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Optimizing Data Transmission in Wireless Sensor Networks Using Beetle Antennae Search Algorithm

Ravindra Kumar[1], Nishant Singh[2]
Dr. Rammanohar Lohia Avadh University, Ayodhya U.P.-India

Abstract: Wireless Sensor Networks (WSNs) have become an integral part of modern communication systems, enabling efficient data gathering and transmission in various applications. However, optimizing the routes for data transmission remains a significant challenge due to the energy constraints of sensor nodes. This paper presents an innovative approach to route optimization in WSNs using the Beetle Antennae Search (BAS) algorithm. The proposed method aims to minimize energy consumption and enhance network lifetime by leveraging the foraging behavior of beetles. Simulation results demonstrate the effectiveness of the BAS algorithm in optimizing routes, leading to improved performance compared to traditional methods.
Keywords: Wireless Sensor Networks (WSNs), Beetle Antennae Search (BAS), Route Optimization, Energy Efficiency, Data Transmission.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) consist of spatially distributed sensor nodes that monitor and transmit data to a central base station. These networks are used in various applications, including environmental monitoring, industrial automation, healthcare, smart agriculture, and smart cities (Akyildiz, Su, Sankarasubramaniam, &Cayirci, 2002). Each sensor node in a WSN is equipped with sensing, processing, and communication capabilities, enabling the collection and transmission of data. However, one of the primary challenges in WSNs is optimizing the data transmission routes to conserve the limited energy resources of the sensor nodes, thereby extending the network's lifetime.

Energy efficiency is a critical consideration in the design and operation of WSNs because sensor nodes are typically powered by batteries with limited capacity. Efficient routing protocols are essential to ensure that data is transmitted in an energy-efficient manner, reducing the likelihood of premature node failures and maintaining network connectivity (Heinzelman, Chandrakasan, & Balakrishnan, 2000). Traditional routing protocols, such as LEACH (Low-Energy Adaptive Clustering Hierarchy) and PEGASIS (Power-Efficient GAthering in Sensor Information Systems), have been proposed to address this challenge. However, these protocols often fall short in dynamically adapting to the changing conditions of the network.

Recent advancements in bio-inspired algorithms have opened new avenues for optimizing WSNs. Algorithms inspired by natural phenomena, such as Ant Colony Optimization (ACO) and Particle Swarm Optimization (PSO), have shown promise in various optimization problems, including WSN routing (Dorigo &Stützle, 2004; Kennedy & Eberhart, 1995). Despite their effectiveness, these algorithms often require significant computational resources or fail to adapt dynamically to the energy constraints and topology changes in WSNs.

This paper introduces the Beetle Antennae Search (BAS) algorithm as a novel optimization technique for route selection in WSNs. Inspired by the foraging behavior of beetles, the BAS algorithm dynamically adjusts routes to minimize energy consumption while ensuring reliable data transmission. The BAS algorithm leverages the natural foraging behavior of beetles, which use their antennae to detect food sources and navigate efficiently towards them. By mimicking this behavior, the BAS algorithm aims to optimize the data transmission routes in WSNs, thereby enhancing the overall network performance and extending its lifetime.

The primary contributions of this paper are as follows:

1) Introducing the BAS algorithm for route optimization in WSNs.
2) Developing a fitness function to evaluate the energy consumption of different routes.
3) Conducting extensive simulations to compare the performance of BAS with traditional routing protocols such as LEACH and ACO.
4) Demonstrating the effectiveness of the BAS algorithm in reducing energy consumption and extending network lifetime.

The remainder of this paper is organized as follows. Section 2 reviews related work on WSN routing protocols and bio-inspired optimization algorithms. Section 3 describes the BAS algorithm and the network model used in this study. Section 4 presents the simulation setup and results. Finally, Section 5 concludes the paper and suggests directions for future research.

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II. RELATED WORK

Several routing algorithms have been proposed to address the energy efficiency and route optimization challenges in WSNs. These algorithms aim to minimize the energy consumption of sensor nodes while ensuring reliable data transmission and extending the network's lifetime. Among the traditional approaches, the Low-Energy Adaptive Clustering Hierarchy (LEACH) and Power-Efficient GAthering in Sensor Information Systems (PEGASIS) are widely studied.

LEACH is a hierarchical routing protocol that organizes the network into clusters, with each cluster having a designated cluster head (CH). The CHs aggregate data from their respective cluster members and transmit it to the base station (Heinzelman, Chandrakasan, & Balakrishnan, 2000). This approach reduces the number of direct transmissions to the base station, thereby saving energy. However, LEACH requires periodic re-clustering, which can lead to increased overhead and energy consumption, especially in large networks.

PEGASIS, on the other hand, is a chain-based protocol where each node communicates only with a close neighbor, and nodes take turns transmitting data to the base station (Lindsey & Raghavendra, 2002). This approach further reduces the energy consumption compared to LEACH by minimizing the number of long-distance transmissions. However, PEGASIS can suffer from delays due to the sequential data transmission process, and its performance can degrade in dynamic network conditions.

In recent years, bio-inspired algorithms have gained popularity for their ability to solve complex optimization problems. Among these, Ant Colony Optimization (ACO) and Particle Swarm Optimization (PSO) have been successfully applied to WSN routing.

ACO is inspired by the foraging behavior of ants, which use pheromone trails to find the shortest paths to food sources (Dorigo &Stützle, 2004). In the context of WSNs, ACO algorithms construct routes by simulating the pheromone-laying and following behavior of ants, resulting in optimized paths that minimize energy consumption. However, ACO can be computationally intensive and may not adapt quickly to changes in network topology or node energy levels.

PSO is inspired by the social behavior of bird flocks or fish schools, where individuals adjust their positions based on personal and group experiences (Kennedy & Eberhart, 1995). In WSN routing, PSO algorithms optimize routes by iteratively adjusting the positions of particles (representing routes) to minimize a fitness function, such as energy consumption. While PSO is generally less computationally intensive than ACO, it can still struggle with dynamic network conditions and may require fine-tuning of parameters for optimal performance.

Despite the advantages of these bio-inspired algorithms, they often require significant computational resources and may not adapt dynamically to the energy constraints and changing conditions of WSNs. This paper introduces the Beetle Antennae Search (BAS) algorithm as a compelling alternative for route optimization in WSNs.

The BAS algorithm is inspired by the foraging behavior of beetles, which use their antennae to detect food sources and navigate efficiently towards them. Previous studies have demonstrated the effectiveness of the BAS algorithm in various optimization problems, such as function optimization and mechanical structure design (Jiang & Li, 2017). However, its application to WSN route optimization has not been extensively explored.

The BAS algorithm offers several advantages over traditional and bio-inspired routing protocols. It is simple to implement, requires fewer computational resources, and can dynamically adapt to changing network conditions. By leveraging the natural foraging behavior of beetles, the BAS algorithm can efficiently optimize data transmission routes, reducing energy consumption and extending network lifetime. This paper aims to explore the potential of the BAS algorithm in WSN route optimization through extensive simulations and comparative analysis.

III. METHODOLOGY

This section details the methodology employed in the research, including the network model, the Beetle Antennae Search (BAS) algorithm, the fitness function, and the simulation setup.

A. Network Model

The network model consists of NNN sensor nodes randomly deployed within a square area of size AAA. The base station (BS) is positioned at the center of this area, serving as the central point for data collection and processing. Each sensor node is initially equipped with an energy level E0E_0E0, which diminishes over time as the nodes perform sensing, processing, and communication tasks. The communication range of each node is specified to ensure connectivity with neighboring nodes, allowing for efficient data transmission routes within the network.

B. Beetle Antennae Search (BAS) Algorithm

The BAS algorithm is inspired by the foraging behavior of beetles, which use their antennae to detect food sources and navigate towards them. The BAS algorithm adapts this natural behavior to optimize routing in WSNs. The following steps outline the BAS algorithm:

1) *Initialization:* Randomly initialize the positions of sensor nodes and establish the initial route for data transmission.
2) *Fitness Function:* Define a fitness function to evaluate the energy consumption associated with a given route. This function will guide the optimization process.
3) *Antennae Search:* Perturb the current route to generate new candidate routes by simulating the exploratory movements of beetle antennae.
4) *Route Update:* Evaluate the fitness of the new routes and update the best route based on the results. This step involves comparing the energy efficiency of the current and candidate routes.
5) *Stopping Criterion:* Terminate the algorithm when the maximum number of iterations is reached or when the improvement in fitness is below a predefined threshold, indicating convergence.

C. Fitness Function

The fitness function FFF is designed to minimize the total energy consumption EEE of the network. The function evaluates the energy efficiency of different routes, guiding the BAS algorithm towards optimal solutions. The fitness function is computed as:

F=∑i=1NEiF = \sum_{i=1}^{N} E_iF=∑i=1NEi

where EiE_iEi represents the energy consumed by node iii for data transmission. This comprehensive measure ensures that the selected routes minimize energy usage, thereby extending the network's lifetime.

D. Simulation Setup

To evaluate the performance of the BAS algorithm, extensive simulations are conducted using a predefined set of parameters. The key parameters for the simulations are as follows:

1) Number of sensor nodes: 50
2) Area size: 100 x 100 units
3) Initial energy per node: 0.5 Joules
4) Maximum iterations: 100
5) Stopping threshold: 0.01

The simulation environment mimics real-world WSN scenarios, allowing for a thorough assessment of the BAS algorithm's effectiveness in optimizing data transmission routes. The performance metrics include total energy consumption, network lifetime, and the efficiency of the optimized routes.

By adhering to this methodology, the research aims to demonstrate the advantages of the BAS algorithm over traditional routing protocols, highlighting its potential for enhancing energy efficiency and extending the operational lifetime of WSNs.

IV. RESULTS AND DISCUSSION

This section presents the results obtained from the simulation experiments and discusses the performance of the Beetle Antennae Search (BAS) algorithm compared to traditional routing algorithms such as LEACH and PEGASIS. The performance metrics include total energy consumption, network lifetime, and route efficiency.

A. Simulation Results

The simulations were conducted using MATLAB, with 50 sensor nodes randomly deployed within a 100 x 100 unit area. Each node started with an initial energy of 0.5 Joules, and the BAS algorithm was run for a maximum of 100 iterations with a stopping threshold of 0.01. The results were compared with those obtained from LEACH and PEGASIS under the same conditions.

1) Total Energy Consumption

The total energy consumption of the network was measured after the completion of each routing algorithm. The BAS algorithm demonstrated a significant reduction in energy consumption compared to both LEACH and PEGASIS.

a) BAS: 12.5 Joules
b) LEACH: 18.3 Joules
c) PEGASIS: 16.7 Joules

The lower energy consumption of the BAS algorithm can be attributed to its ability to dynamically optimize routes based on the current network conditions, minimizing the number of long-distance transmissions and reducing the overall energy usage.

2) Network Lifetime

Network lifetime is defined as the time until the first sensor node depletes its energy. The BAS algorithm extended the network lifetime significantly compared to LEACH and PEGASIS.

a) BAS: 1500 rounds
b) LEACH: 1100 rounds
c) PEGASIS: 1250 rounds

The extended network lifetime of the BAS algorithm is a result of its efficient route optimization, which ensures balanced energy consumption across all nodes, preventing early depletion of individual nodes.

3) Route Efficiency

Route efficiency was evaluated based on the average number of hops required for data transmission and the reliability of the routes.

a) Average number of hops:
   - BAS: 4.2
   - LEACH: 5.5
   - PEGASIS: 6.0

b) Route reliability (percentage of successful transmissions):
   - BAS: 98%
   - LEACH: 92%
   - PEGASIS: 94%

The BAS algorithm showed higher route efficiency, with fewer hops and higher reliability. This is due to its dynamic adaptation to changing network conditions and effective utilization of energy-efficient routes.

B. Discussion

The results clearly demonstrate the advantages of the BAS algorithm over traditional routing protocols in terms of energy efficiency, network lifetime, and route efficiency. The following points highlight the key findings from the simulation experiments:

1) Energy Efficiency

The BAS algorithm's ability to dynamically optimize routes based on real-time network conditions significantly reduces energy consumption. Unlike LEACH, which relies on periodic re-clustering, and PEGASIS, which follows a chain-based approach, the BAS algorithm continuously adjusts routes to minimize energy usage. This adaptability is crucial in WSNs, where energy resources are limited.

2) Network Lifetime

The extended network lifetime achieved by the BAS algorithm is a direct result of its efficient energy management. By balancing energy consumption across all nodes, the BAS algorithm prevents early node failures, ensuring prolonged network operation. This is particularly important in applications where maintaining network connectivity is critical.

3) Route Efficiency

The higher route efficiency of the BAS algorithm, characterized by fewer hops and higher reliability, enhances the overall performance of the WSN. The reduced number of hops not only lowers energy consumption but also decreases latency, improving the speed of data transmission. The high reliability ensures that data packets reach the base station with minimal loss, enhancing the accuracy and dependability of the network.

4) Comparison with Traditional Algorithms

While LEACH and PEGASIS have their merits, they fall short in dynamically adapting to the ever-changing conditions of WSNs. LEACH's periodic re-clustering can lead to increased overhead, while PEGASIS's sequential data transmission can cause delays. The BAS algorithm, on the other hand, offers a more flexible and responsive approach, adjusting routes in real-time to optimize performance.

V. CONCLUSION

The findings from this study have significant implications for the design and deployment of WSNs in various applications, including environmental monitoring, agricultural sensing, and industrial automation. The BAS algorithm's ability to enhance energy efficiency and extend network lifetime can lead to more sustainable and cost-effective WSN deployments. Additionally, the improved route efficiency can result in faster and more reliable data transmission, which is essential for real-time monitoring and control applications.

A. Limitations and Future Work

While the BAS algorithm shows promise, there are limitations to consider. The current study is based on simulations with specific parameters, and real-world deployments may present additional challenges such as varying environmental conditions and hardware limitations. Future work should focus on testing the BAS algorithm in real-world scenarios and exploring its integration with other optimization techniques to further enhance its performance.

Moreover, the scalability of the BAS algorithm needs to be evaluated in larger networks with thousands of nodes. Investigating the algorithm's performance in heterogeneous networks with nodes having different energy capacities and sensing capabilities would also be valuable. Finally, incorporating security measures into the BAS algorithm to protect against potential threats and attacks in WSNs is an important area for future research.

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