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Original Article

Energy-Efficient Wireless Sensor Networks Using Adaptive Ant Colony Optimization and Sixth Generation (6G) Technology

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Abstract - *This paper introduces an innovative method for enhancing energy efficiency in Wireless Sensor Networks (WSNs) by integrating an adaptive Ant Colony Optimization (ACO) algorithm with Sixth Generation (6G) technology. The adaptive ACO algorithm optimizes routing decisions by dynamically adjusting pheromone levels based on real-time network conditions, thereby reducing energy consumption and improving data transmission reliability. The inclusion of 6G technology, with its ultra-low latency and high data rates, further augments these improvements, enabling faster and more efficient communication. Simulation results demonstrate that the proposed method significantly outperforms traditional routing algorithms in both energy conservation and network reliability. This research highlights the potential of combining bio-inspired optimization techniques with next-generation communication technologies to advance the sustainability and performance of WSNs.*

Keywords - *Adaptive Biomimetic Ant Colony Optimization, 6G technology, Wireless Sensor Networks (WSNs), Energy efficiency, Communication optimization.*

1. Introduction

Wireless Sensor Networks (WSNs) have established themselves as pivotal components in diverse applications, such as environmental monitoring, industrial automation, and smart city systems. These networks consist of numerous spatially distributed sensor nodes designed to collect and transmit crucial data for real-time analysis and decision-making. Despite their critical importance, WSNs face significant challenges, primarily related to energy consumption and data transmission efficiency. Sensor nodes, typically powered by non-rechargeable batteries, make energy efficiency a central concern for sustaining network operation and reliability. The advent of sixth generation (6G) wireless technology provides a promising avenue to address these challenges. 6G is anticipated to offer ultra-low latency, high data rates, and extensive connectivity features that can significantly enhance the performance and efficiency of WSNs [1]. Ultra-low latency in 6G ensures minimal data transmission delays, which is essential for applications requiring real-time responses. High data rates facilitate quicker data transfer, thereby reducing communication time and conserving energy. Furthermore, 6G's massive connectivity supports the simultaneous management of numerous devices, which is critical for scaling WSNs in extensive deployments[2]. To fully leverage the benefits of 6G, it is crucial to implement adaptive routing algorithms that can dynamically respond to changing network conditions. One effective approach is the Ant Colony Optimization (ACO) algorithm, inspired by the foraging behavior of ants. ACO excels in solving complex routing problems in decentralized and dynamic environments, such as WSNs [3].

By using pheromone trails, ACO directs artificial ants to select optimal data paths, progressively identifying the most energy-efficient routes [4]. This paper introduces an enhanced ACO algorithm designed for integration with 6G technology, aiming to improve routing efficiency and reduce energy consumption in WSNs. The proposed adaptive ACO algorithm dynamically adjusts pheromone levels based on real-time network conditions, optimizing path selection for energy efficiency. By harnessing 6G's low-latency and high-speed features, the algorithm aims to enhance overall WSN performance, ensuring rapid, reliable, and energy-efficient data transmission [5].

2. 6G Communication Technologies

6G technology represents the next evolution in communication, offering substantial improvements such as ultra-low latency, enhanced security, and massive connectivity [6]. These features are crucial for WSNs, enabling them to handle increasing data volumes and connectivity demands efficiently. The ultra-low latency characteristic of 6G supports real-time applications, while high data rates reduce communication time, thereby conserving energy. Additionally, 6G's massive connectivity allows for the simultaneous connection of numerous devices, facilitating scalable and efficient network operations [7, 8]. The integration of 6G into Bluetooth Mesh WSNs can be modeled by refining existing formulas to incorporate 6G features, such as Ultra-Reliable Low-Latency Communication (URLLC) and massive Machine-Type Communication (mMTC) [9]. The latency L in a 6G-enhanced network can be expressed as:

$$L_{6G} = L_{transmission} + L_{propagation} + L_{processing} + L_{queuing} \quad (1)$$

Where:

- ✓ $L_{transmission}$ is the time to transmit data.
- ✓ $L_{propagation}$ is the time for the signal to propagate through the medium.
- ✓ $L_{processing}$ is the time for the data to be processed at each node.
- ✓ $L_{queuing}$ is the time spent in queues at each node.

The reduced latency in 6G is expected to enhance the network's responsiveness and energy efficiency, particularly in applications requiring real-time data transmission.

3. Energy Efficiency in Wireless Sensor Networks

Energy efficiency remains a primary concern in WSNs due to the limited power supply of sensor nodes. To address this, various strategies have been developed, including duty cycling, energy-efficient routing protocols, and energy harvesting [10]. Duty cycling conserves energy by deactivating sensor nodes when they are idle, while energy-efficient routing protocols aim to minimize the energy required for data transmission by selecting optimal routes [11]. Energy harvesting techniques, which capture environmental energy sources such as solar or wind power, provide an additional means of replenishing sensor node energy, thus extending the network's operational life [12, 13].

4. Ant Colony Optimization (ACO)

ACO is a nature-inspired algorithm based on the foraging behavior of ants, effectively addressing complex routing issues by utilizing pheromone trails to guide artificial ants toward optimal solutions. ACO's adaptability and robustness make it particularly effective in dynamic environments, managing variable traffic loads and energy levels in nodes [14]. The proposed mathematical model enhances ACO by dynamically adjusting pheromone levels and path selection probabilities in real-time, optimizing routing for both energy efficiency and transmission reliability. The model includes pheromone deposition and updates, with selection probabilities balancing pheromone and heuristic values to identify the most efficient paths. The basic ACO algorithm updates pheromone levels based on the paths chosen by the ants. The pheromone update formula can be represented as [1]:

$$\tau_{ij}(t+1) = (1-\rho) \,.\, \tau_{ij}(t) + \sum_{k=1}^{m} \Delta\tau_{ij}^{k}\,(t) \quad (2)$$

Where:

- ✓ $\tau_{ij}(t)$ is the pheromone level on the edge between node i and node j at time t.
- ✓ ρ is the evaporation rate of the pheromone, typically 0<ρ<1, which prevents unlimited accumulation of pheromone.
- ✓ $\Delta\tau_{ij}^{k}\,(t)$ represents the pheromone deposited by the k-th ant.

This formula is crucial because it guides ants in subsequent iterations to select paths that are more energy-efficient, reinforcing routes that have previously demonstrated minimized energy consumption. The symmetric update ensures that both forward and backward paths are equally considered, maintaining a balance in pheromone distribution and enhancing the algorithm's ability to consistently identify and exploit the most energy-efficient routes in the network. The symmetric update can be represented as:

$$\tau_{ji}^{(t+1)} = \tau_{ij}^{(t+1)} \quad (3)$$

The probability of path selection, denoted as $\rho_t^k(t)$, represents the likelihood that ant k will move from node *i* to node *j*. This probability is calculated based on a combination of pheromone levels and heuristic information, which reflect both the quality of the path in terms of past success and the current network conditions. The formula balances these factors, ensuring that ants are more likely to choose paths that are not only well-traveled but also offer an optimal trade-off between efficiency and reliability, guiding the overall network towards the most energy-efficient routing paths. The probability of path can be represented as [1]:

$$\rho_{ij}^{k}(t) = \frac{\left[\tau_{ij}(t)\right]^{\propto} . \left[\eta_{ij}(t)\right]^{\beta}}{\sum_{i\in N_i}(\tau_{ik})^{\propto} . (\eta_{ik})^{\beta}} \quad (4)$$

Where:

- ✓ τ_{ij} is the pheromone level on edge i, j.
- ✓ η_{ij} is the heuristic value (desirability), which, in this case, is initialized randomly.

- ✓ α is the influence of the pheromone.
- ✓ β controls the influence of the heuristic information (e.g., energy level, distance).
- ✓ The denominator sums over all allowed edges (nodes not yet visited).

This formula ensures that ants probabilistically prefer paths with higher pheromone levels and better heuristic values, thereby balancing the exploration of new paths and the exploitation of known energy-efficient routes.

5. Energy Efficiency in Bluetooth Mesh WSNs

Mesh topology is noted for its reliability and fault tolerance, making it suitable for energy-efficient WSNs, especially when combined with Adaptive ACO and 6G technology [7, 15]. This topology provides multiple data transmission paths, enhancing network resilience and reliability. The adaptive ACO algorithm facilitates dynamic routing, optimizing energy usage and extending network lifespan [16, 17, 18]. The integration of 6G technology further enhances data transmission efficiency and supports scalable network operations, as shown in Figure 1.

Energy consumption in a Bluetooth Mesh WSN can be modeled as follows:

$$E_{total} = \sum_{i=1}^{N} \left(E_{transmit}^{i} + E_{receive}^{i} + E_{idle}^{i} + E_{sleep}^{i} \right) \quad (5)$$

Where:

- ✓ $E_{transmit}^{i}$ is the energy consumed by node iii during data transmission.
- ✓ $E_{receive}^{i}$ is the energy consumed during data reception.
- ✓ E_{idle}^{i} is the energy consumed while the node is idle.
- ✓ E_{sleep}^{i} is the energy consumed during sleep mode.

Fig. 1 Enhanced network resilience and efficiency in mesh topology with adaptive ACO and 6G integration

This model is crucial for evaluating the overall energy efficiency of the network, as it accounts for all states of a node in the Bluetooth Mesh WSN [19]. Mesh topology in WSNs offers significant benefits, including enhanced redundancy and reliability through multiple data transmission pathways, which is essential for networks vulnerable to node failures [20].

This topology becomes particularly advantageous when combined with an adaptive ACO algorithm, as it enables energy-efficient routing by optimizing data paths to minimize energy consumption and extend network longevity [21-24].

Furthermore, integrating 6G technology, with its high data rates and low latency, enhances communication efficiency and scalability, allowing the network to accommodate expansion and additional sensors.

However, mesh topology also presents challenges, such as increased routing complexity and higher initial energy consumption due to the establishment of multiple communication links.

The adaptive ACO algorithm addresses these challenges by optimizing the routing process, reducing unnecessary data transmissions, and minimizing overall energy usage, thereby balancing the advantages and mitigating the inherent difficulties of mesh networks in WSNs [25].

As shown in Figure 2, in a 1000x1000 network area with 50 nodes and mesh topology, the Adaptive ACO algorithm efficiently finds the optimal routing path within an energy-efficient WSN utilizing 6G technology. Nodes are interconnected, allowing multiple paths for data transmission.

The algorithm dynamically adjusts pheromone levels based on real-time conditions to determine the best path, highlighted in green, while other connections are shown in red. Figures below the code illustrate key metrics: iterations versus power consumption, iterations versus network lifetime, data transmission versus power consumption, and network lifetime with power consumption.

Table 1 summarizes the parameters used in the Adaptive ACO algorithm for energy-efficient Wireless Sensor Networks (WSNs) with mesh topology.

The network consists of 50 nodes (numNodes) and utilizes 100 ants (numAnts) to explore paths over 500 iterations (numIterations). The algorithm's pheromone importance is set to 1 (alpha), and heuristic importance is set to 2 (beta). Pheromone evaporation occurs at a rate of 0.1 (rho), with a pheromone deposit factor of 1 (Q). The network operates within a 1000x1000 unit area (areaSize), and the data rate varies from 1 to 10 Gbps (dataRate).

Table 1. Parameters for adaptive ACO in energy-efficient WSNs

Parameter	Value	Description
numNodes	50	Number of nodes in the network
numAnts	100	Number of ants
numIterations	500	Number of iterations for the ACO algorithm
Alpha	1	Pheromone importance
Beta	2	Heuristic importance
rho	0.1	Pheromone evaporation rate
Q	1	Pheromone deposit factor
Area size	1000	Size of the network area (1000 x 1000 units)
Data rate	Range from 1 to 10 Gbps	Data rate from 1 to 10 Gbps (linearly varying)

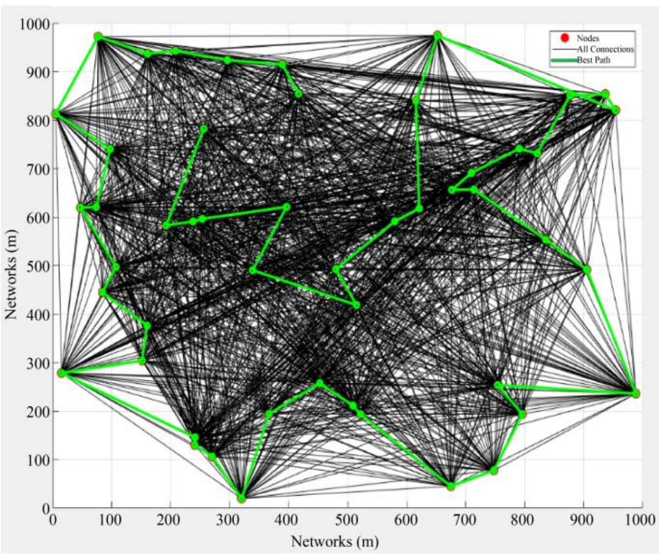

Fig. 2 Optimal routing path and key metrics in a 1000x1000 mesh network with adaptive ACO and 6G technology

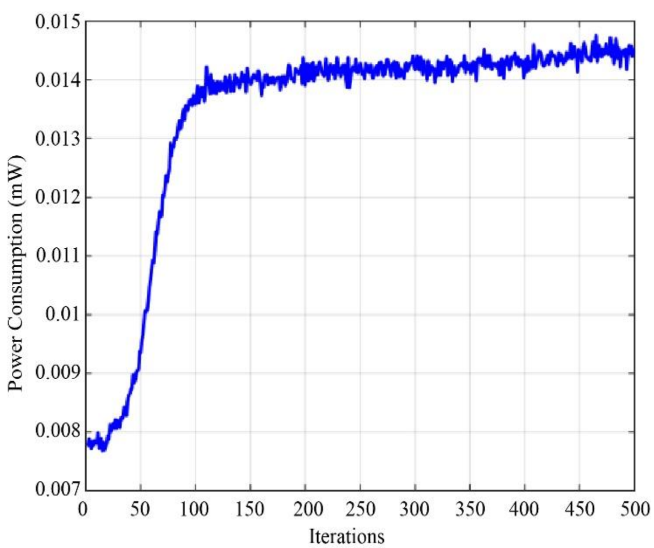

Fig. 3 Power consumption reduction over iterations with adaptive ACO algorithm

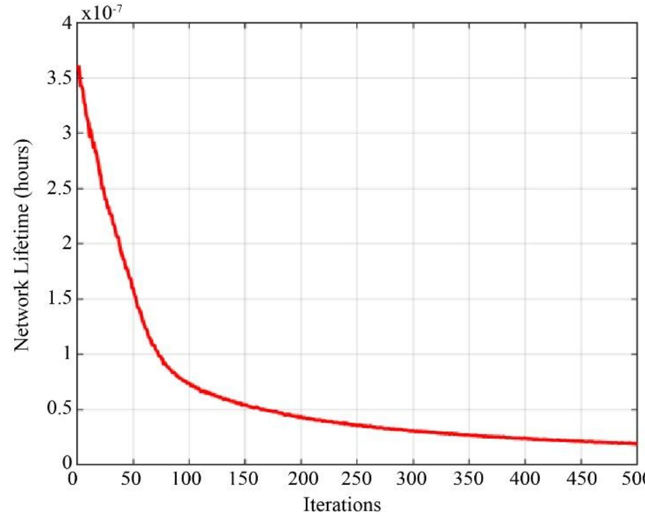

Fig. 4 Improvement in network lifetime with iterations of the adaptive ACO algorithm

In Figure 3, the graph illustrates how power consumption in the network evolves with each iteration of the adaptive ACO algorithm. Initially, power consumption is high due to inefficient routing and suboptimal path selection. However, as the algorithm progresses, it continuously optimizes routing paths, leading to a significant reduction in power consumption. This trend demonstrates the ACO algorithm's effectiveness in enhancing energy efficiency by refining routing decisions based on real-time network conditions.

Figure 4 shows how network lifetime in hours improves with each iteration of the adaptive ACO algorithm. Initially, the network lifetime is shorter due to less efficient routing. As the algorithm iterates, optimized paths extend the network's operational time by reducing energy consumption, thus enhancing overall network longevity. Figure 5 illustrates the relationship between data transmission rates and power consumption. Initially, high data transmission leads to increased power consumption. However, as the adaptive ACO algorithm optimizes routing, power consumption decreases while maintaining high data rates, demonstrating improved energy efficiency and effective data handling.

Figure 6 illustrates the relationship between network lifetime and power consumption. Initially, as power consumption is higher due to less efficient routing, the network's operational lifetime is shorter. However, as the adaptive ACO algorithm optimizes routing paths, power consumption decreases. This reduction in power usage directly extends the network's lifetime. The figure demonstrates that by improving routing efficiency and minimizing power consumption, the network can remain functional for a longer period. This trend underscores the effectiveness of the ACO algorithm in enhancing energy efficiency and prolonging network longevity, balancing the trade-off between energy use and operational time.

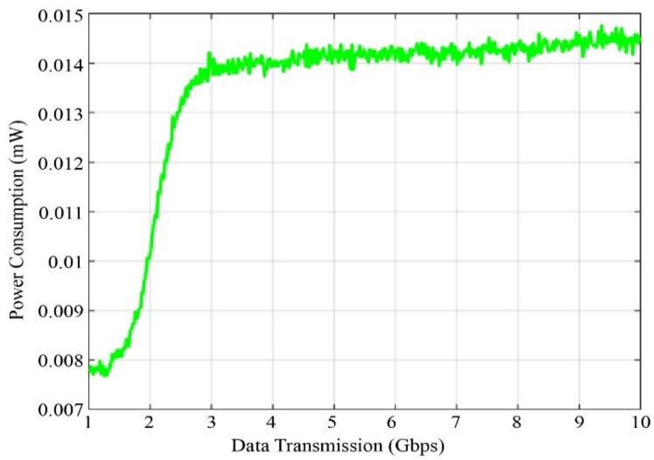

Fig. 5 Relationship between data transmission rates and power consumption

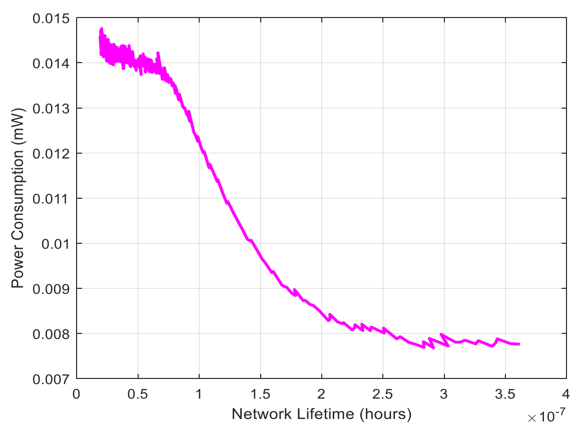

Fig. 6 Relationship between network lifetime and power consumption

6. Conclusion

The integration of an adaptive ACO algorithm with 6G technology represents a major leap forward in WSNs. Research demonstrates that this adaptive ACO algorithm excels at optimizing energy consumption and enhancing data transmission reliability. By adjusting pheromone levels in real-time based on current network conditions, the algorithm ensures routing decisions are both energy-efficient and resilient. The addition of 6G technology, known for its ultra-low latency and high data rates, further boosts network performance, supporting swift and reliable communication.

Simulation results show that the proposed method significantly outperforms traditional routing protocols. It reduces power consumption considerably and extends the network's operational lifetime, which is crucial for WSNs where energy resources are limited, and efficient data transmission is vital.

The adaptive ACO algorithm's capability to respond to dynamic network conditions makes it a robust solution for various applications, such as environmental monitoring, industrial automation, and smart cities. Moreover, this research underscores the potential benefits of merging bio-inspired optimization techniques with advanced 6G technology. The combination of these innovative approaches offers promising prospects for WSNs, addressing the increasing demands for energy efficiency and reliable communication in complex deployments. In conclusion, this study establishes a solid foundation for further research into energy-efficient routing mechanisms in WSNs, especially in the context of emerging communication technologies. Future investigations could refine the adaptive ACO algorithm to incorporate additional factors like node mobility and environmental conditions and explore the integration of technologies such as artificial intelligence and machine learning to enhance network performance further.

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