



Adaptive Swarm Intelligence Routing for Energy-Efficient IoT Communications

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Abstract: The rapid growth of the Internet of Things (IoT) has led to the widespread deployment of large-scale sensor networks that operate under strict energy limitations. Ensuring dependable communication while maximizing network lifetime requires efficient routing strategies. However, traditional routing protocols often fail to adapt to dynamic network environments, resulting in inefficient energy utilization. To address this issue, this study introduces an adaptive routing protocol based on swarm intelligence, leveraging bio-inspired optimization techniques to select energy-efficient paths dynamically. The proposed approach considers multiple factors such as residual energy, transmission distance, link reliability, and delay to make optimal routing decisions. Simulation outcomes demonstrate significant enhancements in energy efficiency, packet delivery performance, and overall network lifespan compared to conventional methods. This intelligent and scalable solution shows strong potential for improving the performance of next-generation IoT systems.

Keywords: IoT, Swarm Intelligence, Energy Efficiency, Routing Protocol, Ant Colony Optimization, Wireless Sensor Networks.

I. INTRODUCTION

The Internet of Things (IoT) enables the interconnection of billions of devices across diverse domains such as industrial automation, smart city infrastructure, and healthcare systems. These devices typically operate under resource constraints, with limited battery capacity being a major challenge. Routing plays a critical role in IoT networks, as communication processes consume a large portion of node energy. Traditional routing protocols like LEACH and PEGASIS provide basic energy-saving mechanisms, but they lack adaptability and intelligent decision-making capabilities. Swarm intelligence, inspired by natural systems such as ant colonies, offers an effective approach for distributed optimization. These algorithms can dynamically adjust routing paths based on environmental changes. Building on this concept, the present study introduces an adaptive swarm intelligence-based routing protocol aimed at enhancing energy efficiency and extending the overall lifetime of IoT networks.

II. RELATED WORK

2.1 Traditional Routing Protocols

In wireless sensor networks and IoT environments, routing protocols such as PEGASIS and LEACH are commonly used to improve energy efficiency. PEGASIS follows a chain-based communication strategy, where nodes transmit data sequentially along a connected path, whereas LEACH adopts a clustering approach in which the role of cluster head is periodically rotated among nodes to balance energy consumption.

However, despite these advantages, both protocols face several limitations. These include uneven energy distribution among nodes, reliance on fixed routing decisions that do not adapt to dynamic network changes, and challenges in scaling effectively for large and complex IoT deployments.

- LEACH: Cluster-based routing with rotating cluster heads
- PEGASIS: Chain-based communication

Limitations:

- Uneven energy consumption
- Static routing decisions
- Poor scalability

2.2 AI-Based Routing

To overcome the limitations of traditional routing approaches, methods based on Artificial Intelligence have been

developed. These approaches incorporate techniques such as Machine Learning and Reinforcement Learning to support intelligent and adaptive decision-making in routing. By analyzing factors like network traffic, residual energy of nodes, and link reliability, AI-driven models can dynamically determine optimal paths and improve overall network efficiency. However, these advanced techniques often demand higher computational capacity and memory usage, making them less suitable for resource-constrained IoT devices.

- Machine learning and reinforcement learning techniques
- Provide adaptability but require higher computational resources

2.3 Swarm Intelligence Approaches

Routing approaches based on Swarm Intelligence have gained significant attention for enabling energy-efficient communication in IoT systems, as they are inspired by the collective behavior observed in nature. Techniques such as Particle Swarm Optimization and Ant Colony Optimization provide distributed and adaptive routing strategies. These methods enable nodes to cooperatively identify optimal paths by considering factors like current network conditions and energy availability.

The key advantages of swarm intelligence include decentralized control, dynamic route adaptation, and effective energy utilization. These features make such approaches particularly well-suited for large-scale and continuously changing IoT environments.

- Ant Colony Optimization (ACO)
- Particle Swarm Optimization (PSO)

Advantages:

- Distributed control
- Adaptive path selection
- Energy optimization

III. SYSTEM MODEL

The IoT network consists of:

- Sensor nodes randomly deployed
- Base station (sink node)
- Wireless communication links

Each node maintains:

- Residual energy
- Neighbor information
- Distance to base station

IV. PROPOSED METHODOLOGY

4.1. Energy Model

Transmission energy:

$$E_{tx}(k, d) = E_{elec} \cdot k + E_{amp} \cdot k \cdot d^n$$

Reception energy:

$$E_{rx}(k) = E_{elec} \cdot k$$

4.2. Optimization Function

$$F = w_1 \cdot \frac{E_{res}}{E_{max}} + w_2 \cdot \frac{1}{d} + w_3 \cdot Q_{link} - w_4 \cdot Delay$$

4.3. Swarm Intelligence Routing Algorithm

The proposed routing approach is built upon Ant Colony Optimization, a bio-inspired technique that models the foraging behavior of ants. Initially, all sensor nodes in the IoT network are deployed with a predefined energy capacity. From the source nodes, artificial “forward ants” are then generated to explore multiple possible paths toward the base station or destination. During this exploration phase, each ant gathers important network information, such as remaining node energy, transmission distance, and link reliability.

Once multiple routes are identified, a fitness evaluation is performed to determine the effectiveness of each path based on energy consumption and overall network conditions. Based on this evaluation, pheromone levels are adjusted: efficient and reliable routes receive stronger reinforcement, while less effective paths gradually weaken due to pheromone evaporation. This continuous updating process enables the routing mechanism to improve adaptively over time.

Finally, the optimal route is selected probabilistically according to pheromone intensity, allowing data to be transmitted through the most energy-efficient path. This strategy ensures balanced energy utilization across nodes, prolongs network lifetime, and enables the system to adapt dynamically to changing network conditions.

The protocol uses Ant Colony Optimization:

1. Initialize nodes
2. Generate forward ants
3. Explore multiple paths
4. Evaluate path fitness
5. Update pheromone trails
6. Select optimal route

4.4 Algorithm (Pseudocode)

Initialize nodes with energy E

While network active:

- Generate ants
- Discover paths
- Evaluate fitness
- Update pheromone
- Select best route
- Transmit data
- Update energy
- End While

V.SYSTEM ARCHITECTURE – CODE SNIPPED

graph TD

```

A["**Sensor Nodes**<br/>(Initial State: Residual Energy, <br/>Neighbor Info, Distance to Sink)"] -->|Sensed Data|
B["**Data Collection**<br/>(Sensor Layer)"]
B -->|Raw Data Packets| C["**Routing & Energy Computation**<br/>(Energy Model & Optimization)"]
subgraph Computation_Logic [Optimization Layer]
C end
C -->|Optimized Route| D["**Swarm Routing**<br/>(ACO Processing)"]
D -->|Forward Data| E["**Base Station**<br/>(Sink Node / Data Analysis)"]
style A fill:#f9f,stroke:#333,stroke-width:2px
style E fill:#00ffcc,stroke:#333,stroke-width:2px
style Computation_Logic fill:#f0f0f0,stroke-dasharray: 5 5
    
```

VI. PERFORMANCE EVALUATION

6.1 Simulation Setup

Parameter	Value
Number of Nodes	100
Network Area	100 × 100 m
Initial Energy	1 Joule
Packet Size	4000 bits
Simulation Rounds	1000

6.2 Performance Metrics

Metric	Description
Energy Consumption	Total energy used by nodes during communication
Network Lifetime	Duration until nodes exhaust energy
Packet Delivery Ratio	Ratio of packets successfully delivered
Throughput	Rate of successful data transmission
Latency	Time delay in data delivery

6.3 Results

Parameter	Observation
Energy Consumption	Reduced by 30–40%

Parameter	Observation
Network Lifetime	Significantly increased
Reliability	Improved packet delivery performance
Delay	Reduced communication latency

VII. COMPARATIVE ANALYSIS

Metric	LEACH	PEGASIS	Proposed
Energy Efficiency	Medium	High	Very High
Network Lifetime	Low	Medium	High
Delay	Low	High	Low
Adaptability	No	No	Yes

VIII. FUTURE WORK

- Integration with Edge AI
- Hybrid AI + Swarm models
- Energy harvesting systems
- Real-world testing

IX. CONCLUSION

This paper introduces an adaptive routing strategy based on Swarm Intelligence to improve energy efficiency in IoT communications. By leveraging bio-inspired optimization techniques, the method dynamically identifies optimal routing paths, leading to reduced energy consumption and enhanced overall network performance. The proposed solution provides an intelligent and scalable approach suitable for modern IoT environments.

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