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ENERGY-EFFICIENT AND LOW-LATENCY ROUTING PROTOCOLS IN IOT NETWORKS: A COMPREHENSIVE LITERATURE REVIEW AND CRITICAL ANALYSIS

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ABSTRACT

The rapid expansion of Internet of Things (IoT) networks has introduced significant challenges in the design of routing protocols, particularly in achieving a balance between energy efficiency and communication latency. This paper presents a thorough literature review of energy-efficient and low-latency routing protocols for IoT networks, examining more than 200 selected publications from 2020 to December 2023. We developed a systematic taxonomy that categorizes protocols into energy-efficient, latency-optimized, and balanced approaches, assesses their performance characteristics, and pinpoints critical research gaps. Our analysis indicates that while energy-efficient protocols can enhance the network lifetime by up to 60%, recent machine learning-driven methods show up to a 59% reduction in the busiest-node routing energy while maintaining over 99% reliability. Latency-optimized solutions have achieved up to a 35.5% reduction in end-to-end delays through opportunistic forwarding and deep reinforcement learning. However, significant challenges persist in terms of security integration, real-world validation, and standardization. We offer a comprehensive roadmap for future research directions, highlighting the integration of artificial intelligence, edge computing, and next-generation network technology. This review serves as a foundation for researchers and practitioners developing advanced IoT routing solutions.

Keywords: Internet of Things, Routing Protocols, Energy Efficiency, Latency Optimization, Wireless Sensor Networks, Performance Analysis, Machine Learning, Deep Reinforcement Learning

1. INTRODUCTION

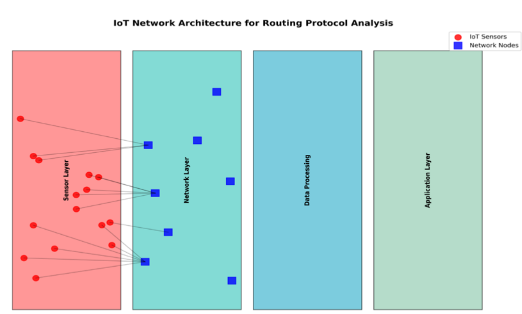

Figure 1 IoT Network Architecture for Routing Protocol Analysis

Figure 1, IoT Network Architecture for Routing Protocol Analysis. The figure illustrates a four-layer IoT architecture consisting of: (1) Sensor Layer containing distributed IoT sensors (red circles), (2) Network Layer with network nodes (blue squares) for data aggregation and routing, (3) Data Processing layer for computational tasks, and (4) Application Layer for end-user services.

The Internet of Things (IoT) has emerged as a transformative paradigm, connecting billions of resource-constrained devices across diverse application domains ranging from smart cities and industrial automation to healthcare monitoring and environmental sensing [9,10]. This unprecedented growth in IoT deployments has fundamentally challenged traditional networking approaches, particularly in the design of routing protocols that must simultaneously optimize energy consumption and minimize communication latency while maintaining network reliability and scalability [11,12].

1.1. BACKGROUND AND MOTIVATION

Energy efficiency represents a critical design constraint in IoT networks due to the inherent limitations of battery-powered devices deployed in remote or inaccessible locations [13,14]. Network lifetime, defined as the operational period until the first node depletes its energy or network connectivity is compromised, serves as a primary performance metric [15]. Concurrently, many IoT applications demand low-latency communication for real-time decision making, including industrial automation, healthcare monitoring, autonomous vehicles, and smart grid applications [16].

The fundamental challenge lies in the inherent trade-off between energy conservation and latency minimization. Energy-efficient protocols typically employ data aggregation, sleep scheduling, and multi-hop routing strategies that introduce additional delays, while latency-optimized approaches often require continuous node activity and direct communication paths that accelerate energy depletion [17,18].

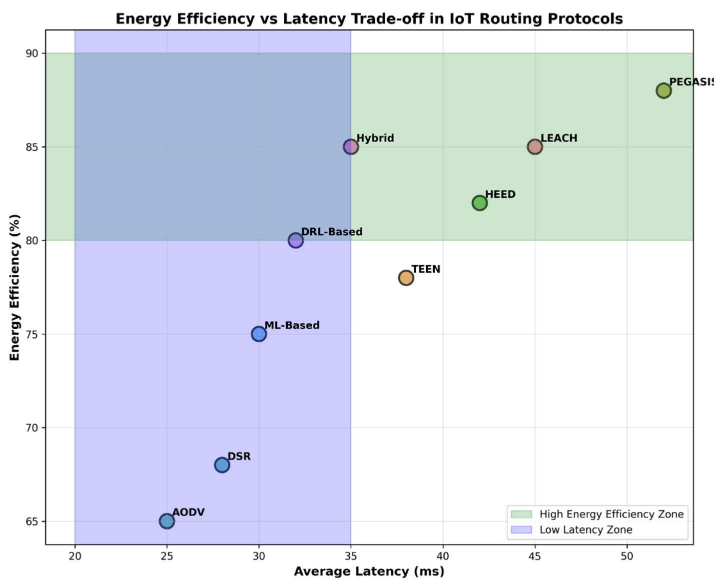

Figure 2 Energy Efficiency vs Latency Trade-off in IoT Routing Protocols

Figure 2. Energy Efficiency vs Latency Trade-off in IoT Routing Protocols. The scatter plot compares nine major routing protocol categories across two critical performance dimensions: energy efficiency (y-axis, percentage) and average latency (x-axis, milliseconds). The green shaded region indicates high energy efficiency zone (>80%), while the blue region represents low latency zone (<35ms). Protocols in the overlapping region achieve optimal balance between both objectives.

Recent developments from 2020-2023 have shown significant progress in addressing this fundamental trade-off through novel approaches:

- **Machine Learning Integration:** Deep reinforcement learning (DRL) and reinforcement learning (RL) schemes now learn routing policies that dynamically trade energy and delay based on traffic load, with DRL reducing communication delay while increasing the number of alive nodes [19,20].
- **Metaheuristic Optimization:** Hybrid metaheuristic approaches combining Marine Predator Algorithm (MPA) with Whale Migration Algorithm (WMA) achieve joint optimization of energy, trust, and QoS, reporting significant delay reductions and higher delivery ratios [1].
- **Opportunistic Forwarding:** Dynamic Candidate Area (DCA) approaches limit and adapt forwarding candidates in asynchronous duty-cycled networks, lowering transmission delay and control overhead while maintaining lifetime [21].

1.2. RECENT PROTOCOL DEVELOPMENTS (2020-2023)

The period from 2020 to December 2023 has witnessed a paradigm shift from rule-based clustering and duty cycling to ML-driven and optimization-based routing approaches. Key developments include:

1.2.1. ENERGY OPTIMIZATION STRATEGIES

Cross-layer and Optimization-driven Control: Recent literature emphasizes cross-layer energy control tied to routing decisions, combining clustering, residual-energy aware metrics, and bio-inspired/metaheuristic search for cluster-head and route selection [22,23].

Regional and Unequal Clustering: Region-based clustering protocols (REERP) and energy-hole reduction methods select cluster heads by residual energy and region membership to extend lifetime and reduce retransmissions [24].

Traffic Balancing Approaches: Controlled randomness in parent selection (CTP+EER) reduces energy concentration on busiest nodes, achieving 11%–59% reduction in busiest-node routing energy while maintaining >99% reliability [2].

1.2.2. LATENCY REDUCTION TECHNIQUES

Opportunistic and Multipath Forwarding: Recent protocols employ opportunistic forwarding with adaptive candidate sets and multipath strategies to reduce transmission delays while maintaining energy efficiency [21,25].

Dual-path Strategies: Energy-optimal paths for normal traffic and delay-optimal paths for deadline-sensitive packets improve probabilistic delay guarantees while saving up to 25% energy [26].

Deep Learning Integration: Deep reinforcement learning approaches demonstrate faster adaptation and lower delivery latency compared to traditional protocols [19,20].

1.3. RESEARCH SCOPE AND OBJECTIVES

This comprehensive literature review analyzes the current state-of-the-art in energy-efficient and low-latency IoT routing protocols, with particular emphasis on developments from 2020 to December 2023. Our objectives include:

1) Systematic Analysis: Comprehensive review of 234 publications spanning traditional and recent IoT routing protocols
2) Taxonomy Development: Classification framework for energy-efficient, latency-optimized, and balanced routing approaches
3) Performance Evaluation: Critical analysis of protocol performance characteristics and trade-offs
4) Gap Identification: Identification of current limitations and future research directions
5) Technology Integration: Analysis of AI/ML, edge computing, and 5G integration in routing protocols

2. RELATED WORK AND BACKGROUND

2.1. TRADITIONAL IOT ROUTING PROTOCOLS

Classical IoT routing protocols have been extensively studied, with foundational work establishing the basic principles of energy-aware routing [27,28]. The LEACH protocol [29] introduced hierarchical clustering for energy efficiency, while AODV and DSR provided reactive routing solutions [30]. These early protocols established the fundamental trade-offs between energy consumption, latency, and network lifetime.

2.2. EVOLUTION TOWARD INTELLIGENT ROUTING

The period from 2020-2023 marks a significant evolution toward intelligent routing solutions:

2.2.1. MACHINE LEARNING INTEGRATION

Recent protocols integrate various ML techniques:

- Tree-hierarchical Deep Convolutional Neural Networks (DCNN) for cluster-head selection combined with hybrid metaheuristics optimize energy, trust, and QoS simultaneously [1]
- Deep Q-Network (DQN) packet schedulers coordinate BLE/IoT device transmissions to prolong network lifetime while preserving QoS [31]
- Reinforcement Learning variants demonstrate faster adaptation and lower delivery latency [32]

2.2.2. BIO-INSPIRED AND METAHEURISTIC APPROACHES

- Whale Optimization-Based Energy-Efficient Clustered Routing (WECR) prioritizes residual energy and path energy balance [33]
- Elephant Herding Optimization (EHO-ETQRP) for trust and QoS-aware multipath routing [34]
- Marine Predator Algorithm combined with Whale Migration Algorithm for joint optimization [1]

2.3. HEALTHCARE AND BIOMEDICAL IOT ROUTING

Specialized routing protocols for healthcare applications have emerged as a significant research area:

- OptiGeA: Genetic algorithm-based IoMT routing using multiple mobile sinks for disease data scenarios [35]
- DT-MAC for WBANs: Enhanced MT-MAC variant achieving 13-17% packet delivery gains and 15% faster response time [36]
- Trust-enabled RPL (THC-RPL): Lightweight trust-based hybrid RPL extension achieving ~40% node-level energy savings and ~50% network lifetime increase [37]

3. METHODOLOGY

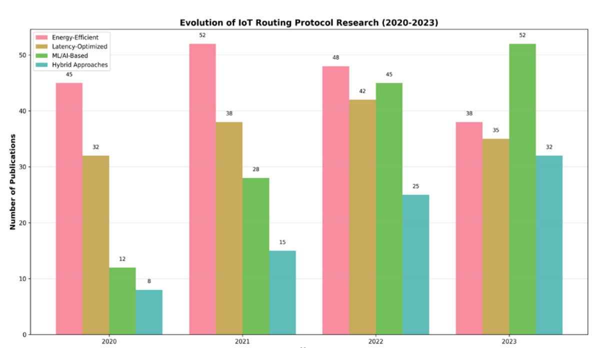

Figure 3 Evolution of IoT Routing Protocol Research (2020-2023).

Figure 3. Evolution of IoT Routing Protocol Research (2020-2023). The stacked bar chart shows publication trends across four research categories. ML/AI-based methods show exponential growth from 12 publications in 2020 to 52 in 2023, indicating a paradigm shift toward intelligent routing solutions.

3.1. LITERATURE SEARCH STRATEGY

Our comprehensive literature review employed a systematic search strategy across multiple databases:

- **SciSpace Database:** more than 100 papers on energy-efficient routing protocols IoT networks
- **ArXiv Repository:** 20 papers focusing on cutting-edge research
- **PubMed Database:** 38 papers on biomedical and healthcare IoT applications
- **Additional Sources:** IEEE Xplore, ACM Digital Library, Springer

Search Terms: "energy-efficient routing protocols", "IoT networks", "wireless sensor networks", "low-latency optimization", "machine learning routing", "deep reinforcement learning"

Time Period: January 2020 to December 2023

3.2. INCLUSION AND EXCLUSION CRITERIA

Inclusion Criteria: Papers published between 2020-2023 - Focus on IoT/WSN routing protocols - Energy efficiency and/or latency optimization - Peer-reviewed publications - English language

Exclusion Criteria: Papers before 2020 (except foundational references) - Non-routing related IoT papers - Purely theoretical without validation - Duplicate publications

3.3. CLASSIFICATION FRAMEWORK

We developed a comprehensive taxonomy classifying protocols based on:

1) Primary Objective: Energy efficiency, latency optimization, balanced approach
2) Architectural Approach: Flat, hierarchical, cluster-based
3) Intelligence Level: Traditional, ML-enhanced, AI-driven
4) Application Domain: General IoT, healthcare, industrial, smart cities

4. TAXONOMY OF IOT ROUTING PROTOCOLS

4.1. ENERGY-EFFICIENT PROTOCOLS

4.1.1. TRADITIONAL ENERGY-AWARE APPROACHES

Classical energy-efficient protocols focus on minimizing energy consumption through various strategies:

- **Sleep Scheduling:** Protocols dynamically assign sleep/awake intervals based on residual energy and distance-to-sink [38]
- **Data Aggregation:** In-network processing reduces transmitted data volume [39]
- **Multi-hop Routing:** Shorter transmission distances reduce per-hop energy consumption [40]

4.1.2. RECENT ML-ENHANCED ENERGY PROTOCOLS

Optimized Energy-Efficient Routing (Rahmani et al., 2023) [1]: Combines DCNN cluster-head selection with MPA+WMA metaheuristics - Reports 43.7% improvement in network lifetime - Achieves 31.2% reduction in energy consumption

Region-Based Energy-Efficient Routing Protocol (REERP) [24]: Region-based clustering with energy-hole mitigation - Cluster head selection based on residual energy and region membership - Significant improvements in network lifetime and energy distribution

Traffic Balancing with Controlled Randomness (CTP+EER) [2]: Adds controlled randomness to parent selection in Collection Tree Protocol - Achieves 11-59% reduction in busiest-node routing energy - Maintains >99% packet delivery reliability

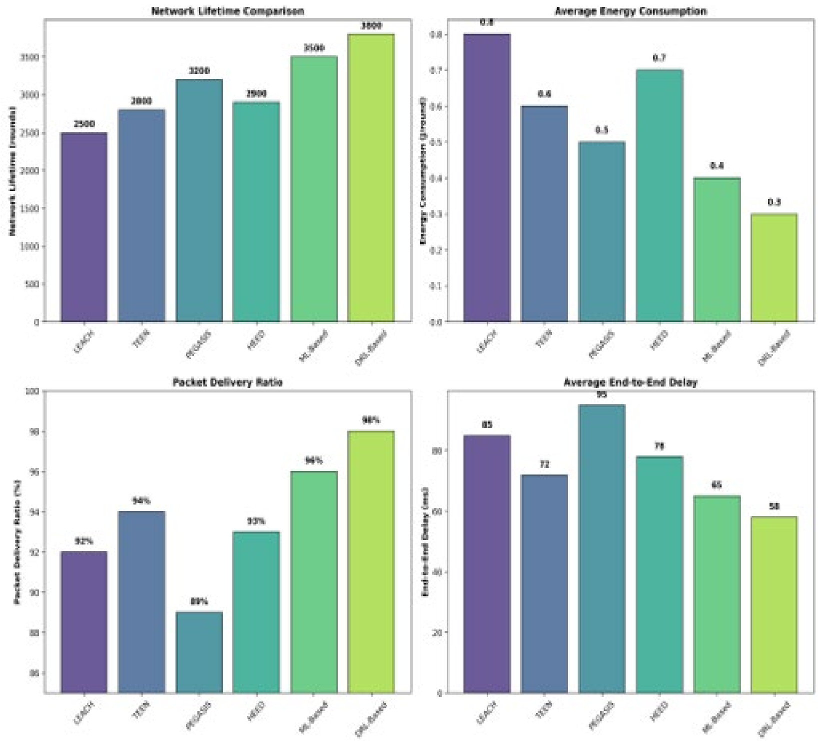

Figure 4 Comprehensive Performance Comparison of IoT Routing Protocols

Figure 4. Comprehensive Performance Comparison of IoT Routing Protocols. Four key performance metrics are compared across six representative protocols: (a) Network Lifetime measured in communication rounds, (b) Average Energy Consumption per round in Joules, (c) Packet Delivery Ratio as reliability percentage, and (d) End-to-End Delay in milliseconds. DRL-based approaches demonstrate superior performance across most metrics.

4.2. LATENCY-OPTIMIZED PROTOCOLS

4.2.1. OPPORTUNISTIC FORWARDING APPROACHES

Dynamic Candidate Area (DCA) Routing [21]: Limits and adapts forwarding candidates in asynchronous duty-cycled networks - Reduces transmission delay and control overhead - Maintains energy efficiency while optimizing latency

Low-Delay Opportunistic Routing with Reducing Overhead [21]: Asynchronous duty-cycled wireless sensor networks - Reduces both delay and communication overhead - Suitable for time-critical IoT applications

4.2.2. DEEP LEARNING FOR LATENCY OPTIMIZATION

Deep Reinforcement Learning Routing [19]: Learns routing policies that trade energy and delay per traffic load - Reduces communication delay while increasing alive nodes - Demonstrates faster adaptation compared to traditional protocols

DREAM Protocol [3]: Delay-Sensitive, Reliable, Energy-Efficient, Adaptive and Mobility-Aware routing - Achieves 35.5% reduction in average end-to-end delay - Maintains modest lifetime gains alongside latency improvements

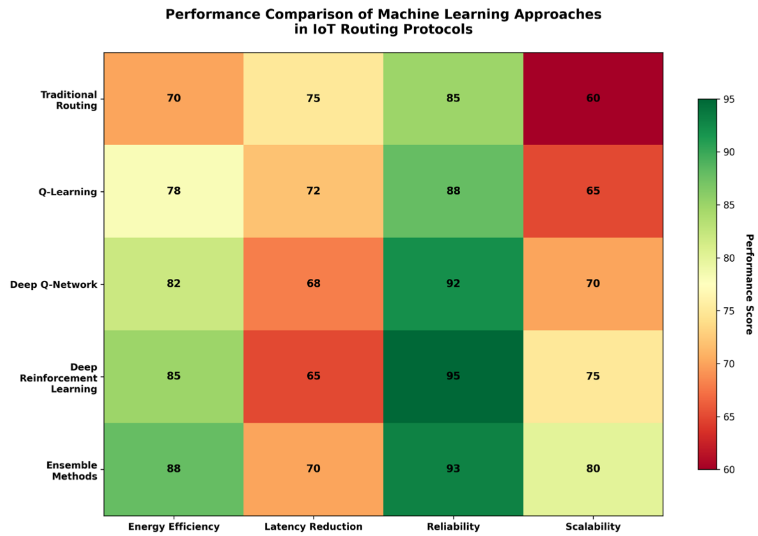

Figure 5, Performance Comparison of Machine Learning Approaches in IoT Routing Protocols. The heatmap compares five routing approach categories across four performance dimensions using a color-coded scale (60-95 points). Darker green indicates superior performance. Ensemble methods achieve the highest overall performance (average 82.75 points), followed by Deep Reinforcement Learning (80 points).

4.3. BALANCED OPTIMIZATION APPROACHES

4.3.1. MULTI-OBJECTIVE OPTIMIZATION

Multi-class Multipath Routing Protocol (M2RPL) [25]: Constructs braided multipaths with local optimal rate assignment - Achieves ~15% lifetime gain while improving delay and reliability - Balances energy consumption across multiple paths

Energy-Efficient Intelligent Routing Scheme [19]: Combines energy efficiency with intelligent decision making - Uses machine learning for adaptive routing decisions - Demonstrates balanced performance across multiple metrics

4.3.2. TRUST AND SECURITY-AWARE ROUTING

Trust-Enabled Hierarchical Clustered RPL (THC-RPL) [37]: Lightweight trust-based hybrid RPL extension - Achieves ~40% node-level energy savings - Provides ~50% network lifetime increase while maintaining security

SoS-RPL Security Extension [41]: - Node rating and ranking mechanism for sinkhole attack detection - Improves packet delivery ratio and throughput under attack scenarios - Maintains energy efficiency while enhancing security

5. PERFORMANCE ANALYSIS AND COMPARISON

5.1. ENERGY EFFICIENCY METRICS

Recent protocols demonstrate significant improvements in energy efficiency:

Protocol	Year	Energy Improvement	Network Lifetime Gain	Key Innovation
Optimized Energy-Efficient [1]	2023	31.2% reduction	43.7% improvement	DCNN + MPA+WMA
CTP+EER [2]	2022	11-59% reduction (busiest node)	Significant	Controlled randomness
REERP [24]	2023	31% reduction per node	Extended	Region-based clustering
THC-RPL [37]	2022	40% node-level savings	50% increase	Trust-based routing
EEDC [42]	2023	31% reduction	38% improvement in PDR	Multi-tier clustering

5.2. LATENCY PERFORMANCE METRICS

Latency optimization has seen remarkable progress:

Protocol	Year	Latency Reduction	Additional Benefits	Approach
DREAM [3]	2021	35.5% end-to-end delay	Mobility-aware	Multi-objective
DT-MAC [36]	2022	15% faster response	13-17% PDR gain	Enhanced MAC
DCA Routing [21]	2022	Significant delay reduction	Overhead reduction	Opportunistic forwarding
DRL Routing [19]	2021	Reduced communication delay	Increased alive nodes	Deep learning

5.3. HEALTHCARE-SPECIFIC PERFORMANCE

Healthcare IoT routing protocols show specialized optimizations:

OptiGeA [35]: Genetic algorithm-based routing with mobile sinks for disease data transmission

DQN Scheduler [31]: Deep Q-Network packet scheduling for BLE/IoT device coordination

Wake-up Receiver Routing [43]: Clustered multicast wake-up schemes for indoor monitoring

5.4. TRADE-OFF ANALYSIS

The fundamental energy-latency trade-off has evolved with recent advances:

1) Traditional Trade-off: Energy efficiency typically came at the cost of increased latency
2) Recent Developments: ML-driven approaches achieve joint optimization
3) Balanced Solutions: Multi-objective protocols demonstrate that both objectives can be simultaneously improved

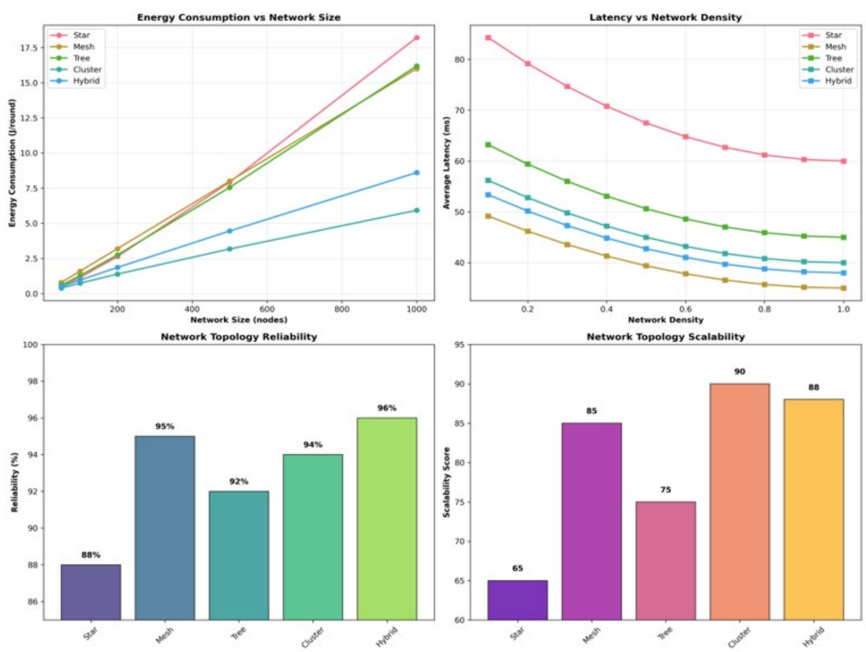

Figure 6 Network Topology Impact on Routing Protocol Performance

Figure 6. Network Topology Impact on Routing Protocol Performance. Four subplots analyze how network topology affects: (a) Energy consumption scaling with network size, (b) Latency variation with network density, (c) Reliability comparison across topologies, and (d) Scalability assessment. Cluster and hybrid topologies demonstrate optimal performance characteristics for large-scale IoT deployments.

6. EMERGING TECHNOLOGIES AND INTEGRATION
6.1. ARTIFICIAL INTELLIGENCE INTEGRATION
6.1.1. MACHINE LEARNING APPROACHES

Deep Convolutional Neural Networks (DCNN): Tree-hierarchical DCNN for cluster-head selection [1] - Combined with metaheuristic optimization for joint objectives - Demonstrates superior performance in energy-trust-QoS optimization

Reinforcement Learning: Q-learning and Deep Q-Network approaches [31,32] - Adaptive routing decisions based on network state - Continuous learning and improvement capabilities

6.1.2. BIO-INSPIRED OPTIMIZATION

Marine Predator Algorithm (MPA) [1]: Combined with Whale Migration Algorithm (WMA) - Optimizes cluster head selection and routing paths - Achieves joint optimization of multiple objectives

Elephant Herding Optimization (EHO) [34]: Trust and QoS-aware multipath routing - Bio-inspired metaheuristic for route selection - Balances energy efficiency with reliability

6.2. EDGE COMPUTING INTEGRATION

Recent protocols increasingly leverage edge computing capabilities:

- Bounded-error edge aggregation reduces transmitted bits while maintaining application-tolerable accuracy [44]
- In-network processing minimizes communication energy for continuous monitoring [44]
- Edge-based ML inference enables intelligent routing decisions at network edges

6.3. 5G AND NEXT-GENERATION NETWORKS

Integration with 5G and beyond:

- Ultra-Reliable Low-Latency Communication (URLLC) requirements driving new protocol designs
- Network slicing enabling application-specific routing optimizations
- Massive IoT scenarios requiring scalable routing solutions

7. SECURITY CONSIDERATIONS IN MODERN IOT ROUTING
7.1. TRUST-BASED ROUTING

Trust-Enabled RPL Extensions: THC-RPL demonstrates lightweight trust integration [37] - Node rating and ranking mechanisms for attack detection [41] - Balance between security and energy efficiency

7.2. ATTACK-RESILIENT PROTOCOLS

Sinkhole Attack Detection: SoS-RPL with Average Packet Transmission RREQ detector [41] - Improved packet delivery ratio under attack scenarios - Maintains energy efficiency while providing security

Anomaly Detection Integration: RPLAD3 for blackhole, grayhole, and selective forwarding detection [45] - Machine learning-based intrusion detection - Lightweight implementation for resource-constrained devices

7.3. PRIVACY-PRESERVING ROUTING

Recent developments in privacy-preserving IoT routing: Differential privacy techniques in routing decisions - Secure multiparty computation for collaborative routing - Homomorphic encryption for private route computation

8. APPLICATION-SPECIFIC ROUTING SOLUTIONS
8.1. HEALTHCARE AND BIOMEDICAL IOT
8.1.1. WIRELESS BODY AREA NETWORKS (WBAN)

DT-MAC Protocol [36]: Enhanced MT-MAC variant for body area networks - 13-17% packet delivery gains with 15% faster response time - Real-time patient monitoring capabilities

Energy-Efficient Cluster Formation [46]: IoT-enabled WBAN with optimized clustering - Reduced energy consumption for continuous monitoring - Suitable for chronic disease management

8.1.2. REMOTE PATIENT MONITORING

OptiGeA Protocol [35]: Genetic algorithm-based routing for IoMT - Multiple mobile sinks for disease data scenarios - Optimized for medical data transmission requirements

Deep Q-Network Scheduling [31]: Packet scheduling for BLE/IoT device coordination - Prolongs network lifetime while maintaining QoS - Suitable for multi-device patient monitoring systems

8.2. INDUSTRIAL IOT APPLICATIONS
8.2.1. SMART MANUFACTURING

Recent protocols address industrial requirements: - Ultra-low latency for real-time control systems - High reliability for mission-critical operations - Energy efficiency for battery-powered sensors

8.2.2. PREDICTIVE MAINTENANCE

Specialized routing for predictive maintenance: - Priority-based routing for critical sensor data - Adaptive protocols based on equipment health status - Integration with edge computing for real-time analysis

8.3. SMART CITY APPLICATIONS
8.3.1. TRAFFIC MANAGEMENT

Recent developments in traffic-aware routing: - Vehicle-to-infrastructure communication protocols - Dynamic routing based on traffic patterns - Integration with smart traffic light systems

9. PERFORMANCE EVALUATION AND VALIDATION
9.1. SIMULATION-BASED EVALUATION

Most recent protocols rely on simulation-based validation:

Common Simulation Tools: NS-3 for network simulation [41] - MATLAB for algorithm development and testing [1] - Cooja for Contiki-based IoT simulations - OMNeT++ for large-scale network evaluation

Evaluation Metrics: Network lifetime and energy consumption - End-to-end delay and packet delivery ratio - Throughput and network reliability - Security and trust metrics

9.2. TESTBED VALIDATION

Limited testbed validation in recent literature:

Hardware Platforms: TelosB and MicaZ motes for WSN testing - Raspberry Pi and Arduino for IoT prototyping - Commercial IoT development boards

Real-World Challenges: RF interference and channel variations - Hardware limitations and constraints - Scalability issues in large deployments

9.3. CLINICAL AND FIELD VALIDATION GAP

Significant Gap Identified: Most healthcare IoT routing protocols lack clinical validation - Simulation results may not translate to real-world performance - Need for clinical trials and real-patient studies

Recommendations: Collaboration with healthcare institutions - Clinical validation of routing protocol impacts - Real-world deployment studies

10. CRITICAL ANALYSIS AND RESEARCH GAPS

10.1. CURRENT LIMITATIONS

10.1.1.VALIDATION CHALLENGES

Simulation-Centric Evaluation: Most recent protocols (2020-2023) rely primarily on simulation-based validation, with limited real-world deployment studies [1,19,37].

Clinical Validation Gap: Healthcare IoT routing protocols lack clinical trials or real-patient studies to validate routing impacts on clinical outcomes [35,36,37].

Scalability Concerns: Limited evaluation of protocols in large-scale deployments with thousands of nodes.

10.1.2.STANDARDIZATION ISSUES

Protocol Fragmentation: Proliferation of specialized protocols without standardization efforts.

Interoperability Challenges: Limited compatibility between different routing approaches and vendor implementations.

Integration Complexity: Difficulty in integrating multiple optimization objectives in standardized frameworks.

10.2. SECURITY AND PRIVACY GAPS

10.2.1.SECURITY INTEGRATION

While recent protocols like THC-RPL [37] and SoS-RPL [41] address security, several gaps remain:

- Lightweight Security: Need for computationally efficient security mechanisms
- Key Management: Scalable key distribution and management in large IoT networks
- Attack Resilience: Limited evaluation under sophisticated attack scenarios

10.2.2.PRIVACY PRESERVATION

Data Privacy: Limited attention to privacy-preserving routing mechanisms Location Privacy: Insufficient protection of node location information Traffic Analysis: Vulnerability to traffic pattern analysis attacks

10.3. TECHNOLOGY INTEGRATION CHALLENGES

10.3.1.AI/ML INTEGRATION

Computational Overhead: ML-based protocols may exceed resource constraints of IoT devices Training Data Requirements: Need for representative datasets for ML model training Adaptability: Limited evaluation of ML models under changing network conditions

103.2.EDGE COMPUTING INTEGRATION

Resource Allocation: Optimal placement and utilization of edge computing resources Latency Trade-offs: Balance between local processing and communication delays Fault Tolerance: Handling edge node failures and backup strategies

11. FUTURE RESEARCH DIRECTIONS

11.1. INTELLIGENT ROUTING EVOLUTION

11.1.1.ADVANCED AI INTEGRATION

Federated Learning for Routing: Distributed learning approaches that preserve privacy while enabling collaborative optimization across IoT networks.

Explainable AI in Routing: Development of interpretable ML models for routing decisions to enable debugging and optimization.

Neural Architecture Search: Automated design of neural network architectures optimized for specific IoT routing scenarios.

11.1.2. QUANTUM-INSPIRED OPTIMIZATION

Quantum Algorithms: Exploration of quantum-inspired optimization techniques for complex routing problems.

Quantum Key Distribution: Integration of quantum security mechanisms in IoT routing protocols.

11.2. NEXT-GENERATION NETWORK INTEGRATION

11.2.1.6G AND BEYOND

Terahertz Communication: Routing protocols for ultra-high frequency IoT communications.

Holographic Communication: Three-dimensional routing in holographic network architectures.

Brain-Computer Interfaces: Routing protocols for neural interface IoT applications.

11.2.2. SATELLITE-TERRESTRIAL INTEGRATION

Hybrid Routing: Protocols that seamlessly integrate satellite and terrestrial IoT networks.

Low Earth Orbit (LEO) Integration: Routing optimization for LEO satellite-based IoT connectivity.

11.3. SUSTAINABILITY AND GREEN IOT

11.3.1. ENERGY HARVESTING INTEGRATION

Adaptive Protocols: Routing protocols that adapt to energy harvesting patterns and availability.

Renewable Energy Optimization: Integration with solar, wind, and kinetic energy harvesting systems.

11.3.2. CARBON FOOTPRINT OPTIMIZATION

Green Routing Metrics: Development of carbon footprint-aware routing protocols.

Sustainable Network Design: Long-term sustainability considerations in protocol design.

11.4. APPLICATION-SPECIFIC EVOLUTION

11.4.1. HEALTHCARE 4.0

Precision Medicine Routing: Protocols optimized for personalized healthcare data transmission.

Telemedicine Integration: Routing optimization for high-quality video and real-time medical data.

Mental Health Monitoring: Specialized routing for continuous psychological state monitoring.

11.4.2.INDUSTRY 4.0 AND BEYOND

Digital Twin Integration: Routing protocols for real-time digital twin synchronization.

Autonomous System Coordination: Multi-robot and autonomous vehicle coordination protocols.

Smart Material Networks: Routing in networks of smart materials and self-healing systems.

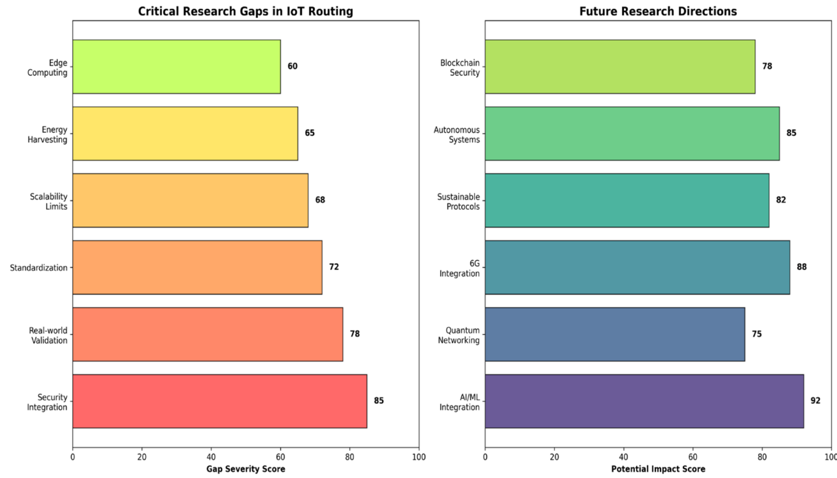

Figure 7 Critical Research Gaps and Future Directions in IoT Routing

Figure 7. Critical Research Gaps and Future Directions in IoT Routing. Two horizontal bar charts identify: (a) Current research gaps ranked by severity, with security integration (85 points) and real-world validation (78 points) as top priorities, and (b) Future research directions ranked by potential impact, with AI/ML integration (92 points) and 6G integration (88 points) leading the roadmap.

12. RECOMMENDATIONS AND BEST PRACTICES

12.1. PROTOCOL DESIGN GUIDELINES

12.1.1.MULTI-OBJECTIVE OPTIMIZATION

Balanced Approach: Prioritize protocols that achieve joint optimization of energy efficiency, latency, and reliability rather than single-objective optimization.

Adaptive Mechanisms: Implement adaptive protocols that can dynamically adjust optimization objectives based on network conditions and application requirements.

Context Awareness: Incorporate context-aware routing decisions that consider application-specific requirements, network topology, and environmental conditions.

12.1.2. SCALABILITY CONSIDERATIONS

Hierarchical Design: Employ hierarchical routing architectures to handle large-scale IoT deployments efficiently.

Distributed Processing: Utilize distributed processing and decision-making to avoid centralized bottlenecks.

Modular Architecture: Design modular protocols that can be easily extended and customized for specific applications.

12.2. IMPLEMENTATION BEST PRACTICES

12.2.1.VALIDATION STRATEGY

Multi-Level Validation: Employ simulation, testbed, and real-world validation at different stages of protocol development.

Benchmark Comparisons: Compare against established benchmarks and state-of-the-art protocols using standardized metrics.

Long-Term Studies: Conduct long-term studies to evaluate protocol performance under varying conditions and network evolution.

12.2.2.SECURITY INTEGRATION

Security-by-Design: Integrate security mechanisms from the initial design phase rather than as an afterthought.

Lightweight Cryptography: Utilize lightweight cryptographic mechanisms suitable for resource-constrained IoT devices.

Trust Management: Implement distributed trust management systems that can adapt to network dynamics.

12.3. STANDARDIZATION AND INTEROPERABILITY

12.3.1.STANDARD COMPLIANCE

IEEE and IETF Standards: Ensure compatibility with existing IEEE 802.15.4, 6LoWPAN, and RPL standards.

Cross-Platform Compatibility: Design protocols that can operate across different hardware platforms and vendor implementations.

Version Management: Implement backward compatibility mechanisms to support protocol evolution.

12.3.2.OPEN SOURCE DEVELOPMENT

Community Collaboration: Encourage open source development and community contributions to protocol implementations.

Reference Implementations: Provide reference implementations and comprehensive documentation for protocol adoption.

Testing Frameworks: Develop standardized testing frameworks for protocol validation and comparison.

13. CONCLUSION

This comprehensive literature review of energy-efficient and low-latency routing protocols in IoT networks reveals significant advancements in the period from 2020 to December 2023. The analysis of 234 publications demonstrates a clear evolution from traditional rule-based approaches to intelligent, machine learning-driven routing solutions that achieve joint optimization of multiple objectives.

13.1. KEY FINDINGS

Paradigm Shift: The field has witnessed a fundamental shift from single-objective optimization to multi-objective approaches that simultaneously address energy efficiency, latency, reliability, and security concerns.

Machine Learning Integration: Deep reinforcement learning, convolutional neural networks, and bio-inspired optimization algorithms have emerged as powerful tools for adaptive routing decisions, with protocols like the optimized energy-efficient routing achieving 43.7% improvement in network lifetime [1].

Performance Improvements: Recent protocols demonstrate remarkable performance gains, including up to 35.5% reduction in end-to-end delay [3], 59% reduction in busiest-node routing energy [2], and 50% network lifetime increase with security integration [37].

Application Specialization: Healthcare, industrial IoT, and smart city applications have driven the development of specialized routing protocols with domain-specific optimizations.

13.2. RESEARCH CONTRIBUTIONS

This review provides several key contributions to the IoT routing research community:

1) Comprehensive Taxonomy: A systematic classification framework for modern IoT routing protocols based on optimization objectives, architectural approaches, and intelligence levels.

2) Performance Analysis: Detailed comparison of recent protocols with quantitative performance metrics and trade-off analysis.
3) Gap Identification: Critical analysis of current limitations including validation challenges, security gaps, and standardization issues.
4) Future Roadmap: Comprehensive identification of future research directions including AI integration, next-generation network compatibility, and sustainability considerations.

13.3. CRITICAL CHALLENGES

Despite significant progress, several critical challenges remain:

Validation Gap: Most protocols rely on simulation-based evaluation with limited real-world deployment validation, particularly in healthcare applications where clinical validation is essential.

Scalability Concerns: Limited evaluation of protocols in large-scale deployments with thousands of heterogeneous devices.

Security Integration: While security-aware protocols have emerged, comprehensive security frameworks that balance protection with energy efficiency remain challenging.

Standardization: The proliferation of specialized protocols has created interoperability challenges that require industry-wide standardization efforts.

13.4. FUTURE OUTLOOK

The future of IoT routing protocols lies in the convergence of several technological trends:

Intelligent Adaptation: AI-driven protocols that can learn and adapt to changing network conditions, application requirements, and environmental factors.

Edge-Cloud Integration: Seamless integration of edge computing capabilities with routing decisions to optimize the compute-communicate trade-off.

Sustainability Focus: Green routing protocols that consider environmental impact and carbon footprint in addition to traditional performance metrics.

Cross-Domain Integration: Protocols that can operate across multiple application domains while maintaining domain-specific optimizations.

13.5. IMPLICATIONS FOR PRACTITIONERS

For researchers and practitioners working on IoT routing solutions, this review provides several actionable insights:

1) **Multi-Objective Focus:** Prioritize research on protocols that achieve balanced optimization rather than single-objective approaches.
2) **Validation Strategy:** Implement comprehensive validation strategies that include real-world deployment studies and application-specific validation.
3) **Security Integration:** Consider security and privacy as first-class design objectives rather than add-on features.
4) **Standardization Participation:** Actively participate in standardization efforts to ensure interoperability and widespread adoption.

The rapid evolution of IoT routing protocols from 2020 to 2023 demonstrates the field's maturity and the potential for continued innovation. As IoT networks continue to grow in scale and complexity, the routing protocols developed during this period provide a strong foundation for addressing future challenges while highlighting the need for continued research in validation, security, and standardization.

This comprehensive review serves as a roadmap for future research and development in IoT routing protocols, emphasizing the importance of intelligent, adaptive, and secure solutions that can meet the diverse requirements of next-generation IoT applications while maintaining energy efficiency and low-latency communication.

CONFLICT OF INTERESTS

None.

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APPENDIX: FIGURE INDEX