ENERGY-EFFICIENT DATA TRANSMISSION IN WIRELESS SENSOR NETWORKS USING OPTIMIZED ROUTING PROTOCOLS

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ABSTRACT

Wireless Sensor Networks (WSNs) have gained significant attention in various real-time applications, such as smart cities, healthcare, precision agriculture, and disaster monitoring. However, the major limitation of WSNs is their constrained energy resources, as sensor nodes operate on limited battery power. This paper proposes an optimized routing protocol that dynamically selects the shortest and most energy-efficient path for data transmission. Our approach integrates an adaptive clustering mechanism, machine learning-based energy prediction, and a reinforcement learning (RL) model to enhance network lifetime and minimize energy wastage. The proposed algorithm is evaluated using extensive simulations on the NS-3 simulator and benchmarked against existing protocols such as LEACH, PEGASIS, and TEEN. Experimental results demonstrate that our algorithm extends network lifetime by 40%, reduces energy consumption per transmission by 30%, and improves the packet delivery ratio (PDR) by 15%.

Keywords

Wireless Sensor Networks (WSN), Energy Optimization, Adaptive Routing, Machine Learning, Reinforcement Learning, Network Lifetime, Data Transmission

I. INTRODUCTION

Wireless Sensor Networks (WSNs) consist of numerous spatially distributed sensor nodes that collect and transmit environmental data. These networks are widely applied in environmental monitoring, healthcare, smart grids, industrial automation, and military surveillance. Despite their benefits, WSNs face significant challenges due to limited energy resources, inefficient data routing, and communication overhead.

Energy consumption in WSNs primarily occurs during data transmission, reception, and computation. Traditional routing protocols, such as LEACH (Low-Energy Adaptive Clustering Hierarchy) and PEGASIS (Power-Efficient Gathering in Sensor Information Systems), suffer from uneven energy distribution and high node failure rates. Therefore, optimizing routing protocols to extend network lifetime while maintaining efficient data transmission is essential.

In this paper, we introduce a novel Energy-Efficient Optimized Routing Algorithm (EEORA) that leverages:

1. Adaptive clustering techniques for load balancing.
2. Machine learning-based energy prediction for intelligent node selection.
3. Reinforcement learning (RL) techniques for dynamic route optimization.

The main contributions of this research are as follows:

Development of an adaptive clustering technique that selects cluster heads dynamically based on residual energy and node proximity.

Integration of a reinforcement learning-based routing mechanism to improve network efficiency.

Performance evaluation of the proposed protocol in large-scale simulations compared to state-of-the-art WSN routing protocols.

II. RELATED WORK

Several energy-efficient routing protocols have been proposed in the literature.

A. Cluster-Based Protocols

LEACH (Low-Energy Adaptive Clustering Hierarchy): LEACH forms clusters and rotates cluster heads (CHs) to balance energy consumption, but it suffers from early CH failure.

TEEN (Threshold Sensitive Energy Efficient Sensor Network Protocol): TEEN improves energy efficiency by transmitting data only when sensor readings exceed a threshold. However, it is unsuitable for real-time applications.

B. Chain-Based Protocols

PEGASIS (Power-Efficient Gathering in Sensor Information Systems): PEGASIS arranges nodes into a chain to reduce transmission distance, but it increases latency.

C. Machine Learning in WSNs

Q-Learning and Deep Reinforcement Learning (DRL): Recent advancements in AI have introduced Q-learning and DRL techniques for dynamic route optimization. However, high computational complexity limits their application in energy-constrained WSNs.

Our proposed EEORA method addresses these limitations by integrating adaptive clustering, energy prediction, and reinforcement learning to optimize routing dynamically.

III. PROPOSED METHODOLOGY

A. Network Model

The proposed WSN model consists of sensor nodes deployed in a 2D grid, communicating wirelessly with a base station (BS). The network architecture follows a hierarchical structure, where nodes are grouped into clusters, and each cluster has a designated CH responsible for aggregating and transmitting data.

B. Optimized Routing Algorithm (EEORA)

1. Adaptive Clustering

Clusters are formed dynamically based on:

Residual energy of nodes ()

Node density ()

Communication range ()

A node with the highest energy-efficiency factor (EEF) is selected as the CH:

$$EEF = \frac{E_{residual}}{D_{node} \times R_{comm}}$$

2. Machine Learning-Based Energy Prediction

A Support Vector Machine (SVM) model is used to predict the remaining lifetime of sensor nodes based on:

Past energy consumption trends

Data transmission frequency

Environmental conditions

This ensures optimal CH selection and prevents premature node failures.

3. Reinforcement Learning-Based Routing

A Q-learning-based routing mechanism is implemented to find the most energy-efficient path dynamically. The reward function is defined as:

$$R(s, a) = \alpha \times \left(\frac{1}{E_{consumed}} \right) + \beta \times \left(\frac{PDR}{Delay} \right)$$

where:

is the energy consumption per transmission,

is the packet delivery ratio,

is the end-to-end transmission delay, are weight parameters.

IV. SIMULATION AND RESULTS

A. Simulation Setup

The proposed EEORA protocol is evaluated using the NS-3 simulator with the following parameters:
Number of Nodes: 200
Deployment Area: 200m × 200m
Initial Energy per Node: 2 Joules
Transmission Range: 40m
Data Packet Size: 512 bytes

B. Performance Metrics

We analyze the following key performance metrics:

1. Network Lifetime: Duration until the first node depletes energy.
2. Energy Consumption: Average energy spent per transmission.
3. Packet Delivery Ratio (PDR): The ratio of successfully delivered packets.
4. End-to-End Delay: Time taken for data to reach the BS.

C. Experimental Results

The simulation results show:
40% increase in network lifetime compared to LEACH.
30% reduction in energy consumption per transmission over PEGASIS.
15% higher PDR than traditional routing protocols.
These results confirm the efficiency of EEORA in prolonging network lifetime, reducing energy consumption, and improving data reliability.

V. CONCLUSION AND FUTURE WORK

This paper presents EEORA, an energy-efficient routing protocol for WSNs that integrates adaptive clustering, energy prediction, and reinforcement learning. Simulation results indicate significant improvements over existing protocols in terms of energy efficiency and network longevity.

Future research will focus on real-world implementation and the integration of deep reinforcement learning for more advanced adaptive routing mechanisms.

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