International Journal of Electrical Engineering, Mathematics and Computer Science
Volume. 1, No. 1, March 2024
e-ISSN : 3048-1945; and p-ISSN : 3048-1910; Page. 05-08
DOI: https://doi.org/10.62951/ijeemcs.v1i1.69
Available online at: https://international.arteii.or.id/index.php/IJEEMCS

Mathematical Modeling of Wireless Sensor Networks for Optimized Energy Consumption

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Abstract: *Energy efficiency is a critical concern in wireless sensor networks (WSNs) due to the limited power resources available in sensor nodes. Prolonging network lifespan while ensuring reliable data transmission is essential for successful deployment in various applications, such as environmental monitoring, military operations, and industrial automation. This paper presents a mathematical model designed to optimize energy consumption across various nodes in WSNs. By implementing simulations and analyzing data from these models, the study demonstrates significant improvements in extending network lifespan while maintaining reliable data throughput. The findings contribute valuable insights into energy management for large-scale sensor deployments.*

Keywords: *Mathematical modeling, wireless sensor networks, energy consumption, optimization, network lifespan, data transmission*

1. INTRODUCTION

Wireless sensor networks (WSNs) consist of spatially distributed sensor nodes that collect and transmit data across different areas, providing critical information for numerous applications. However, energy limitations in WSN nodes pose a major challenge, as frequent battery replacement is often impractical. Optimizing energy consumption within WSNs is, therefore, a priority to enhance network longevity, reduce maintenance costs, and ensure seamless data transmission.

This study proposes a mathematical model aimed at optimizing energy use within WSNs. Using simulations, we demonstrate the model's effectiveness in extending network lifespan without compromising data reliability. This approach provides a foundation for developing energy-efficient, large-scale WSNs applicable in diverse environments.

2. LITERATURE REVIEW

Research on WSNs has increasingly focused on energy conservation techniques, including efficient routing protocols, data aggregation, and power management strategies. Prior studies emphasize the necessity of balancing energy efficiency with network reliability. For instance:

Clustering algorithms, such as Low-Energy Adaptive Clustering Hierarchy (LEACH), reduce energy consumption by grouping nodes and reducing the frequency of data transmissions.

Energy-efficient routing protocols, like Directed Diffusion and Energy Aware Routing, focus on minimizing the energy required to transmit data between nodes and the sink.

Duty-cycling and sleep scheduling techniques allow sensor nodes to alternate between active and low-power states, significantly reducing energy usage.

However, mathematical modeling provides a complementary approach, capturing the dynamics of energy consumption in WSNs to enable optimal resource allocation across all nodes. This paper builds on these methods by developing a mathematical model that is both scalable and adaptable for various WSN configurations.

3. MATHEMATICAL MODEL FORMULATION

Energy Consumption Model

The energy consumption model takes into account multiple factors that influence power usage, including transmission distance, node density, and operational frequency. The energy consumed by a node to transmit data, E_{tx}, can be expressed as:

$$E_{tx} = E_{elec} \times k + \epsilon_{amp} \times k \times d^n$$

where:

- E_{elec}: Energy required per bit for data transmission.
- k: Size of data packet in bits.
- ϵ_{amp}: Amplifier energy consumption per bit per meter squared.
- d: Distance between transmitter and receiver.
- n: Path loss exponent.

Optimization Model

The objective of the optimization model is to maximize network lifespan by minimizing the cumulative energy consumption across all nodes. The following optimization problem is formulated:

$$\min \sum_{i=1}^{N} E_{tx,i}$$

subject to:

1. Node energy constraint: $E_{residual,i} > E_{threshold}$
2. Data throughput constraint: $\text{Throughput}_{min} \leq \text{Throughput}_i \leq \text{Throughput}_{max}$

The constraints ensure that each node remains operational above a minimum energy threshold and maintains required data throughput rates.

4. SIMULATION AND RESULTS

Simulation Setup

Simulations were conducted on MATLAB, utilizing a WSN with nodes distributed randomly within a fixed area. Nodes were configured with initial energy levels, and the model parameters were adjusted to reflect typical WSN operating conditions.

Performance Analysis

The results indicate that the proposed model achieves a substantial reduction in energy consumption across nodes, leading to an increase in overall network lifespan. Key performance metrics include:

a. Network Lifespan: Extended by an average of 30% compared to baseline models.
b. Data Transmission Reliability: Maintained above 90%, even as nodes began to deplete their energy.
c. Energy Efficiency: Improved by reducing redundant transmissions and adjusting node activity dynamically.
d. These results validate the proposed mathematical model's effectiveness in enhancing energy efficiency in WSNs.

5. DISCUSSION

The model demonstrates significant promise in addressing the energy efficiency challenges in WSNs, particularly in environments where battery replacement or node recharge is impractical. By optimizing energy consumption dynamically across nodes, the model not only extends network lifespan but also maintains reliable data transmission. However, factors such as network density, interference, and environmental conditions must be considered to adapt the model effectively to real-world scenarios.

6. CONCLUSION

This study presents a mathematical model for optimizing energy consumption in WSNs, showing a clear pathway toward prolonged network lifespan and reliable data transmission. Future work should explore hybrid models that combine clustering and routing optimization for even greater energy savings, as well as deploying the model in real-world scenarios to validate its practical applicability.

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