RESEARCH PAPER

A Cross-Layer Link Capacity and Energy-Aware Multipath Routing Framework with Dynamic Load Balancing for Mobile Ad Hoc Networks

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Abstract

Mobile Ad Hoc Networks (MANETs) are characterized by dynamic topology changes, limited bandwidth, and constrained battery resources, making efficient routing a challenging task. Frequent link failures, congestion, and uneven traffic distribution often degrade network performance and reduce network lifetime. Although multipath routing protocols improve reliability by maintaining multiple routes between source and destination nodes, many existing approaches do not simultaneously consider link capacity, node energy, and traffic load during route selection.

To address these limitations, this paper proposes a novel **Energy-Aware Multipath Routing with Dynamic Load Balancing (EMRD-LB)** framework for MANETs. The proposed approach integrates cross-layer information, including link capacity, residual energy, queue utilization, and path stability, to identify efficient and reliable communication paths. During route discovery, multiple candidate routes are evaluated using a multi-objective path selection mechanism that considers bottleneck link capacity, energy drain rate, load variance, and route stability. Furthermore, an adaptive load-balancing strategy dynamically distributes traffic across selected paths according to real-time network conditions, thereby reducing congestion and improving resource utilization.

The effectiveness of the proposed framework is evaluated through NS-2 simulations under varying network densities and compared with QMR, MMEE, and AOMDV routing protocols. Simulation results demonstrate that EMRD-LB achieves a higher packet delivery ratio, lower routing overhead, reduced packet drops, and better residual energy preservation while maintaining competitive end-to-end delay. By efficiently utilizing available network resources and balancing traffic loads, the proposed framework enhances communication reliability, energy efficiency, and overall network lifetime in dynamic MANET environments.

Keywords: Mobile Ad Hoc Networks, Multipath Routing, Energy-Aware Routing, Cross-Layer Design, Dynamic Load Balancing, Link Capacity, Network Lifetime.

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Introduction:

Mobile Ad Hoc Networks (MANETs) are decentralized wireless networks in which mobile nodes communicate directly without relying on fixed infrastructure or centralized administration. Due to their self-configuring nature, MANETs have become an attractive solution for military communications, disaster recovery operations, emergency response systems, intelligent transportation, and Internet of Things (IoT)-based applications. In these environments, nodes cooperate with one another to establish communication paths and forward data packets across multiple hops. However, the dynamic mobility of nodes frequently changes network topology, making reliable route establishment and maintenance a challenging task.

Routing is one of the most critical functions in MANETs because communication between distant nodes depends on intermediate nodes for packet forwarding. Traditional routing protocols such as AODV, DSR, and TORA are designed to discover routes on demand and reduce routing overhead. Although these protocols perform efficiently in relatively stable environments, their performance degrades under high node mobility, heavy traffic loads, and limited energy conditions. Frequent route failures often result in increased packet loss, higher end-to-end delay, excessive control overhead, and reduced network lifetime.

To overcome the limitations of single-path routing, multipath routing protocols have been proposed to establish multiple alternative routes between source and destination nodes. Multipath routing improves reliability, fault tolerance, and load distribution by allowing traffic to be forwarded through several paths simultaneously or by maintaining backup routes for route recovery. Protocols such as AOMDV and its variants have demonstrated significant improvements in packet delivery and route availability. Nevertheless, many existing multipath routing approaches primarily focus on route diversity and path availability while paying limited attention to link capacity, congestion conditions, and energy consumption during route selection.

Another major challenge in MANETs is the limited battery power of mobile nodes. Since nodes act as both hosts and routers, excessive participation in packet forwarding can rapidly deplete node energy and shorten network lifetime. Furthermore, uneven traffic distribution may overload certain routes, creating network congestion and increasing packet drops. As a result, routing decisions based solely on hop count or route availability are insufficient for achieving sustainable and efficient communication in dynamic MANET environments.

Recent studies have explored energy-aware routing, congestion control mechanisms, cross-layer optimization, and load-balancing techniques to improve network performance. Although these approaches provide valuable improvements, most existing solutions consider only a subset of routing parameters and fail to jointly optimize link capacity, residual energy, traffic load, and path stability. Consequently, bottleneck links, overloaded nodes, and premature energy depletion continue to affect overall network efficiency.

To address these challenges, this paper proposes a novel **Energy-Aware Multipath Routing with Dynamic Load Balancing (EMRD-LB)** framework for MANETs. The proposed framework integrates cross-layer information from the physical, MAC, network, and energy layers to support intelligent routing decisions. Link capacity estimation, residual energy monitoring, energy drain rate analysis, queue utilization assessment, and path stability evaluation are combined within a multi-objective route selection mechanism. Multiple candidate paths are ranked according to their overall quality, and traffic is dynamically distributed among selected routes based on current network conditions. This strategy minimizes congestion, balances network load, improves resource utilization, and extends network lifetime.

The major contributions of this work are summarized as follows:

1. A cross-layer routing framework is developed to integrate link quality, energy status, and traffic conditions into routing decisions.

2. A link-capacity estimation mechanism is designed to identify reliable communication links and avoid congestion-prone routes.

3. A multi-objective path selection model is proposed by jointly considering residual energy, energy drain rate, load variance, path stability, and link capacity.

4. A dynamic load-balancing strategy is introduced to distribute traffic adaptively across multiple available routes.

5. Extensive simulation experiments demonstrate the effectiveness of the proposed EMRD-LB framework in improving packet delivery ratio, reducing routing overhead, minimizing packet drops, and enhancing energy efficiency compared with existing routing protocols.

The remainder of this paper is organized as follows. Section 2 reviews the related literature on multipath routing, energy-aware routing, and load-balancing techniques in MANETs. Section 3 presents the proposed EMRD-LB framework and system model. Section 4 describes the link-capacity estimation and energy evaluation mechanisms. Section 5 explains the route selection and dynamic load-balancing process. Section 6 discusses simulation settings and performance evaluation results. Finally, Section 7 concludes the paper and outlines future research directions.

2. Literature Review

The development of multipath routing protocols in MANETs has focused on improving reliability, energy efficiency, congestion control, and load balancing. Researchers have proposed various routing strategies based on link stability, energy awareness, cross-layer optimization, intelligent algorithms, and traffic distribution mechanisms. Table 1 summarizes the most relevant studies and highlights their key contributions and limitations.

Table 1. Summary of Existing Literature on Multipath Routing in MANETs

Ref.	Author(s) & Year	Approach	Key Features	Advantages	Limitations
[1]	Roy and Roy (2017)	Stable Multipath Routing	Residual energy, Link Expiration Time (LET), load balancing	Improved reliability and network lifetime	Limited consideration of congestion and link capacity
[2]	Jeyaraj et al. (2023)	Hybrid SM-CSBO	Multi-objective optimization using Cuckoo Search and Butterfly Optimization	Enhanced QoS and energy efficiency	High computational complexity
[3]	Salem and Yadav (2016)	Load Balancing Routing	QoS-aware traffic distribution	Improved throughput and network lifetime	Performance affected by dynamic topology changes
[4]	Sahu et al. (2024)	INTSM	Dynamic traffic sharing and congestion prediction	Reduced delay and improved throughput	Assumes predictable traffic patterns
[5]	Tarique et al. (2009)	Multipath Routing Survey	Classification of multipath routing techniques	Comprehensive review of routing categories	Does not provide implementation framework
[6]	Maheshwari and Nedunchezhian (2012)	Load Balancing Survey	Energy and traffic-based load balancing	Identifies major research challenges	Lacks practical routing mechanism
[7]	Mahdi et al. (2021)	Cluster-Based Multipath Routing	Traffic distribution and congestion reduction	Reduced delay and improved reliability	Simplified analytical assumptions
[8]	Harshdeep et al. (2019)	Efficient Multipath AODV	Reduced flooding and congestion control	Better routing precision	Increased route discovery complexity
[9]	Geetha (2021)	AOMDV	Multiple link-disjoint routes	Improved fault tolerance and	Additional RREQ overhead

Ref.	Author(s) & Year	Approach	Key Features	Advantages	Limitations
				packet delivery	
[10]	Darabkh et al. (2017)	AODV-SMR	Secure non-overlapping multipath routing	Reduced packet loss and enhanced reliability	Complex path maintenance
[11]	Savola (2001)	DSR	Route caching and source routing	Low routing overhead	Poor scalability in large networks
[12]	Prasan et al. (2019)	HDF-Based Multipath Routing	Optimal path selection from multipath routes	Improved route quality	Dependent on prediction accuracy
[13]	Mohsen and Ahmed (2008)	CM-AODV	Cross-layer signal-quality routing	Enhanced link reliability	Cross-layer implementation complexity
[14]	Upadhayaya and Gandhi (2010)	NDMLNR	Node and link stability with bandwidth awareness	Improved QoS and network lifetime	High route discovery overhead
[15]	Shivakumar and Patil (2020)	EECRP-PSO	Cross-layer energy-efficient routing	Reduced delay and energy consumption	High computational cost
[16]	Ali et al. (2014)	QoS-Aware Multipath Routing	Bandwidth and delay threshold routing	Better QoS support	Sensitive threshold selection
[17]	Robinson and Rajaram (2015)	EMPSO	PSO-based energy-aware routing	Improved route optimization	Training and processing overhead
[18]	Banu et al. (2025)	ML-Driven Multipath Routing	ACO, ETX, LSTM, Random Forests	Intelligent link prediction	High training complexity
[19]	Sharma and Sharma (2012)	LOCA-GAMNET	Location-aware genetic routing	Reduced packet loss	Requires location information
[20]	Yu and Liang (2015)	Node-Disjoint Multipath Routing	Complete path separation	Better fault tolerance	Increased routing overhead

Research Gap Analysis

From the literature, it is evident that existing routing protocols primarily focus on one or two optimization objectives such as energy efficiency, route stability, congestion control, or load balancing. However, very few studies jointly consider **link capacity estimation, residual energy, energy drain rate, path stability, and dynamic traffic load distribution** within a single routing framework. Furthermore, most existing approaches lack an adaptive mechanism for real-time traffic redistribution based on network congestion and resource availability.

Therefore, there is a need for an integrated routing solution that simultaneously addresses energy efficiency, congestion control, load balancing, and link-capacity awareness. Motivated by these limitations, this work proposes the **EMRD-LB framework**, which combines cross-layer link-capacity estimation with energy-aware multipath routing and dynamic load balancing to improve overall MANET performance.

Proposed Work:
Ad hoc communication is adopted in many applications to improvise services related to data transmission and reliability. This research adopts a simulation-based experimental methodology to design, implement, and evaluate a link capacity-aware, load-balanced, energy-efficient multipath routing for mobile ad hoc networks (MANETs). The proposed (EMRD-LB) approach enhances traditional multipath routing by making it aware of link capacity, traffic distribution, and remaining energy during route discovery and data transmission. To develop and adopt the proposed strategy, the methodology consists of four major phases.

1. System Model and Assumption
2. Link Capacity Estimation
3. Energy Estimation
4. Data Forwarding and Load Balancing

3.1 System Model and Assumption

Consider a mobile ad hoc network as G = (V, E), where V = {v_1, v_2, v_3,…v_n} is the set of mobile nodes in the network and E represents bidirectional wireless links. The nodes are configured by initial energy, transmission range R, node mobility as a random waypoint model, symmetric links (meaning if node v_i can hear v_j, then v_j can hear v_i), MAC protocol RTS/CTS mechanism to handle the hidden terminal problem, physical and MAC layers available to the network layer, and a routing protocol for route decisions. These assumptions are useful for deploying the network and implementing it under network simulation 2. Collectively, the nodes form a dynamic topology that enables multipoint communication between the source and destination, with multiple paths available simultaneously; however, this topology frequently changes, which is crucial for maintaining stability in the network. The proposed EMRD-LB uses the concept of signal strength and location-based service to predict the direction of the destination and somehow increase the network stability of communication. In this methodology, our objective is to balance network load and provide efficient energy-based routing, which requires the key concept of identifying each node's load dependency parameters, such as link capacity, queue utilization, available channel bandwidth, incoming and outgoing data flow rate, and getting the mobile node load on the other side to achieve energy efficiency. To achieve this, we gather details about each node's current energy, the energy depletion rate per data packet, and the estimated energy consumption and lifetime of the node, which are essential for determining the node's status and prioritizing timely route changes based on its remaining lifetime. The overall proposed system provides congestion-free and balanced-load communication to mobile ad hoc networks.

3.2 Link Capacity Estimation

In the mobile ad hoc network channel bandwidth is very limited because the number of available channels is shared by multiple users. In the ad hoc network channel contention is very high due to frequent changes in the topology and routing table. In ad hoc communication, measuring link capacity is crucial due to dynamically shared nodes sharing the common channel and changing network topology. In the proposed EMRD-LB routing, link capacity estimation depends on bandwidth, channel, MAC contention, queue occupancy, and transmission time, which are formalized in eq (1) to eq (11).

The available bandwidth on link (i, j) is estimated as:
$B_{ij}^{avail} = B_{ij}^{max} - B_{ij}^{used}$…………………..(1)
Where
B_{ij}^{max}= maximum channel capacity of 802.11b standard
B_{ij}^{avail} = Bandwidth consumed by existing flow
The available link capacity LC_{ij} between nodes I and j is calculated as:
$LC_{ij} = B \times (1 - C_{ij}) \times (1 - Q_{ij})$………………(2)
Where
B= Nominal channel bandwidth
C_{ij} = Channel contention
Q_{ij} = Queue utilization
The available bandwidth and link capacity are less than the predefined threshold, so they are excluded from route formation.
The channel utilization is also measured to identify the availability of the channel, which is calculated as follows:

$U_{ij} = \frac{T_{busy}}{T_{max}}$………………(3)
Where the time channel is sensed as busy and is the maximum window size.
In the communication duration of transmission time is also important because it identifies how long data is carried by the medium, which helps to estimate the time taken for data from source to receiver. The proposed system is able to estimate the transmission time, which helps to identify the channel busyness of the shared channel and the expected contention time for new transmitter nodes. The expected transmission

time (ETT) combines link capacity and packet loss to evaluate as follows between the i and j nodes:

$$ETT_{ij} = \frac{P_s}{B_{ij}^{avail}} \times \frac{1}{1-f_{ij}} \text{.........................(4)}$$

Where
P_s= Size of packet (bytes)
f_{ij}= forwarded data delivery ratio on link (i , j)

3.3 Energy Estimation

Mobile ad hoc network devices have limited battery power and without that energy, it is not possible to provide communication between nodes. The overall network formation depends on the battery so that our objective is to minimize the energy consumption via proper route selection and unwanted message flooding. In this section our objective is to predict the lifetime of a node in communication.

The total energy consumption for node v_i

$$E_i^{consume} = E_i^t + E_i^r + E_i^i + E_i^s \text{ ....(5)}$$

Where E_i^t = Transmission energy, E_i^r= reception energy, E_i^i= idle energy, and E_i^s= sensing energy.

The residual energy $E_i^{residual}$ is calculated as:

$$E_i^{residual} = E_i^{initial} - E_i^{consume} \text{ ,,,,,,,,,,,,,,,,,,,,,,,,,,,,(6)}$$

The node life time predict as

$$T_i^{lt} = \frac{E^{residual}}{E_i^{consume\_rate}} \text{ ....(7)}$$

Where $E_i^{consume\_rate}$ = is average energy consumption per unit time.

3.4 Data Forwarding and Load Balancing

The proposed routing system uses the multipath routing mechanism, which is enhanced through the above methodology and guaranteed for efficient and reliable route discovery from source to destination. The multipath route selection is based on node disjoint paths and evaluated as minimum link capacity, average residual energy, and hop count. The route discovery process is initiated by the source node and broadcasts RREQ with a path capacity vector, accumulated energy cost, and bottleneck link capacity, which is received at intermediate nodes, and calculates the local link capacity between C_{ij} and neighbor N_j node, updates the bottleneck link capacity and energy cost, and recalculates the load variance based on queue length and forwards RREQ if the packet is not duplicated. Finally, the destination receives multiple RREQs from disjoint paths and computes the path score by eq (8). The destination node selects the top k paths with the highest scores and sends RREP back along each selected path; the source node maintains an active path table with metrics that are updated from time to time.

$$Score(p) = \alpha \times C_{min}(p) + \beta \times \frac{1}{E_{drain}(p)} + \gamma \times \frac{1}{\sigma^2(p)} + \delta \times S(p) \text{...............(8)}$$

Where
$C_{min}(p)$= Minimum link capacity on path p (0-1)
$E_{drain}(p)$= Maximum energy drain rate on path p
$\sigma^2(p)$= Variance of queue lengths on path p
S(p)= path stability score (0-1)

The eq(8) is used to find the paths, and the source node starts data transmission, where the proposed system applies the dynamic load balancing mechanism, minimizes network congestion, and improves efficiency. To balance the network load, calculate each path's dynamic weight and then normalize it; after that, select the path with probability and finally update statistics and if congestion is detected, then immediately trigger a load balancing alert message to redistribute the traffic across all available paths. The dynamic weight is calculated by eq(9) and the normalized weight by eq(10).

$$Score(p) = \alpha \times C_{min}(p) + \beta \times \frac{1}{E_{drain}(p)} + \gamma \times \frac{1}{\sigma^2(p)} \text{.................(9)}$$

Normalized weight calculates as:

$$w_i' = {}^{w_i}\!/_{\sum(w_j)} \text{..............(10)}$$

The congestion threshold calculate by eq(11)

$$Threshold = \mu_{queue} + 2\sigma_{queue} \text{.....................(11)}$$

Where μ_{queue} and σ_{queue} are mean and standard deviation of queue length across all paths.

Finally load balancing factor LBF:

$$LBF = \frac{\sigma^2 queue}{\pi^2 queue} \text{.....................(12)}$$

The proposed EMRD-LB routing provides reliable and congestion-free communication, which is more adaptable for mobile ad hoc network communication as compared to existing routing strategies.

1. EMRD-LB Functional Architecture

This diagram 1 illustrates the five-layer structure for the link estimation and load balancing process for mobile ad hoc networks; it shows how information flows from the lower layers (MAC and physical) through processing modules to produce the key metrics used in path selection. This is a comprehensive architecture diagram of a five-layer structure that has information sources, processing modules, a core engine, an output decision, and data plane operation. Each layer transforms raw measurements into more abstract metrics used for routing, load balancing, and energy optimization. The architecture collects cross-layer metrics capacity, quality, load, and energy from MAC, physical, network, and energy layers. These metrics are processed by the channel monitor, quality estimator, capacity calculator, and energy monitor to produce normalized link-level metrics. The EMRD-LB core engine estimates path capacity, computes a multi-objective score per path and selects primary and backup multipath to perform dynamic load balancing. The data plane uses these decisions for forwarding and maintenance with feedback loops enabling real-time adaptation.

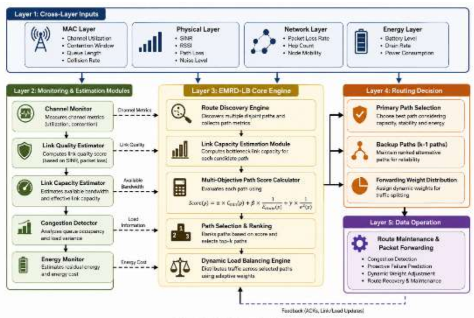

Figure 1: EMRD-LB Protocol Architecture

2. Algorithm:

In this section, describe the proposed algorithm to discover routes and data forwarding using link capacity and energy-aware routing, which is capable of balancing network loads and providing congestion-free communication. The basic idea behind the routing procedure is to be aware of the energy of each node, load, signal strength routing, and link capacity to select a route. In the next phase, start data sending from the selected route and update the weight vector as formalized in the algorithm and detect the congestion if it occurs; otherwise, the selected path is ready to continue data sending.

Algorithm: EMRD-LB

Input:

N: Mobile node,
S: Source node
D: Destination Node
C_{ij}: link capacity
Q_l: Queue length
P_{lost}: Packet loss rate
E_l: Energy level
P_c: Power consumption
R_p: AOMDV
LV: load variance
EDR: energy drain rate
Ψ: radio range 550^2m

Output: average NRL, delay, PDR, Drop, ARE, AEC, Data receiving

Procedure 1: Route Discover

Source S broadcast RREQ(R_p, S, D)
For each $N_i \in M$
Configure $P_{lost} = 0$, E_l, P_c for N_i
If Ni in Ψ **than**
Calculate local C_{ij}
Update bottleneck link capacity = min (current, C_{ij})
Append C_{ij} to path capacity vector
Update EDR = max(drain_rate, N_i.drain_rate)
Recalculate LV based on Q_l
If RREQ not duplicate **than**
Forward RREQ to next hop
D waits for Δt to receive multiple RREQs
For each received RREQ r:
Compute path Score(r)
D select path and ranked
Send RREP to S by selected path
S maintain active path table
Else
Stop forwarding
End if
Else
D not found or unreachable route
End if
End for

Procedure 2: Data Forwarding

Input:

pkt: data packet
P: active path set {$P_1, P_2, \ldots\ldots P_k$}

Output: path selection for pkt

Procedure:

For each path $P_i \in P$
Calculate dynamic weight

$$Score(p) = \alpha \times C_{min}(p) + \beta \times \frac{1}{E_{drain}(p)} + \gamma \times \frac{1}{\sigma^2(p)}$$

Normalized weight calculates as:

$$w_i' = {}^{w_i}/_{\sum(w_j)}$$

If $w_i' > \text{avg}(w_i')$ **than**
Select path's
If Q_i > threshold **than**
Network is congested
$w_i \leftarrow w_i - \delta(0<\delta<1)$
trigger load balancing alert

Else
Start data forwarding to D
End if
Else
Not selected
End if
End for

3. Simulation Parameters & Results

The performance of all the approaches is measured on the same simulation parameters. The simulation parameters are mentioned in table 1. The Network Simulator version 2 (ns-2) is used for the simulation. The different node density is considered under the same simulation area. This ensures a fair comparison between the various methodologies employed. Additionally, the results will answer questions about how node density impacts overall network performance and efficiency. The packet size is considered 512 Bytes and the simulation time is 100 sec in all node density scenarios.

Table 1 Simulation Parameters

Simulation Area	1000m X 1000m
Number of Nodes	25, 50, 75, 100
Node Movement	Random Uniform Distribution
Node Speed	0-20 m/n
Traffic Type	CBR, UDP
Packet Size	512 Byte
Network Protocol	QMR, AOMDV, MMEE, EMRD-LB
Channel Type	Wireless Phy
Radio Range	550m^2
Simulation Time	100s

3.1 Average Normal Routing Load & Delay Analysis

In the dynamic network, successful data transfer and data receiving are not straightforward tasks. The nodes' movement and direction are not easy to predict. The possibility of congestion in the network is more likely to enhance the packet dropping. The proper load balancing scheme is required to control the congestion and handle the load efficiently in a dynamic network. In this graph 2, compare the average normal routing load (Avg. NRL) and average delay (Avg. Delay) performance of novel EMRD-LB with MMEE, QMR, and AOMDV. The EMRD-LB shows 2% less overhead from AOMDV. In the case of average delay performance, AOMDV and EMRD-LB are in line. The average delay of QMR is high due to the complex communication among the nodes for reliable data transfer. The performance of the proposed scheme is capable of enhancing the data packets received with lower delay and overhead.

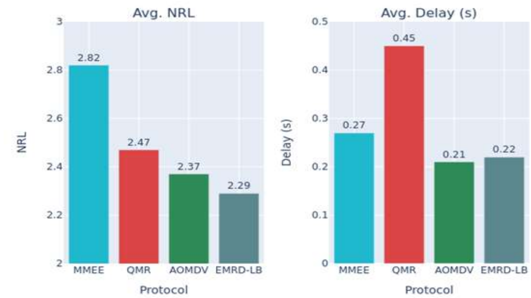

Figure 2: Average NRL and Delay Analysis

3.2 Heatmap Performance Analysis

A heat map is the geographical distribution of data values by different colors. In the figure 3 shows a heat map which is the visualization tool for representing the performance of QMR, MMEE, AOMDV, and EMRD-LB. The color code represents the strong and weak performance of the approaches. The performance of the proposed scheme is better due to the proper handling of the congestion in the network. The effective load balancing technique minimizes the packet loss and reduces overhead in the network. The AOMDV approach performance is better but not able to efficiently utilize the energy resource for routing. The higher number of data packets received means the proposed scheme is able to handle the congestion properly and provides better performance. The performance score of EMRD-LB is the highest as compared to all approaches.

Figure 3: Heatmap Performance Analysis

3.3 Average Performance Across All Scenarios

The performance metrics considered for all approaches are same and the performance of all is mentioned in table 2. The AOMDV is the previous approach whose performance is better than the other two approaches. In the given table the novel EMRD-

LB performance is better than AOMDV because it properly balances the load and reduces the wastage of energy in retransmission. The average PDR of EMRD-LB is 10% more as compared to AOMDV, the average NRL is 2% less and the average ARE is 20% more. The delay performance of AOMDV and EMRD-LB is almost equal. The novel approach is able to handle the congestion properly and enhance the energy utilization.

Table 2 Average Performance of all scenarios

Protocol	Avg PDR (%)	Avg NRL	Avg Delay (s)	Avg Drop	Avg ARE	Avg AEC
MMEE	81.09	2.82	0.27	757.75	34.09	31.46
QMR	79.56	2.47	0.45	885.75	35.15	29.32
AOMDV	81.58	2.37	0.21	830.25	31.01	30.63
EMRD-LB	92.18	2.29	0.22	341.50	46.06	23.66

3.4 Normalized Multi-Metric Radar Chart

The overhead in the network is required to properly handle the exchange of data between the sender and the receiver. In the MANET connection establishment is not basic because of the movement of nodes. The sender sends the connection establishment packets to the receiver, who then confirms receipt to the sender. In this graph, 4 measure the overhead performance of MMEE, QMR, AOMDV, and the novel EMRD-LB approach. The performance of EMRD-LB is better because of strong link establishment and proper load handling in the network. The performance of all the approaches is measured in 100 seconds of simulation time. The novel approach is showing higher efficiency, low drop, low NRL, and a very slightly high delay in the network. The proper channel utilization of a wireless link shows less drop and negligible retransmission of data packets between sender and receiver. This indicates that the scheme can sustain a stable connection even under varying conditions. Additionally, the results suggest that employing approach for load balancing could further enhance network performance and minimize overhead.

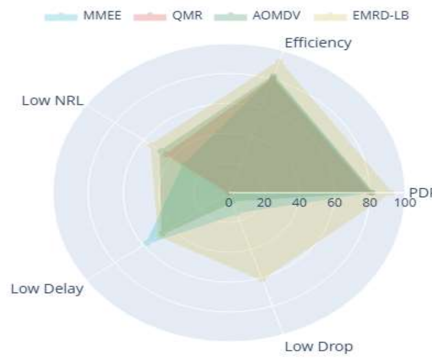

Figure 4: Normlized Multi-metric redar Chart Analysis

3.5 Percentage of Data Receives Distribution

The protocol can significantly increase the number of packets successfully delivered to their intended destinations by enhancing the routing approach and distributing the load across various routes. In the process of determining the overall data-receiving percentage of the network and developing reliable links, the effectiveness of the multipath protocol is an important factor to consider. The described technique provides an efficient solution to congestion issues in dynamic networks. In the figure 5 shows the packet-receiving network yields superior results in the suggested EMRD-LB. Improvements in routing performance and congestion management are achieved by the EMRD-LB technique, which ultimately leads to improved bandwidth utilization as compared to AOMDV, QMR, and MMEE. The novel approach demonstrates a 10% higher Packet Delivery Ratio (PDR) compared to AOMDV, and it is expected to perform even better against other methods.

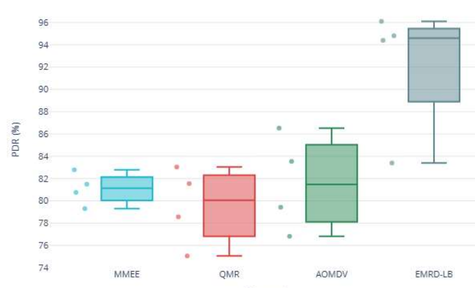

Figure 5: Data Receiving Percentage Analysis

3.6 Average Drop Count

The data dropping is the common in the network due to resource un-availability, destination not available, heavy traffic or congestion and improper load balancing. In the figure 6 compared to the QMR, TA-AOMDV, and MMEE strategies that were previously used in MANET, the unique EMRD-LB load balancing method delivered a lower number of average dropped data. Each and every module's performance is simulated using the same simulator and same simulation time consider for all scenarios. The EMRD-LB is displaying less data dropping and less overhead in the network. Increasing congestion on the network indicates that it is utilizing the limited bandwidth and processing capability of mobile nodes, which is a consequence of the network's increasing congestion. The averahe dropping of EMRD-LB is only 300packets but AOMDV is 700 packets (minimum) and rest of them are more than 700packets. According to the measurements of performance, the EMRD-LB has superior performance in dynamic networks as compared to other schemes.

Figure 6: Average Drop Count Analysis

3.7 Performance Rankings

The better performance of the approach in the dynamic network determines its ranking. If the performance is higher, that means the ranking is higher. In previous approaches, the ranking of the AOMDV protocol was higher compared to others because it handled the load properly in the network. The ranking of all the previous approaches with novel EMRD-LB w.r.t. performance metrics is mentioned in table 3. The proposed EMRD-LB approach is able to handle the load and utilizes the energy of nodes properly, which enhances network lifetime. The ranking is one of EMRD-LB in PDR, NRL, and Drop, but in the delay ranking, it is two. The routing performance is showing less packet dropping and overhead in the network. These improvements indicate that EMRD-LB optimizes resource utilization and ensures a more reliable communication process.

Table 3 Performance Ranking Analysis

Metric	**Rank 1**	**Rank 2**	**Rank 3**	**Rank 4**
PDR (↑)	**EMRD-LB (92.18%)**	AOMDV (81.58%)	MMEE (81.09%)	QMR (79.56%)
NRL (↓)	**EMRD-LB (2.29)**	AOMDV (2.37)	QMR (2.47)	MMEE (2.82)
Delay (↓)	AOMDV (0.21s)	**EMRD-LB (0.22s)**	MMEE (0.27s)	QMR (0.45s)
Drop (↓)	**EMRD-LB (341.5)**	MMEE (757.75)	AOMDV (830.25)	QMR (885.75)

4. Conclusion and Future Work

Mobile Ad Hoc Networks (MANETs) face significant challenges due to dynamic topology changes, limited bandwidth availability, constrained battery resources, and frequent network congestion. These challenges often result in packet loss, increased routing overhead, reduced throughput, and shortened network lifetime. Therefore, designing an efficient routing mechanism that can simultaneously address energy efficiency, congestion control, and load balancing remains a critical research issue.

This paper presented EMRD-LB (Energy-Aware Multipath Routing with Dynamic Load Balancing), a novel routing framework designed to improve routing performance in MANET environments. The proposed approach integrates link-capacity estimation, residual energy monitoring, path stability assessment, and dynamic load balancing into a unified multipath routing framework. By selecting routes based on both available link capacity and node energy levels, EMRD-LB effectively avoids overloaded and energy-depleted nodes, thereby reducing congestion and improving network reliability.

Simulation results demonstrate that the proposed EMRD-LB protocol outperforms existing routing protocols such as QMR, MMEE, and AOMDV across multiple performance metrics. The proposed scheme achieves a higher packet delivery ratio, lower routing overhead, reduced packet drops, and improved residual energy preservation while maintaining competitive end-to-end delay. Furthermore, the adaptive traffic distribution mechanism enables efficient utilization of network resources and enhances overall network lifetime. The results confirm that incorporating energy awareness and dynamic load balancing into multipath routing significantly improves communication performance in highly dynamic MANET scenarios.

Despite these improvements, the proposed framework does not explicitly consider node location information during route discovery and maintenance. Since MANET nodes frequently change their positions, location-aware routing can provide additional insights for predicting link stability and reducing route failures. Therefore, future work will focus on integrating location-awareness and mobility prediction techniques into the EMRD-LB framework. In addition, machine learning-based traffic prediction and intelligent route adaptation mechanisms can be explored to further optimize energy consumption, reduce route re-establishment overhead, and enhance routing performance under highly dynamic network conditions. Such enhancements are expected to improve the scalability, robustness, and efficiency of next-generation MANET routing protocols.

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