

A Comprehensive Review of Deep Learning and Swarm Intelligence-Based Energy-Efficient Routing in Wireless Sensor Networks

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Abstract—Wireless Sensor Networks (WSNs) have become one of the most significant technologies in modern Internet of Things (IoT) environments due to their ability to monitor physical and environmental conditions in real time. WSNs are widely used in healthcare systems, military surveillance, industrial automation, environmental monitoring, smart agriculture, disaster management, and intelligent transportation systems. However, sensor nodes operate with limited battery resources, constrained memory capacity, low computational capability, and short communication range. Therefore, energy-efficient routing remains one of the major research challenges in Wireless Sensor Networks.

Traditional routing protocols such as LEACH, PEGASIS, TEEN, and HEED mainly focus on clustering and multi-hop communication mechanisms to reduce communication overhead and prolong network lifetime. Nevertheless, these protocols suffer from limitations including random cluster head selection, uneven energy dissipation, packet loss, congestion, poor scalability, and inability to adapt to dynamic network conditions.

Artificial Intelligence (AI)-based routing optimization techniques have recently emerged as effective solutions for overcoming these limitations. Deep Learning (DL) methods provide intelligent route prediction, adaptive communication, traffic forecasting, congestion estimation, and dynamic routing optimization capabilities. Swarm Intelligence (SI) algorithms imitate collective biological behaviors to discover optimal communication paths with minimum energy consumption.

This paper presents a detailed review of deep learning and swarm intelligence-based energy-efficient routing techniques in Wireless Sensor Networks. Various techniques including Deep

Neural Networks (DNN), Convolutional Neural Networks (CNN), Recurrent Neural Networks (RNN), Deep Reinforcement Learning (DRL), Graph Neural Networks (GNN), Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO), Artificial Bee Colony (ABC), and Firefly Algorithm (FA) are discussed comprehensively. Hybrid AI-based routing approaches combining deep learning and swarm intelligence are also analyzed. Furthermore, comparative analysis based on energy efficiency, scalability, latency, throughput, packet delivery ratio, and computational complexity is presented. The paper also discusses security challenges, edge computing integration, IoT convergence, and future research directions including federated learning, explainable AI, blockchain-enabled routing security, and quantum-inspired optimization.

Index Terms—Wireless Sensor Networks, Deep Learning, Swarm Intelligence, Energy-Efficient Routing, Internet of Things, Artificial Intelligence, Reinforcement Learning, Optimization Algorithms

I. INTRODUCTION

Wireless Sensor Networks (WSNs) are distributed communication systems consisting of multiple sensor nodes deployed across geographical regions to monitor environmental or physical parameters such as humidity, pressure, vibration, temperature, sound, and motion. Sensor nodes collaboratively gather information and transmit the collected data to sink nodes or base stations using wireless communication technologies.

The rapid development of Internet of Things (IoT) applications has significantly increased the importance of Wireless Sensor Networks. WSNs are extensively used in modern

smart applications such as smart cities, industrial automation, military surveillance, healthcare systems, environmental monitoring, intelligent transportation systems, structural health monitoring, and precision agriculture.

Despite their advantages, WSNs face several challenges because sensor nodes possess limited battery power, constrained memory, low processing capability, and short communication range. Since sensor nodes are generally deployed in inaccessible or hazardous environments, replacing or recharging batteries becomes difficult. Consequently, minimizing energy consumption and extending network lifetime are primary objectives in WSN routing design.

Routing protocols determine communication paths between sensor nodes and sink nodes. Traditional routing protocols such as LEACH, PEGASIS, TEEN, and HEED mainly focus on clustering and multi-hop communication to reduce communication overhead and improve energy efficiency. However, these routing protocols suffer from several limitations including:

- Random cluster head selection
- Uneven energy dissipation
- Increased communication delay
- Packet loss
- Poor scalability
- Congestion problems
- Limited adaptability to topology changes

Artificial Intelligence (AI)-based routing optimization methods have emerged as effective solutions for overcoming these limitations. AI-driven routing approaches dynamically optimize communication paths according to network conditions such as residual energy, node density, traffic load, congestion level, and link reliability.

Among AI techniques, Deep Learning (DL) and Swarm Intelligence (SI) have demonstrated remarkable performance improvements in routing optimization. Deep learning enables intelligent prediction and adaptive routing decisions, while swarm intelligence algorithms imitate natural biological systems to discover optimal communication paths with minimum energy consumption.

II. ARCHITECTURE OF WIRELESS SENSOR NETWORKS

A typical Wireless Sensor Network consists of hundreds or thousands of sensor nodes distributed across monitoring regions.

A. Components of Sensor Nodes

Each sensor node contains the following components:

- 1) Sensing Unit
- 2) Processing Unit
- 3) Communication Unit
- 4) Memory Unit
- 5) Power Supply Unit

The sensing unit gathers environmental information using sensors. The processing unit processes collected information and performs routing decisions. The communication module enables wireless data transmission among nodes. The memory unit stores sensed data and routing information, while the power supply unit provides energy for node operation.

B. Characteristics of WSNs

Wireless Sensor Networks possess several characteristics:

- Self-organizing capability
- Multi-hop communication
- Dynamic topology
- Resource-constrained operation
- Large-scale deployment
- Fault tolerance
- Energy limitations

C. Applications of WSNs

WSNs are used in several domains:

- 1) *Environmental Monitoring*: Sensors monitor temperature, humidity, pollution, and forest fire conditions.
- 2) *Healthcare Systems*: Wearable sensors monitor patient health conditions in real time.
- 3) *Industrial Automation*: Industrial WSNs monitor machinery, production systems, and industrial safety conditions.
- 4) *Military Surveillance*: Military WSNs support battlefield monitoring and target detection.
- 5) *Smart Agriculture*: Sensors monitor irrigation systems, crop conditions, and soil moisture.

III. ENERGY-EFFICIENT ROUTING IN WSNs

Routing protocols are responsible for selecting communication paths between sensor nodes and sink nodes.

The primary objectives of routing protocols include:

- Minimizing energy consumption
- Extending network lifetime
- Reducing communication overhead
- Improving throughput
- Reducing latency
- Improving packet delivery ratio
- Balancing node energy utilization

A. Classification of Routing Protocols

Routing protocols are classified into:

- 1) Flat Routing Protocols
- 2) Hierarchical Routing Protocols
- 3) Location-Based Routing Protocols
- 4) Hybrid Routing Protocols

B. LEACH Protocol

LEACH is a hierarchical clustering protocol designed for energy conservation.

Advantages include:

- Reduced communication overhead
- Efficient data aggregation
- Improved energy efficiency

Limitations include:

- Random cluster head selection
- Uneven energy dissipation
- Poor scalability

C. PEGASIS Protocol

PEGASIS organizes nodes into communication chains.

Advantages include:

- Reduced transmission distance
- Better energy conservation

Limitations include:

- Increased communication delay
- Poor fault tolerance

D. TEEN Protocol

TEEN is suitable for reactive and time-critical applications.

Advantages include:

- Reduced unnecessary transmissions
- Lower communication overhead

IV. MACHINE LEARNING IN WSN ROUTING

Machine Learning techniques have become increasingly important in routing optimization.

A. Supervised Learning

Supervised learning algorithms use labeled datasets for routing optimization.

Applications include:

- Traffic prediction
- Congestion detection
- Fault prediction
- Link quality estimation

B. Unsupervised Learning

Unsupervised learning identifies hidden patterns without labeled datasets.

Algorithms include:

- K-Means Clustering
- Hierarchical Clustering
- Self-Organizing Maps

C. Reinforcement Learning

Reinforcement learning enables sensor nodes to learn routing policies using reward-based mechanisms.

Advantages include:

- Dynamic adaptation
- Intelligent route discovery
- Better energy balancing

V. DEEP LEARNING-BASED ROUTING OPTIMIZATION

Deep Learning techniques provide intelligent routing decisions by learning network behaviors.

A. Deep Neural Networks (DNN)

DNNs analyze parameters including:

- Residual energy
- Node density
- Traffic load
- Link reliability
- Congestion level

Advantages include:

- Intelligent route prediction
- Better scalability
- Improved throughput
- Enhanced packet delivery ratio

Limitations include:

- High computational complexity
- Increased training overhead
- Memory-intensive operations

B. Convolutional Neural Networks (CNN)

CNNs are used for spatial feature extraction.

Applications include:

- Traffic analysis
- Congestion detection
- Topology monitoring

C. Recurrent Neural Networks (RNN)

RNNs process sequential traffic data.

Applications include:

- Traffic forecasting
- Dynamic route adaptation
- Congestion prediction

D. Deep Reinforcement Learning (DRL)

DRL combines reinforcement learning with deep neural networks.

Popular algorithms include:

- Deep Q-Network
- Actor-Critic
- PPO

Advantages include:

- Dynamic routing optimization
- Better load balancing
- Enhanced network lifetime
- Intelligent adaptability

E. Graph Neural Networks (GNN)

GNNs are suitable for WSN routing because network topology resembles graph structures.

Applications include:

- Link prediction
- Topology optimization
- Route discovery
- Congestion analysis

VI. SWARM INTELLIGENCE-BASED ROUTING OPTIMIZATION

Swarm Intelligence algorithms imitate collective biological behaviors observed in nature.

A. Particle Swarm Optimization (PSO)

PSO is inspired by bird flocking behavior.

Applications include:

- Cluster head selection
- Route optimization
- Energy balancing

Advantages include:

- Fast convergence
- Better energy conservation
- Improved throughput

B. Ant Colony Optimization (ACO)

ACO is inspired by ant foraging behavior.

Advantages include:

- Adaptive routing
- Multi-path optimization
- Fault tolerance

C. Artificial Bee Colony (ABC)

ABC imitates honey bee food-searching behavior.

Advantages include:

- Better exploration capability
- Reduced packet loss
- Improved energy efficiency

D. Firefly Algorithm (FA)

Firefly algorithms are inspired by attraction among fireflies.

Applications include:

- Congestion reduction
- Energy-aware routing
- Path optimization

VII. HYBRID DEEP LEARNING AND SWARM INTELLIGENCE APPROACHES

Hybrid AI models combine learning capability with optimization capability.

A. DRL-PSO Hybrid Model

This approach combines DRL for intelligent learning and PSO for optimization.

Advantages include:

- Faster convergence
- Better route optimization
- Enhanced network lifetime

B. DNN-ACO Hybrid Model

This model combines DNN traffic prediction with ACO route optimization.

C. GNN-ABC Hybrid Model

This approach integrates graph learning and bee colony optimization.

VIII. SECURITY ISSUES IN AI-BASED ROUTING

Security remains a major concern in AI-driven routing systems.

A. Adversarial Attacks

Malicious inputs manipulate AI routing models.

B. False Data Injection

Malicious nodes inject false routing information.

C. Black Hole Attacks

Malicious nodes attract and drop packets intentionally.

D. Sybil Attacks

Nodes create fake identities to affect routing decisions.

IX. EDGE COMPUTING AND WSN INTEGRATION

Edge computing improves routing efficiency by processing data near sensor nodes.

Benefits include:

- Reduced latency
- Lower bandwidth usage
- Better scalability
- Real-time optimization

X. IOT AND WSN CONVERGENCE

The integration of WSNs with IoT technologies has expanded application domains significantly.

IoT-enabled WSNs support:

- Smart homes
- Smart healthcare
- Smart grids
- Smart transportation
- Smart agriculture

XI. PERFORMANCE METRICS

Several metrics evaluate routing performance.

A. Energy Consumption

Represents energy utilized during communication.

B. Network Lifetime

Measures operational duration before node failure.

C. Packet Delivery Ratio

Measures successful packet transmission rate.

D. Latency

Represents communication delay.

E. Throughput

Measures successfully transmitted data volume.

XII. COMPARATIVE ANALYSIS

TABLE I
COMPARISON OF ROUTING TECHNIQUES

Technique	Energy	Scalability	Complexity	Adaptability
LEACH	Medium	Medium	Low	Low
PEGASIS	Medium	Medium	Medium	Low
TEEN	Medium	Medium	Medium	Medium
PSO	High	High	Medium	Medium
ACO	High	Medium	High	High
ABC	High	Medium	Medium	Medium
DNN	Very High	High	Very High	High
DRL	Very High	Very High	Very High	Excellent
Hybrid DL+SI	Excellent	Excellent	High	Excellent

XIII. RESEARCH CHALLENGES

Several challenges remain in AI-based routing systems.

A. Computational Complexity

Deep learning models require high computational capability.

B. Training Overhead

Large datasets and long training durations are required.

C. Scalability Issues

Large-scale deployments increase communication overhead.

D. Security Threats

AI-based routing systems are vulnerable to attacks.

E. Dynamic Topology

Node mobility affects routing stability.

XIV. FUTURE RESEARCH DIRECTIONS

Future research may focus on:

- Lightweight deep learning models
- Federated learning
- Explainable AI
- Blockchain-enabled security
- Edge AI integration
- Quantum-inspired optimization
- Energy harvesting-aware routing

XV. DISCUSSION

The analysis presented in this paper indicates that traditional routing protocols are insufficient for modern large-scale WSN environments.

Deep Learning techniques demonstrate excellent performance in traffic prediction, congestion analysis, and intelligent routing optimization. However, computational complexity remains a major limitation.

Swarm Intelligence algorithms provide distributed optimization and energy balancing capabilities with lower implementation complexity compared to deep learning models.

Hybrid AI approaches combine the advantages of both techniques and achieve superior performance in terms of:

- Energy efficiency
- Throughput
- Packet delivery ratio
- Network lifetime
- Scalability

XVI. CONCLUSION

Energy-efficient routing remains one of the most critical challenges in Wireless Sensor Networks because sensor nodes operate using limited battery resources.

Deep Learning techniques including DNN, CNN, RNN, DRL, and GNN provide intelligent and adaptive routing optimization. Swarm Intelligence algorithms including PSO, ACO, ABC, and Firefly Algorithm provide distributed optimization inspired by biological systems.

Hybrid approaches combining deep learning and swarm intelligence provide superior performance in terms of energy efficiency, scalability, throughput, packet delivery ratio, and network lifetime.

Future WSN routing systems are expected to integrate AI, blockchain, edge computing, and quantum-inspired optimization techniques for building intelligent and sustainable communication systems.

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