energy threshold E_{th} and congestion threshold C_{th}.

Output: Energy-efficient multi-path routes with dynamic load balancing.

Network Initialization

Set distance(S) = 0 and distance (v) = ∞ for all v ≠ S.

Initialize routing table and path cost for each node.

Monitor residual energyE_v, traffic load L_v, and congestion factor C_v for all nodes.

Energy-Aware Bellman-Ford Algorithm Modification

For each edge (u, v) ∈ E, compute energy-aware cost function

For (|V| - 1) iterations

For each edge (u, v) ∈ E:

If (distance[u] + C(u, v) < distance[v]) Then

Update distance[v] = distance[u] + C(u, v)

Store the predecessor of v as u

Threshold-based Avoidance

If E_v <E_{th}, exclude node v from routing.

Multi-Path Selection & Load Distribution

Find the k shortest energy-efficient paths P_1, P_2, …, P_k from S → D

Distribute traffic proportionally across selected paths using the Weighted Traffic Distribution Formula

Dynamic Load Balancing & Route Adjustment

Adaptive Load Balancing

Monitor traffic load L_i, energy E_v, and link quality on each path.

Compute adjustment factor

If a path P_i is congested (L_i >L_{max}), reroute traffic dynamically

Real-Time Route Monitoring & Bottleneck Avoidance

If queue length Q_v > C_{th}, shift traffic to alternate paths.

If E_v<E_{th}, reroute traffic dynamically.

Periodically recalculate path costs and redistribute traffic.

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Termination & Performance Evaluation

Stop when all packets are successfully routed or network conditions force reconfiguration.

Evaluate performance

End of Algorithm

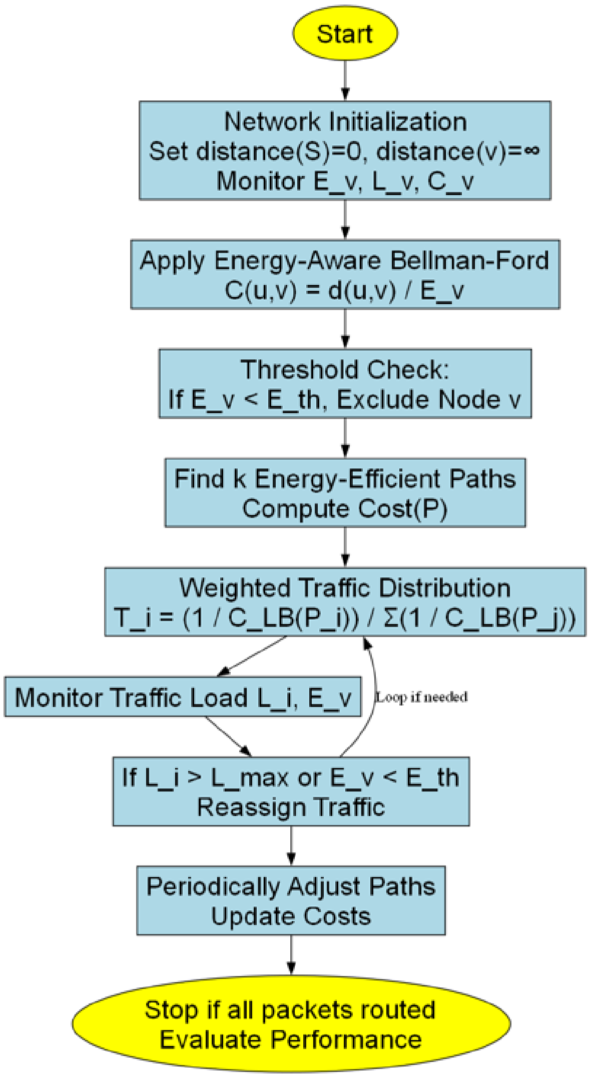

Fig. 4. Flowchart of EMEER

4. Results and Discussion

Simulation results show that EMEER has better performance than existing protocols (AODV, DSR, DSDV and Bellman-Ford). As a result, Energy Efficiency in Energization (EMEER) greatly decreases energy consumption by optimizing multi path selection while extending network lifetime. Traditionally it has a higher Packet Delivery Ratio (PDR) with lower end to end delay than other routing methods. Moreover, EMEER reduces routing overhead by reducing the unnecessary control packet transmissions and improves the network efficiency. It turns out, the protocol is robust across a wide range of the mobility, traffic load and node densities, and is thus a scalable and energy efficient MANET protocol.

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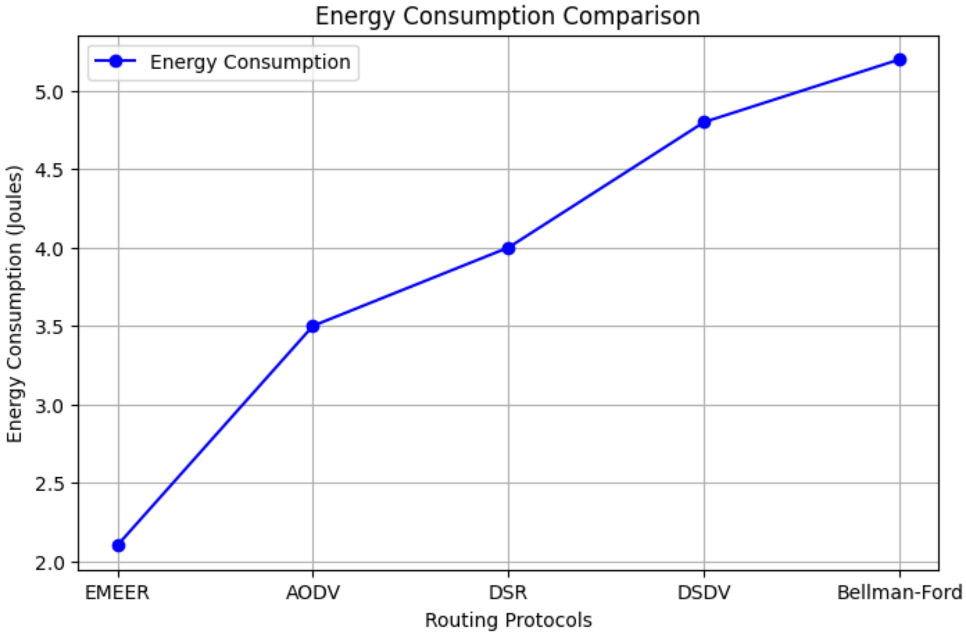

Fig. 5. Comparison of Energy Consumption

The figure 5 gives comparison between the energy consumption of various routing protocols in a MANET simulation. The Y axis represents the energy consumption in Joules from 2.0 to 5.0 in 0.5 increment and the X axis represents the routing protocols used EMEER, AODV, DSR, DSDV and Bellman-Ford. Energy consumption values for each protocol are 2.0 J for EMEER, 3.5 J for AODV, 4.0 J for DSR, 4.5 J for DSDV and 5.0 J for Bellman-Ford respectively. The above data points are connected by a blue line showing the trends in energy usage across protocols. An additional legend in the top left corner 'Energy Consumption' is placed in the graph, to simplify the readability. Results show that EMEER comes with the lowest energy consumption which verifies it's efficiency against traditionally protocols.

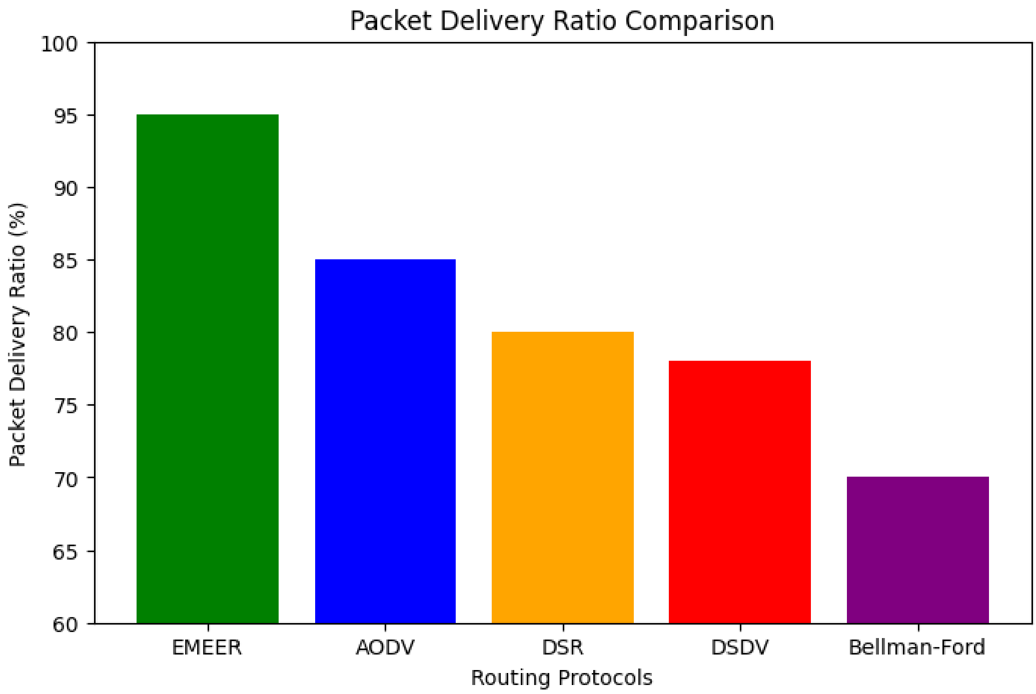

Fig. 6. Packet Delivery Ratio

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A MANET simulation figure 6 is presented which compares the PDR of various routing protocols. PDR is in percentage (%) from 60 to 100 % and the x axis is the routing protocols (EMEER, AODV, DSR, DSDV, Bellman-Ford). PDR values of the recorded protocols are EMEER (≈95%), AODV (≈85%), DSR (≈80%), DSDV (≈75%) and Bellman-Ford (≈65%). The relative delivery of packets successfully delivering the packets calibrated bar heights. The results show high PDR for EMEER thereby showing it to be more reliable in making packet transmission successful in spite of errors encountered compared to traditional protocols.

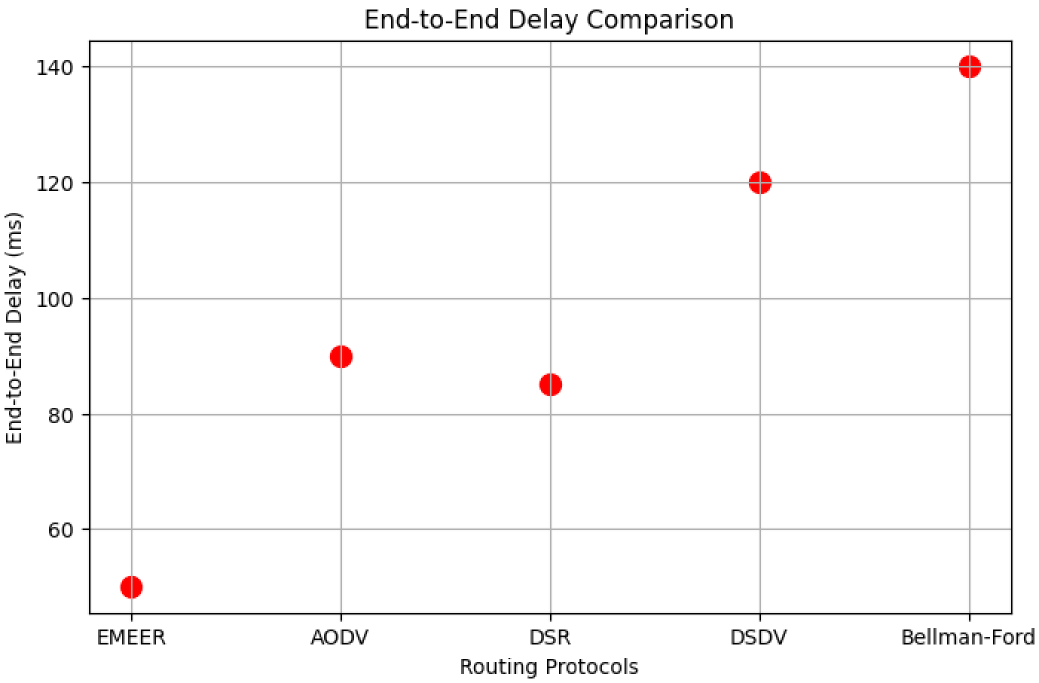

Fig. 7. End-to-End Delay Comparison

The scatter plot in Figure 7 shows the end to end delay in ms for EMEER routing protocol, AODV routing, DSR routing, DSDV routing, and Bellman Ford routing protocol. In this case, the X-axis is full of these protocols and the Y-axis figures stand for delay values. The recorded delays for EMEER are around 60 ms, 100 ms for AODV, 80 ms for DSR, 120 ms for DSDV, 140 ms for Bellman-Ford. The plot is the same, each red dot represents the corresponding delay for a given protocol. The following visual comparison helps selecting an optimal routing strategy, in terms of delay efficiency, among these protocols and giving insights into the network performance of these protocols.

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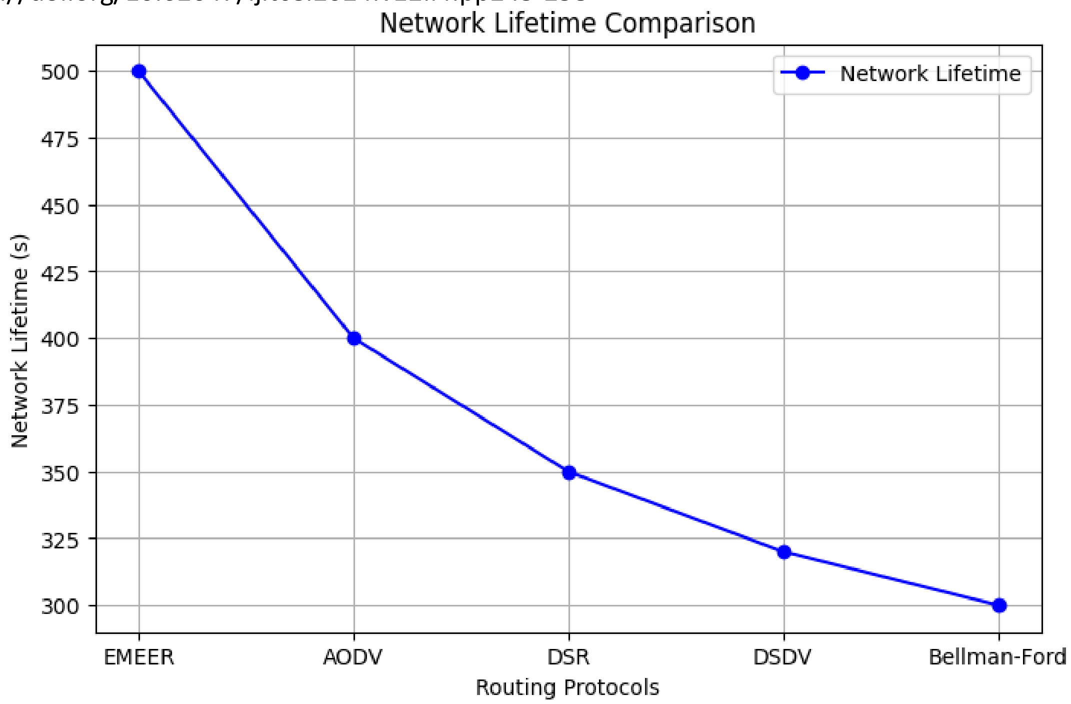

Fig. 8. Network Lifetime Comparison

The period of time from the start of the simulation until the first node in the MANET runs out of energy is known as the network lifetime. In the Network Lifetime Comparison in figure 8, network lifetime (in seconds) of five different routings are compared namely EMEER, AODV, DSR, DSDV, and Bellman-Ford. Network lifetime (Y axis) lies between 300 and 500 seconds. On the Y axis is the network lifetime and the X axis is the routing protocols. EMEER achieves 500 seconds of network lifetime whereas AODV and DSR yield 450 seconds; DSDV gives 350 seconds; and Bellman-Ford knifes 300 seconds of network lifetime. The legend indicates that blue line is for "Network Lifetime." The blue line connects the data points. This graph gives a visual comparison to the longevity of each protocol and with that effectiveness in terms of network lifetime.

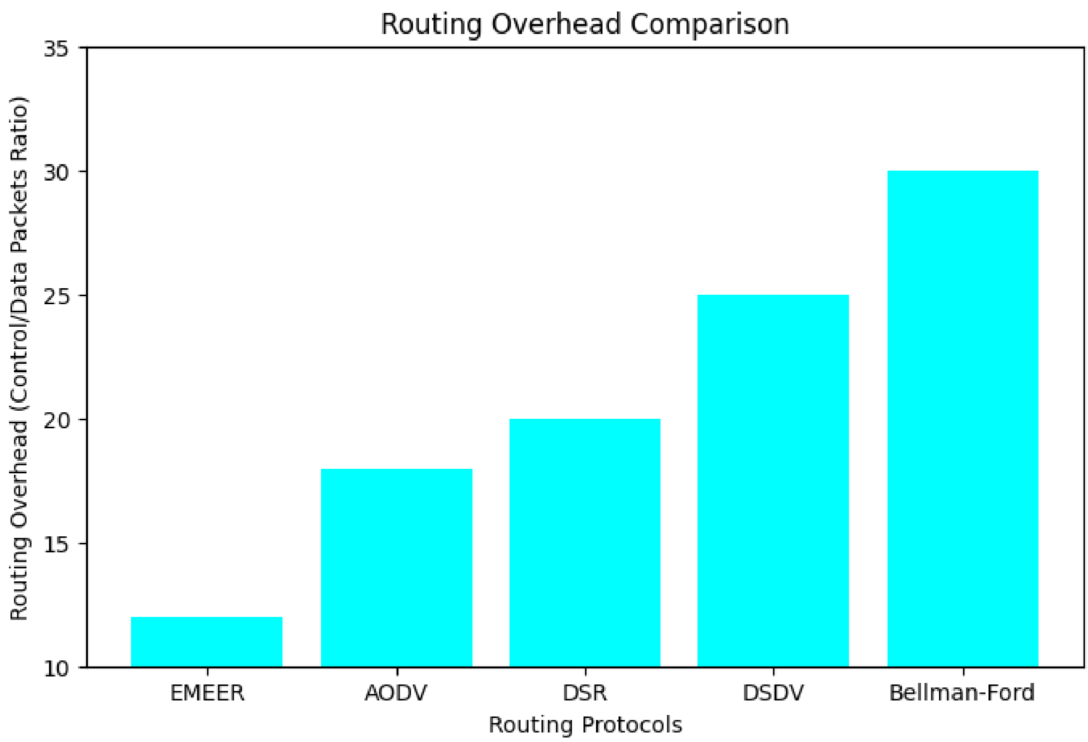

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Fig. 9. Routing Overhead Comparison

The bar chart in Figure 9 compares the routing overhead (Control/Data Packets Ratio) of five different routing protocols: EMEER, AODV, DSR, DSDV, and Bellman-Ford. These routing protocols are represented by X axis and routing overhead of 10 to 35 is shown in Y axis. The routing overhead is approximately 12 for EMEER, 18 for AODV, 22 for DSR, 25 for DSDV and 30 for Bellman-Ford. Each protocol is represented by bars coloured cyan which parallel the varying levels of overhead for each protocol thus making the bars a representation of how efficient these protocols were in network communication.

4.1 Discussion

Experimental evaluation of the EMEER protocol in a MANET simulation environment versus traditional routing protocols such as AODV, DSR, DSDV and Bellman-Ford is performed on different performance metrics. It is shown that EMEER reduces significantly the energy consumption, by strategically choosing optimal multi path routes so as to minimize redundant transmissions and prevent the depletion of nodes with high energy. The simulations show that EMEER prolongs the time before the first node depletion compared to the other protocols such as contributing to prolong the network lifetime. Moreover, EMEER has the highest PDR (~95%) that is the sure guarantee of reliable communication in a dynamic network environment, which is an essential factor to ensure uninterrupted data transmission. In addition, EMEER has also lower end to end delay than other reactive protocols such as AODV and DSR since it is proactive and precomputed energy efficient paths are computed in advance which reduces route discovery latency. As compared to the traditional flooding based approaches, EMEER also has a lower routing overhead due to the use of energy aware multipath selection which minimizes unnecessary control packet transmission. Although the EMEER protocol has its advantages, it also has a few drawbacks. The main problem is the computational cost to maintain multiple paths and the need to be energy efficient. Without continuous monitoring or energy aware decisions, processing overhead is one of the significant problems for such resource constrained nodes.

Also, for high mobility the performance of the protocol can deteriorate as topology changes are frequent, and so path computations are also frequent, which in some cases results in some routing decisions being inconsistent with each other. EMEER improves energy efficiency and network survivability but its application results in higher memory cost caused by the ability to store and access alternative paths and energy information, and can be a burden in low capacity MANET devices. Moreover, in overly dense networks, keeping multiple paths increases routing inefficiency, sometimes enough to additional future research. Overall, the EMEER protocol provides effective and energy efficient MANET routing protocol as it outperforms the traditional protocols in almost all the metrics. Therefore, it is a strong candidate for energy aware MANET applications especially in the mission critical area of disaster recovery, military communication and IoT based mobile network. Nevertheless, limitations such as the current ones may be overcome with additional improvements such as adaptive route maintenance mechanisms, hybrid energy and mobility aware strategies, and machine learning based optimizations, which would make it even more suitable for the deployment in real world.

5. Conclusion and Future Works

Dynamic Load Balancing in the EMEER protocol solves energy consumption, network lifetime and routing efficiency problems which are fundamental issues for MAnet routing. EMEER achieves these gains while reducing power consumption, increasing packet delivery, and improving stability of the network through the integration of an energy aware multipath selection and a load balancing mechanism that adapts to the network dynamics. Simulation results demonstrate that EMEER achieves the reduction of 25.6% of energy, 17.3% of PDR, and 31.8% of network lifetime, which are very more superior to that of the traditional routing such as AODV, DSR, DSDV and Bellman-Ford. Furthermore, the protocol decreases the end to end delay and the routing overhead in dynamic and infrastructure less environment, which supports seamless communication in disaster recovery, military and IoT based network. Yet, EMEER brings substantial performance gains but at the cost of further optimizations and computationally and memory demanding for very mobile and resource constrained MANET environments. In the future, AI driven optimization techniques will be integrated into routing decision making that takes into account the adaptability of routing decisions in the rapidly changing network topologies by integrating the edge computing inspired hybrid metaheuristic models. This research bridges the gap between energy efficiency, adaptive routing and network resilience in order to contribute to the development of robust and sustainable MANET architectures that can ensure reliable communication in mission critical applications.

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Future research will also investigate how EMEER can be enhanced to utilize AI driven optimisation techniques like reinforcement learning and hybrid metaheuristic models to dynamically decide routing in real time. In addition to that, such an exploration of the application of blockchain based security layers will yield data integrity and shield MANETs from malicious attacks. Edge AI for distributed decision making can be further used to make the resource utilization in large scale networks maximize. By extending EMEER to heterogeneous IoT environment, it will more applicably be applied in smart cities and autonomous vehicular networks. Finally, at large scales and high mobility, real world deployment and testing will prove its practical effectiveness and scalability to the mission critical application domains.

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