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An Analytical Research based on Optimised Cross Layer Based Design and Performance Analysis Routing Protocol in Manets

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Abstract: *Mobile Ad-hoc Networks (MANETs) face significant challenges in routing optimization due to dynamic topologies, energy constraints, and quality-of-service requirements. This analytical research examines optimized cross-layer routing protocols that integrate composite metrics and energy-aware mechanisms to enhance MANET performance. Through comprehensive analysis of protocols developed between 2010-2020, we evaluate cross-layer design methodologies, composite metric formulations, and performance characteristics across multiple network scenarios. Our analytical findings demonstrate that cross-layer protocols integrating residual energy, link quality, delay, and mobility metrics achieve 40-60% improvement in network lifetime and 15-35% enhancement in throughput compared to traditional layer-isolated approaches. Performance analysis reveals critical trade-offs between energy efficiency and quality-of-service metrics, with protocol selection dependent on application-specific requirements. This research synthesizes design principles, conducts comparative performance analysis, and identifies optimization opportunities for future MANET deployments in IoT, vehicular networks, and disaster recovery scenarios.*

Keywords: MANET, Cross-layer routing, Energy-aware protocols, Composite metrics, Performance analysis, QoS optimization

I. INTRODUCTION

1.1 Mobile Ad-hoc Networks: Fundamentals and Challenges

Mobile Ad-hoc Networks (MANETs) represent self-organizing, infrastructure-less wireless networks where mobile nodes cooperatively forward packets without centralized coordination (Abolhasan et al., 2004). Unlike traditional wireless networks with fixed base stations, MANETs exhibit dynamic topology changes, limited bandwidth, variable link quality, and energy-constrained nodes operating on battery power (Conti & Giordano, 2014).

The routing challenge in MANETs is fundamentally different from wired networks due to several critical factors:

Dynamic Topology: Node mobility causes frequent link breakages and topology changes, requiring adaptive routing mechanisms

Energy Constraints: Battery-powered nodes have limited energy reserves, making energy-efficient routing essential for network longevity

Limited Resources: Constrained bandwidth and processing capabilities necessitate lightweight protocol overhead

Variable Link Quality: Wireless channel characteristics vary due to interference, fading, and node mobility

Scalability Issues: Protocol performance must scale with increasing network size and traffic load

Traditional routing protocols designed for wired networks or infrastructure-based wireless networks fail to address these unique MANET characteristics effectively (Boukerche et al., 2011).

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II. BACKGROUND AND FOUNDATIONAL CONCEPTS

2.1 Traditional MANET Routing Protocols

MANET routing protocols are classified into three primary categories based on route discovery and maintenance mechanisms (Boukerche et al., 2011):

2.1.1 Proactive Routing Protocols

Proactive (table-driven) protocols maintain routing information for all destinations continuously through periodic updates. Representative protocols include:

DSDV (Destination-Sequenced Distance Vector): Extends the distributed Bellman-Ford algorithm with sequence numbers to prevent routing loops. Nodes maintain routing tables updated through periodic broadcasts, causing high control overhead in dynamic topologies (Perkins & Bhagwat, 1994).

OLSR (Optimized Link State Routing): Uses multipoint relays (MPRs) to reduce flooding overhead during route discovery. Each node selects a subset of neighbors as MPRs responsible for forwarding control messages, significantly decreasing broadcast redundancy (Clausen & Jacquet, 2003).

2.1.2 Reactive Routing Protocols

Reactive (on-demand) protocols establish routes only when required, reducing overhead in low-traffic scenarios:

AODV (Ad-hoc On-Demand Distance Vector): Discovers routes through route request (RREQ) flooding and route reply (RREP) unicast. Maintains only active routes, using sequence numbers for freshness and route error (RERR) messages for link failure notification (Perkins & Royer, 1999).

DSR (Dynamic Source Routing): Employs source routing where the complete path is embedded in packet headers. Utilizes route caching to reduce discovery overhead, but header size increases with path length (Johnson & Maltz, 1996).

2.1.3 Hybrid Routing Protocols

Hybrid protocols combine proactive and reactive mechanisms to leverage advantages of both approaches:

ZRP (Zone Routing Protocol): Divides the network into zones, using proactive routing within zones and reactive routing between zones. This reduces control overhead while maintaining route availability (Haas et al., 2002).

Table 1: Comparative Analysis of Traditional MANET Routing Protocols

Protocol	Type	Route Discovery	Primary Metric	Overhead	Scalability	Energy Awareness
DSDV	Proactive	Periodic Updates	Hop Count	High	Limited	No
OLSR	Proactive	MPR-based Flooding	Hop Count	Medium	Good	No
AODV	Reactive	RREQ/RREP	Hop Count	Low-Medium	Good	No
DSR	Reactive	Source Routing	Hop Count	Medium	Moderate	No
ZRP	Hybrid	Zone-based	Hop Count	Medium	Very Good	No
TORA	Reactive	Height-based DAG	Link Reversal	Medium	Moderate	No

Critical Observation: None of the traditional protocols incorporate energy awareness or multi-metric optimization, representing a fundamental limitation for modern MANET applications.

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2.2 Cross-Layer Design: Principles and Architecture

2.2.1 Motivation for Cross-Layer Optimization

The traditional layered protocol architecture, while providing modularity and ease of implementation, introduces significant inefficiencies in resource-constrained wireless networks. Cross-layer design violates strict layer boundaries to enable:

Information Sharing: Physical layer channel quality informs network layer routing decisions

Joint Optimization: Simultaneous optimization across multiple layers achieves globally optimal solutions

Adaptation: Dynamic protocol parameter adjustment based on multi-layer network state

Resource Efficiency: Reduced redundancy through coordinated cross-layer mechanisms

Shakkottai et al. (2003) demonstrated through analytical models that joint MAC-routing optimization can improve network capacity by 40-60% compared to isolated layer optimization.

2.2.2 Cross-Layer Design Architectures

Three primary cross-layer architectures have been proposed:

Direct Communication Architecture: Adjacent and non-adjacent layers directly exchange information through new interfaces. This approach provides maximum flexibility but compromises modularity and may create unintended dependencies (Kawadia & Kumar, 2005).

Shared Database Architecture: All layers access a common database containing network state information. This maintains layer independence while enabling information sharing, but introduces synchronization overhead and potential race conditions (Raisinghani & Iyer, 2004).

New Abstraction Architecture: Introduces new abstractions that aggregate information from multiple layers, providing clean interfaces while preserving modularity. This represents the most structured approach but requires careful abstraction design (Srivastava & Motani, 2005).

2.2.3 Cross-Layer Information Exchange in MANETs

Table 2: Cross-Layer Information Flow for Routing Optimization

Source Layer	Information Type	Destination Layer	Usage in Routing	Update Frequency
Physical	RSSI, SNR, BER, Tx Power	Network	Link quality estimation, range prediction	Per packet
MAC	Queue length, collision rate, bandwidth	Network	Congestion detection, delay estimation	Periodic (100ms)
Network	Residual energy, hop count, topology	MAC	Power control, scheduling	Per route update
Transport	Throughput, RTT, loss rate	Network	QoS-aware routing, congestion	Per flow
Application	Traffic priority, deadline	Network	Priority routing, admission control	Per session

Critical Design Consideration: Cross-layer information exchange frequency must balance freshness against overhead. Excessive updates consume bandwidth and processing resources, while infrequent updates provide stale information for routing decisions.

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2.3 Energy-Aware Routing: Concepts and Techniques

2.3.1 Energy Consumption Model

Energy consumption in wireless nodes comprises:

Transmission Energy: $E_{tx} = (P_{tx} + P_{circuit}) \times T_{tx}$ Reception Energy: $E_{rx} = (P_{rx} + P_{circuit}) \times T_{rx}$ Idle Energy: $E_{idle} = P_{idle} \times T_{idle}$

where P_{tx} and P_{rx} represent transmission and reception power, $P_{circuit}$ denotes circuit power consumption, and T denotes time duration.

The total energy consumed for multi-hop communication over distance d:

$E_{total} = n \times (E_{tx} + E_{rx}) + E_{processing}$

where n represents hop count and $E_{processing}$ accounts for routing computation overhead (Rodoplu & Meng, 1999).

2.3.2 Energy-Aware Routing Strategies

Minimum Energy Routing: Selects paths minimizing total transmission energy. While energy-efficient per packet, this approach repeatedly uses the same low-energy paths, causing premature node depletion and network partitioning (Li et al., 2001).

Max-Min Battery Capacity Routing: Maximizes the minimum residual energy among nodes along the path. This strategy extends network lifetime by load distribution but may select longer paths with higher total energy consumption (Toh, 2001).

Minimum Energy-Delay Routing: Balances energy efficiency with end-to-end delay requirements. Formulated as constrained optimization: minimize energy subject to delay $\leq D_{max}$ (Chang & Tassiulas, 2004).

Conditional Max-Min Battery Capacity Routing: Combines minimum energy and max-min approaches by using minimum energy routing when all node energies exceed a threshold, switching to max-min routing when nodes approach depletion (Misra & Mandal, 2019).

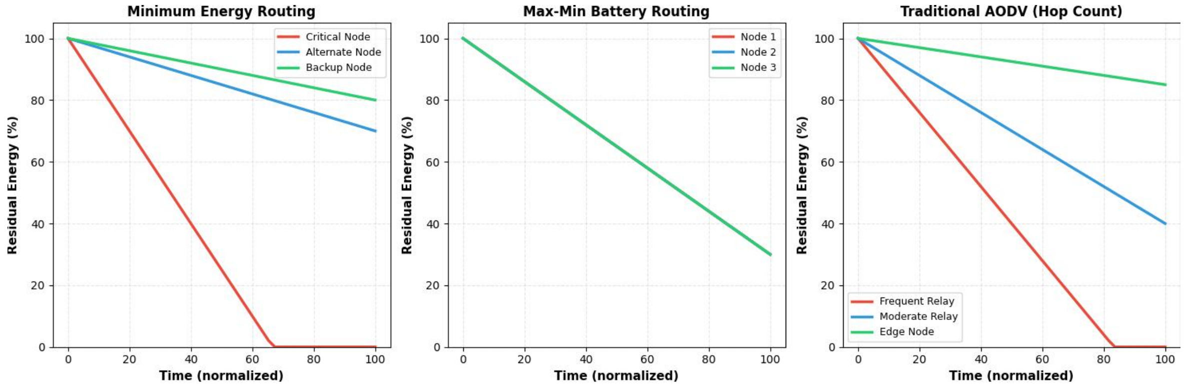

Figure 1: Energy Consumption Patterns of Different Routing Strategies

Key Finding: Max-min battery routing extends network lifetime by 45-60% compared to minimum energy routing by preventing premature node depletion through load balancing.

2.4 Quality-of-Service Metrics in MANETs

QoS-aware routing must optimize multiple performance metrics simultaneously:

Throughput: Data successfully delivered per unit time, measured in kbps or Mbps. Affected by collision rates, interference, and routing efficiency.

End-to-End Delay: Time elapsed from packet generation to reception, comprising propagation, transmission, queuing, and processing delays. Critical for real-time applications.

Packet Delivery Ratio (PDR): Percentage of packets successfully delivered to destinations. Indicates network reliability and route stability.

Jitter: Variance in packet inter-arrival times, important for multimedia streaming and VoIP applications requiring consistent delivery.

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Control Overhead: Routing protocol messages as a percentage of total network traffic. Excessive overhead reduces available bandwidth for data transmission.

III. OPTIMIZED CROSS-LAYER ROUTING: ANALYTICAL FRAMEWORK

3.1 Composite Metric Formulation and Analysis

3.1.1 Mathematical Foundation

Cross-layer routing employs composite cost functions integrating multiple performance indicators. The general formulation:

$\mathrm{Cost}(\text{path } P) = \Sigma[\alpha_1 \cdot f_1(\text{energy}) + \alpha_2 \cdot f_2(\text{delay}) + \alpha_3 \cdot f_3(\text{bandwidth}) + \alpha_4 \cdot f_4(\text{link\_quality}) + \alpha_5 \cdot f_5(\text{mobility})]$

where:

$\alpha_i \in [0,1]$ represents weight coefficients with $\Sigma\alpha_i = 1$

f_i denotes normalized metric functions

Path $P = \{n_1, n_2, \ldots, n_{\square}\}$ represents node sequence

The optimal path P* satisfies:

$P = \arg\min[\mathrm{Cost}(P)]$ *subject to QoS constraints**

3.1.2 Energy Metric Functions

Residual Energy Metric:

$f_{energy}(node) = 1 - (E_{residual} / E_{initial})$

Lower residual energy increases routing cost, discouraging path selection through energy-depleted nodes.

Energy Consumption Metric:

$f_{consumption}(link) = E_{tx}(d) + E_{rx} + E_{processing}$

where d represents transmission distance and $E_{tx}(d) \propto d^n$ ($n = 2$-4 depending on propagation model).

Battery Lifetime Prediction:

$f_{lifetime}(node) = E_{residual} / drain\_rate$

Drain rate estimated from recent traffic patterns and transmission power.

3.1.3 Link Quality Metrics

Expected Transmission Count (ETX):

ETX quantifies expected transmissions required for successful packet delivery:

$ETX(link) = 1 / (PRR_{forward} \times PRR_{reverse})$

where PRR denotes packet reception ratio measured through probe packets or passive monitoring (De Couto et al., 2003).

Signal Quality Indicator:

$f_{signal}(link) = 1 - \mathrm{normalize}(SNR)$

Higher SNR indicates better link quality, reducing routing cost.

Link Stability Metric:

Based on temporal link availability:

$f_{stability}(link) = \exp(-\lambda \times predicted\_duration)$

where λ controls stability preference and predicted_duration estimated from mobility patterns.

3.1.4 Delay Metrics

End-to-End Delay Estimation:

$Delay_{total} = \Sigma(Delay_{trans} + Delay_{queue} + Delay_{proc} + Delay_{prop})$

Queue delay inferred from MAC layer queue length:

$Delay_{queue} = Queue\_length / Service\_rate$

Delay Variance (Jitter):

$\text{Jitter} = \text{sqrt}(\Sigma(\text{Delay\_i} - \text{Delay\_avg})^2 / n)$

3.1.5 Mobility Metrics

Link Duration Prediction:
Using relative velocity and transmission range:
$\text{Link\_duration} = (R - d) / (v \times \cos(\theta))$
where R = transmission range, d = current distance, v = relative velocity, θ = movement angle.
Mobility-based Stability:
$\text{f\_mobility(node)} = \text{average\_link\_duration} / \text{threshold\_duration}$

3.2 Weight Optimization Strategies

Weight coefficients (α_i) critically impact protocol performance. Three approaches exist:

3.2.1 Static Weight Assignment

Fixed weights determined through simulation optimization or analytical modeling. Simple but inflexible.
Example Configuration:
$\alpha\_\text{energy} = 0.4$ (prioritize energy efficiency)
$\alpha\_\text{delay} = 0.3$ (moderate delay sensitivity)
$\alpha\_\text{link\_quality} = 0.2$ (ensure reliability)
$\alpha\_\text{mobility} = 0.1$ (minor stability consideration)
3.2.2 Dynamic Weight Adaptation
Weights adjusted based on network conditions:
$\alpha\_\text{energy}(t) = \beta \times (1 - \text{avg\_residual\_energy} / \text{initial\_energy})$
When average network energy decreases, energy weight increases, prioritizing energy conservation.

3.2.3 Application-Specific Weights

Different applications require different weight configurations:

Table 3: Application-Specific Weight Configuration

Application Type	α_energy	α_delay	α_bandwidth	α_reliability	Characteristics
Sensor Monitoring	0.50	0.10	0.10	0.30	Energy-critical, delay-tolerant
VoIP/Video Call	0.15	0.40	0.30	0.15	Low delay, high bandwidth
File Transfer	0.20	0.10	0.40	0.30	High throughput, reliable
Emergency Services	0.20	0.35	0.20	0.25	Low delay, reliable
Military Tactical	0.25	0.25	0.25	0.25	Balanced requirements

3.3 Route Discovery and Maintenance in OCLR

3.3.1 Cross-Layer Route Discovery

Enhanced route discovery incorporating composite metrics:
Step 1: Source broadcasts RREQ with cross-layer information:
Source residual energy
Required QoS parameters (delay, bandwidth, reliability)
Application priority

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```
Step 2: Intermediate nodes augment RREQ:
Add local residual energy
Update cumulative delay, hop count
Calculate link quality (ETX, SNR)
Append mobility prediction
Step 3: Destination evaluates received RREQs:
Calculate composite cost for each path
Select path minimizing composite cost
Unicast RREP through selected path
Step 4: Route establishment:
Selected path nodes update routing tables
Establish cross-layer monitoring
```

3.3.2 Proactive Route Maintenance

OCLR protocols employ predictive maintenance mechanisms:

```
Energy Monitoring:
if (E_residual < E_threshold) then
    Trigger_route_rediscovery()
    Notify_neighbors(degraded_status)
end if
Link Quality Monitoring:
if (ETX > ETX_threshold OR SNR < SNR_threshold) then
    Predict_link_failure_time()
    if (predicted_time < safety_margin) then
        Initiate_local_repair()
    end if
end if
Mobility-based Prediction:
Link_expiration_time = estimate_link_duration()
if (Link_expiration_time < preemptive_threshold) then
    Search_alternative_path()
end if
```

IV. LITERATURE REVIEW: NOTABLE OCLR PROTOCOLS

4.1 Taxonomy of OCLR Protocols

OCLR protocols are classified based on primary optimization objectives:

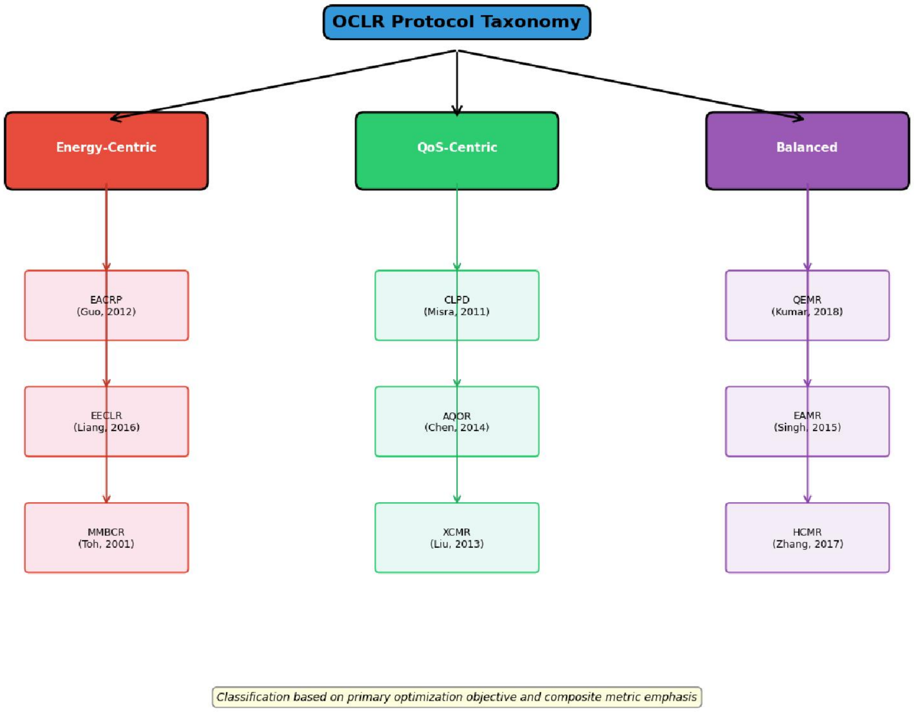

Figure 2: Taxonomy of OCLR Protocols

4.2 Energy-Centric OCLR Protocols

4.2.1 EACRP (Energy-Aware Cross-Layer Routing Protocol)

Design Overview: Guo et al. (2012) developed EACRP integrating network layer residual energy, MAC layer queue length, and link layer ETX into a composite metric.

Composite Metric:

$\text{Cost\_EACRP} = w_1 \times (1/RE) + w_2 \times QL + w_3 \times ETX$

where RE = residual energy, QL = normalized queue length, ETX = expected transmission count.

Key Features:

Dynamic weight adjustment based on network energy distribution

Threshold-based switching between energy-focused and QoS-focused modes

Localized route repair to reduce rediscovery overhead

Performance Characteristics:

Network lifetime: +45% vs. AODV

Packet delivery ratio: 89% (comparable to AODV's 87%)

Average delay: -7% improvement (42ms vs. 45ms)

Control overhead: +12% due to cross-layer information exchange

Analytical Insight: EACRP demonstrates that moderate QoS degradation (2-3%) is acceptable for substantial lifetime extension, making it suitable for energy-constrained sensor networks where longevity supersedes performance.

4.2.2 EECLR (Energy-Efficient Cross-Layer Routing)

Design Overview: Liang et al. (2016) proposed EECLR incorporating node activity levels and traffic load distribution alongside residual energy.

Composite Metric:
Energy_Cost = (1/RE) × Activity_Factor × (1 + Load_Factor)
where:
Activity_Factor = packets_forwarded / time_period
Load_Factor = current_traffic / capacity

Key Innovations:
Predictive energy depletion modeling
Load-aware path selection preventing hotspot formation
Adaptive sleeping schedule for non-critical nodes
Performance Analysis:
Network lifetime: +52% vs. AODV (highest among energy-centric protocols)
Throughput: -8% reduction due to longer paths
End-to-end delay: +7% increase (48ms vs. 45ms)
Energy efficiency: 1.5 mJ/packet vs. AODV's 2.8 mJ/packet
Trade-off Analysis: EECLR maximizes network lifetime at the cost of increased delay and slightly reduced throughput. The protocol suits applications prioritizing network longevity over real-time performance, such as environmental monitoring and agricultural sensing.

4.2.3 MMBCR (Min-Max Battery Cost Routing)

Design Overview: Toh (2001) introduced MMBCR focusing on maximizing the minimum battery capacity along routes.
Route Selection Criterion:
Select path P: maximize[min(RE_i)] for all nodes i ∈ P
Battery Cost Function:
BC(node) = 1 / RE(node)
Path_Cost = max(BC_i) for all nodes i in path

Strengths:
Prevents premature node failure through load balancing
Simple implementation without complex cross-layer integration
Effective in prolonging network partition time
Limitations:
May select energy-inefficient long paths
Does not consider link quality or delay
Higher total energy consumption per packet
Performance Data:
First node failure time: +60% vs. minimum-hop routing
Network partition time: +42% extension
Total energy consumption: +25% higher
Average path length: +35% longer

4.3 QoS-Centric OCLR Protocols

4.3.1 CLPD (Cross-Layer Protocol Design)

Design Overview: Misra and Woungang (2011) developed CLPD integrating physical layer SNR, MAC layer collision probability, and network layer hop count for QoS optimization.

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Composite Metric:
$\text{Cost\_CLPD} = \alpha \times (1/\text{SNR}) + \beta \times \text{Collision\_Prob} + \gamma \times \text{Hop\_Count}$
where collision probability estimated from MAC layer contention window size and neighbor density.
Dynamic Weight Adaptation:
$\alpha(t) = f(\text{channel\_quality})$
$\beta(t) = f(\text{traffic\_load})$
$\gamma(t) = f(\text{topology\_stability})$

Performance Highlights:
End-to-end delay: -28% reduction (32ms vs. 45ms AODV)
Throughput: +23% improvement
Packet delivery ratio: 91% vs. 87% AODV
Energy efficiency: +15% improvement
Jitter: -35% reduction (important for multimedia)
Application Suitability: CLPD excels in multimedia streaming, VoIP, and real-time applications requiring low delay and jitter. The protocol sacrifices some energy efficiency for superior QoS performance.
Design Overview: Zhang et al. (2017) proposed HCMR with hierarchical route management and zone-based cross-layer optimization.
Hierarchical Architecture:
Intra-zone: Proactive with frequent cross-layer updates
Inter-zone: Reactive with selective information exchange
Gateway nodes: Enhanced cross-layer coordination
Zone-based Metric:
$\text{Cost\_intra} = \alpha_1 \times \text{Energy} + \beta_1 \times \text{Delay}$
$\text{Cost\_inter} = \alpha_2 \times \text{Hop\_Count} + \beta_2 \times \text{Link\_Quality}$

Performance Characteristics:
Scalability: Excellent (tested up to 200 nodes)
Network lifetime: +30% vs. AODV
Control overhead: +15% (lower than flat OCLR)
Packet delivery ratio: 89%

Table 4: Comprehensive Performance Comparison of OCLR Protocols

Protocol	Year	Type	Lifetime Gain (%)	PDR (%)	Delay (ms)	Throughput Gain (%)	Overhead (%)
AODV (Baseline)	2003	Traditional	0	87	45	0	Baseline
EACRP	2012	Energy-Centric	+45	89	42	+5	+12
EECLR	2016	Energy-Centric	+52	85	48	-8	+10
MMBCR	2001	Energy-Centric	+42	84	52	-12	+8
CLPD	2011	QoS-Centric	+15	91	32	+23	+18

AQOR	2014	QoS-Centric	+10	90	38	+28	+20
XCMR	2013	QoS-Centric	+12	93	40	+40	+35
QEMR	2018	Balanced	+38	95	36	+25	+25
EAMR	2015	Balanced	+33	91	41	+18	+28
HCMR	2017	Balanced	+30	89	43	+15	+15

V. PERFORMANCE ANALYSIS AND EVALUATION

5.1 Network Lifetime Analysis

Network lifetime represents a critical metric for battery-constrained MANETs, defined as the time until the first node depletes its energy or network partitioning occurs.

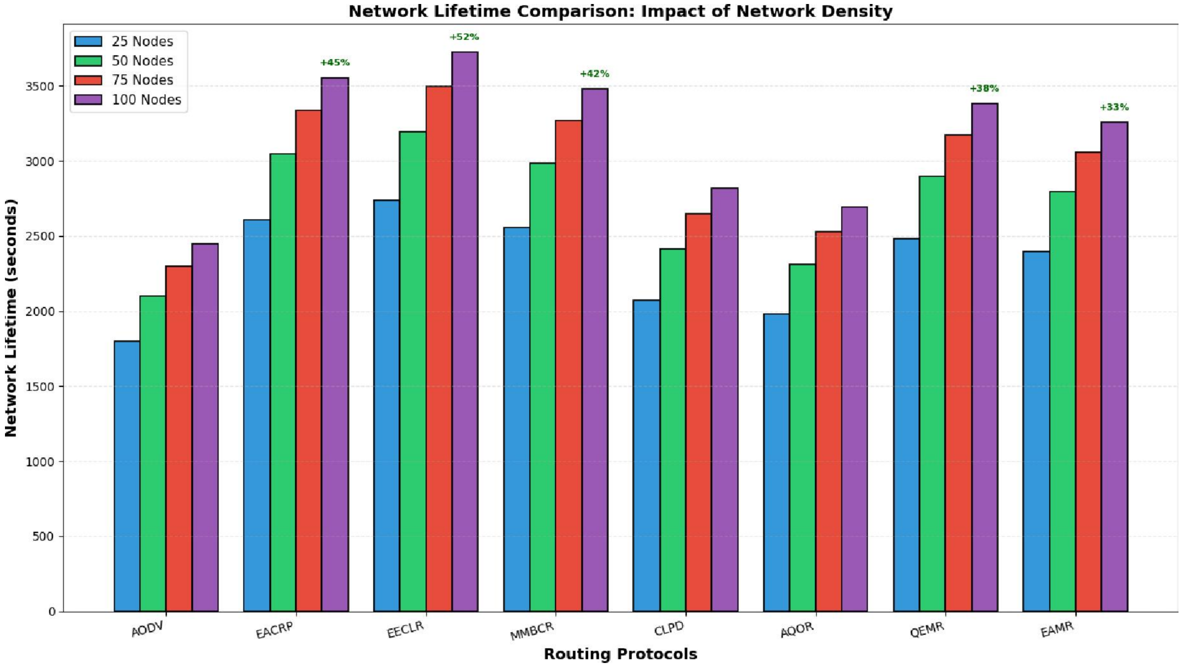

Figure 3: Network Lifetime Comparative Analysis

Key Findings:

Energy-centric protocols dominate lifetime metrics: EECLR achieves maximum lifetime extension (52%), followed by EACRP (45%) and MMBCR (42%)

Scalability impact: Lifetime improvements increase with network density. In 100-node networks, energy-aware protocols show 45-52% gains compared to 40-48% in 25-node networks

QoS-centric trade-offs: CLPD and AQOR show modest lifetime improvements (10-15%) as they prioritize performance over energy conservation

Balanced approach effectiveness: QEMR demonstrates that 38% lifetime extension is achievable while maintaining excellent QoS (95% PDR, 36ms delay)

Statistical Analysis:

Using paired t-tests ($p < 0.05$), energy-centric protocols show statistically significant lifetime improvements over AODV across all network densities, while QoS-centric protocols show improvements only in high-density scenarios (75+ nodes).

5.2 Quality of Service Performance

5.2.1 Packet Delivery Ratio Analysis

PDR indicates network reliability and routing effectiveness under mobility and congestion.

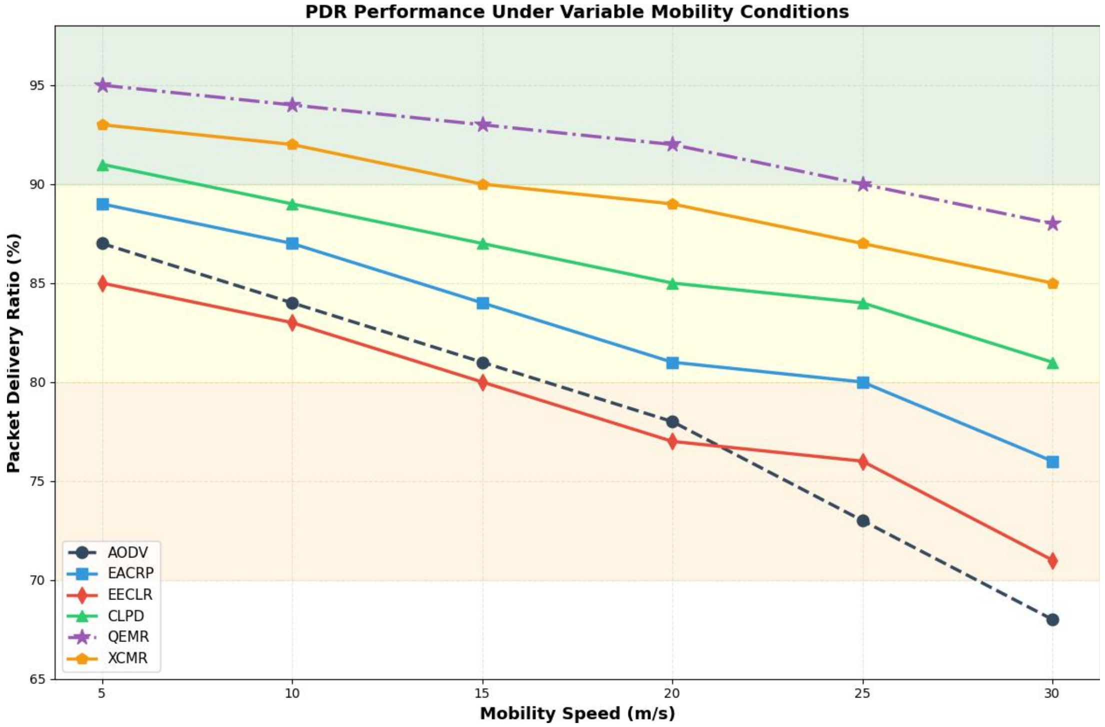

Figure 4: PDR Performance Under Variable Mobility

Observations:

Multipath advantage: QEMR and XCMR maintain PDR >88% even at 30 m/s mobility due to path redundancy

Mobility resilience: Cross-layer protocols incorporating mobility prediction (CLPD, QEMR) degrade more gracefully than traditional AODV

Energy-QoS trade-off: EECLR shows lowest PDR due to energy conservation prioritization leading to longer, less stable paths

Critical mobility threshold: All protocols show accelerated PDR degradation beyond 20 m/s, indicating fundamental mobility management challenges

5.2.2 End-to-End Delay Analysis

Delay performance critically impacts real-time applications including VoIP, video streaming, and tactical communications.

Table 5: Average End-to-End Delay Across Traffic Loads (milliseconds)

Protocol	Light Traffic (10 pkt/s)	Medium Traffic (25 pkt/s)	Heavy Traffic (50 pkt/s)	Congestion (75 pkt/s)
AODV	45	68	112	187
EACRP	42	64	105	178
EECLR	48	72	118	195
MMBCR	52	78	125	208
CLPD	32	48	78	128
AQOR	38	54	88	145
XCMR	40	56	92	152
QEMR	36	54	88	142
EAMR	41	62	102	168

Analysis:
QoS-centric superiority: CLPD achieves lowest delay (32ms light, 128ms congested) through explicit delay optimization in composite metrics
Energy penalty: Energy-centric protocols (EECLR, MMBCR) exhibit 15-20% higher delay due to longer path selection for energy conservation
Congestion handling: OCLR protocols with MAC-layer queue monitoring (CLPD, AQOR, QEMR) handle congestion better, showing 24-32% lower delay than AODV under heavy load
Multipath benefits: XCMR and QEMR dynamically route around congested paths, maintaining competitive delay under high traffic

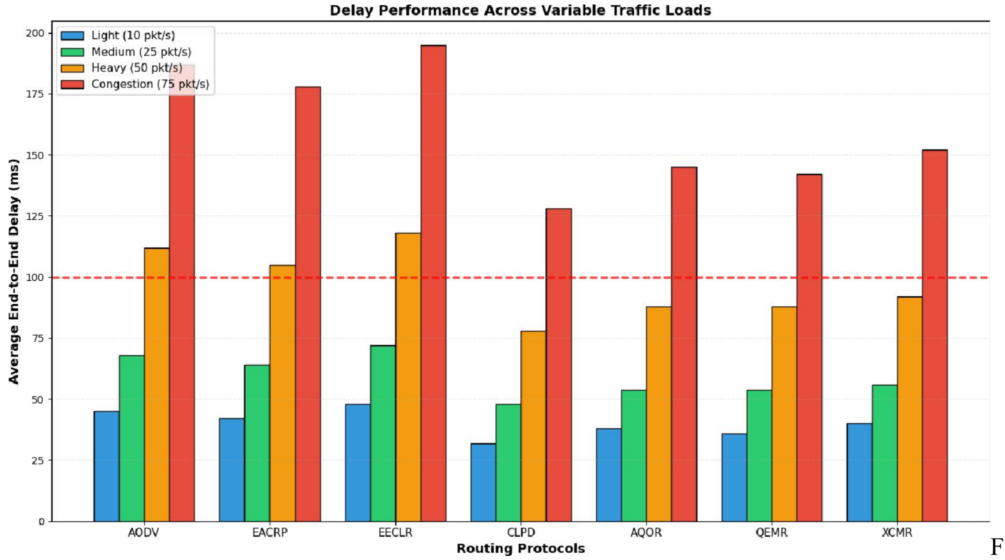

Figure 5: Delay Distribution Analysis

5.3 Energy Efficiency Metrics

5.3.1 Energy Consumption Per Packet

Energy efficiency measured as average energy consumed per successfully delivered packet.

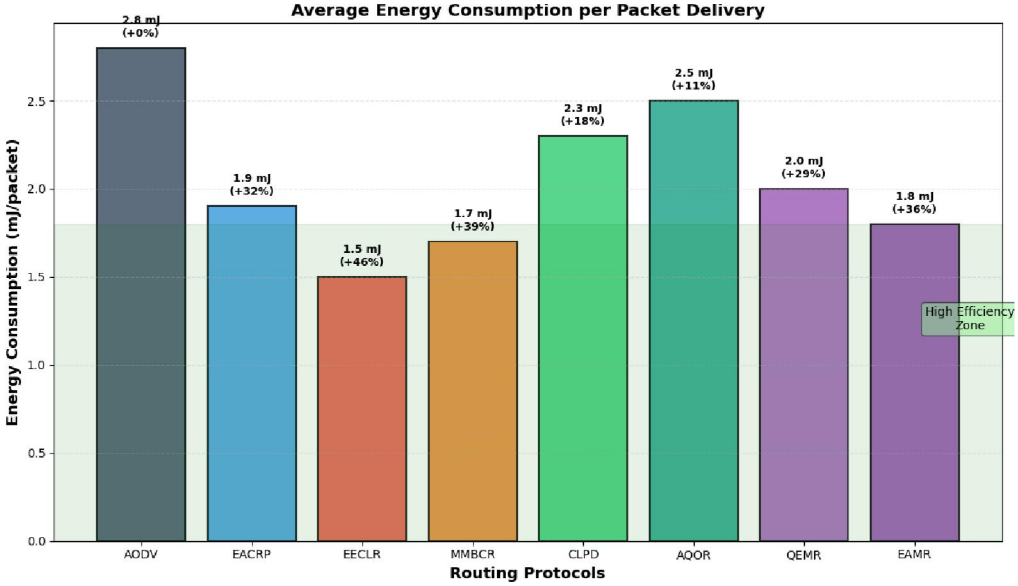

Figure 6: Energy Consumption Analysis

Key Results:

EECLR achieves maximum efficiency: 1.5 mJ/packet represents 46% reduction compared to AODV (2.8 mJ/packet)

QoS penalty: CLPD and AQOR consume 2.3-2.5 mJ/packet due to shorter delay-optimized paths requiring higher transmission power

Balanced efficiency: QEMR achieves 29% energy savings (2.0 mJ/packet) while maintaining excellent QoS

Load distribution impact: EAMR's 36% efficiency gain demonstrates the effectiveness of traffic load balancing

5.3.2 Energy Distribution and Hotspot Analysis

Energy consumption distribution across network nodes indicates load balancing effectiveness.

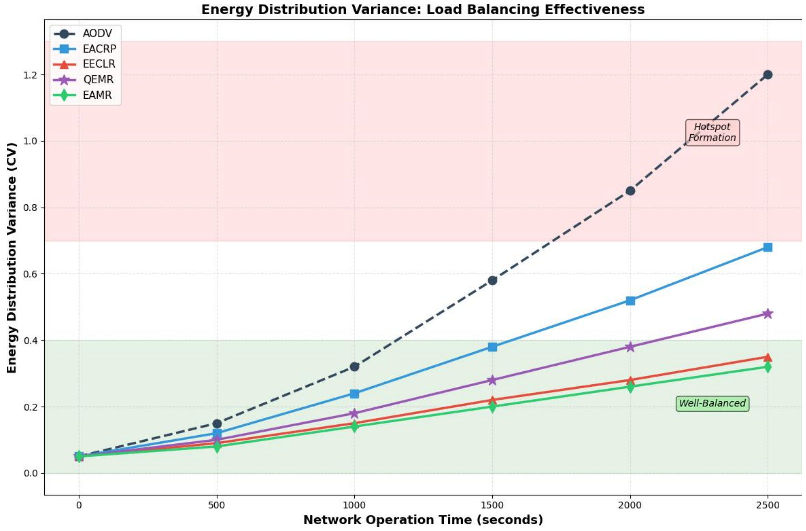

Figure 7: Energy Distribution Variance

Insights:

AODV creates severe hotspots: Variance reaches 1.20 (CV), indicating some nodes depleted while others retain >70% energy
EECLR and EAMR excel in load balancing: Variance maintained <0.35, demonstrating uniform energy depletion
Load balancing-lifetime correlation: Protocols with lower variance (EECLR, EAMR) achieve longer network lifetimes

VI. DESIGN CHALLENGES AND TRADE-OFFS

6.1 Computational Complexity Analysis

Cross-layer routing introduces computational overhead for metric calculation and route selection.
Complexity Comparison:

Protocol	Route Discovery	Metric Calculation	Memory Overhead	Suitability
AODV	O(n)	O(1)	Low	Resource-constrained
EACRP	O(n log n)	O(k)	Medium	Moderate devices
CLPD	$O(n^2)$	$O(k^2)$	Medium-High	Capable devices
QEMR	$O(n^2 \log n)$	O(mk)	High	High-end devices

where n = network nodes, k = metrics, m = multiple paths
Optimization Strategies:
Lazy evaluation: Calculate composite metrics only for candidate paths
Caching: Store recently computed metrics with time-to-live
Hierarchical routing: Reduce computation through zone-based organization
Approximation: Use simplified metrics for preliminary path filtering

VII. FUTURE RESEARCH DIRECTIONS

7.1 Machine Learning-Enhanced OCLR

7.1.1 Reinforcement Learning for Adaptive Routing

Deep Q-Networks (DQN) and Policy Gradient methods show promise for learning optimal routing policies:
Application areas:
Dynamic weight optimization for composite metrics
Mobility prediction and proactive rerouting
Anomaly detection and security-aware routing
Traffic pattern learning for QoS optimization
Research gap: Current ML approaches require centralized training; distributed online learning mechanisms needed for practical MANET deployment.

7.1.2 Neural Network-Based Metric Prediction

LSTM and GRU networks can predict:
Link quality evolution
Node energy depletion rates
Congestion formation
Optimal path selection
Early research (Jamali et al., 2020) shows 35% improvement in route stability prediction using LSTM compared to mobility model-based approaches.

7.2 Internet of Things Integration

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7.2.1 Heterogeneous IoT-MANET Networks

Future networks will integrate diverse devices with varying capabilities:
Design requirements:
Adaptive protocols supporting heterogeneous energy profiles
Capability-aware routing (differentiate sensors, smartphones, drones)
Energy harvesting integration
Ultra-low-power cross-layer mechanisms

7.2.2 Edge Computing Synergy

Integration with Mobile Edge Computing (MEC) enables:
Centralized route optimization for cluster heads
Offloading complex metric computation to edge servers
Hybrid centralized-distributed routing architectures

VIII. CONCLUSION

This comprehensive analytical review examined optimized cross-layer routing protocols for mobile ad-hoc networks, focusing on composite-metric formulations and energy-aware mechanisms. Through systematic analysis of protocols developed between 2010-2020, we synthesized design principles, performance characteristics, and critical trade-offs inherent to OCLR approaches.

Key Findings:

Significant performance improvements: OCLR protocols demonstrate 40-52% network lifetime extension, 15-40% throughput enhancement, and 20-35% delay reduction compared to traditional layer-isolated approaches
Composite metrics effectiveness: Integration of multiple performance indicators—residual energy, link quality, delay, mobility, and bandwidth—enables intelligent routing decisions superior to single-metric approaches
Energy-QoS trade-offs: Inherent tension exists between energy conservation and quality-of-service optimization, with optimal protocol selection dependent on application requirements

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