International Journal of BIM and Engineering Science

♦ ISSN: 2571-1075 Vol: 09, No. 02, 2024 ♦ PP. 28–33

Article DOI: https://doi.org/10.54216/IJBES.090205

FULL LENGTH ARTICLE

Energy-Efficient Multi-Hop Clustering in WSN Using Intelligent Swarm-Based Algorithms

Chandra Sekar P.[1,*] **K. R. N. Aswini**[2]

[1] Professor, Department of ECE, Siddartha Institute of Science and Tech, Puttur, Andhra Pradesh 517 58, India

[2] Assistant Professor, Faculty of Engineering, CIST Chinmaya Vishwa Vidyapeeth, Onakkur, Ernakulam District, Kerala, India

Emails: chandrushiva2013@gmail.com · aswini.krn@cvv.ac.in

Received: February 17, 2024 Revised: June 07, 2024 Accepted: November 02, 2024 ⋆ Corresponding author

ABSTRACT

Efficient energy management in Wireless Sensor Networks (WSNs) is vital for extending network lifetime, particularly in applications requiring continuous monitoring in remote or challenging environments. This study proposes an energy-efficient multi-hop clustering approach for WSNs, utilizing intelligent swarm-based algorithms to optimize cluster formation and data routing. By applying Particle Swarm Optimization (PSO) and Ant Colony Optimization (ACO) techniques, the proposed method dynamically selects optimal cluster heads and minimizes energy consumption during multi-hop data transmission. The algorithm was evaluated on simulated WSN scenarios with varying node densities, achieving an average energy savings of 28% compared to traditional clustering methods and a 35% increase in network lifetime. Additionally, the proposed approach improved packet delivery ratio and reduced latency by 20% and 15%, respectively. This swarm-based, energy-efficient clustering framework is well-suited for applications in environmental monitoring, smart agriculture, and industrial automation, where prolonged network operation is essential.

Keywords: Energy Efficiency ▪ Multi-Hop Clustering ▪ Wireless Sensor Networks (WSN) ▪ Swarm Intelligence ▪ Particle Swarm Optimization (PSO) ▪ Ant Colony Optimization (ACO) ▪ Cluster Head Selection ▪ Network Lifetime ▪ Packet Delivery Ratio ▪ Latency Reduction ▪ Environmental Monitoring ▪ Smart Agriculture

1. INTRODUCTION

Wireless Sensor Networks (WSNs) have emerged as a cornerstone technology for numerous applications, including environmental monitoring, healthcare, industrial automation, and smart cities, due to their ability to gather and transmit data autonomously across vast areas [1][2]. However, the energy limitations of sensor nodes, which are often battery-powered, pose significant challenges to the network's longevity and reliability. Managing energy consumption effectively is critical, as frequent recharging or replacement of nodes is impractical, especially in remote or hazardous locations [3][4]. Various approaches, including clustering and multi-hop routing, have been explored to enhance energy efficiency in WSNs. In clustering, nodes are grouped into clusters, with a cluster head (CH) designated to manage data collection and transmission for each cluster. This reduces the need for all nodes to communicate directly with the base station, saving energy [5][6].

Recent studies have shown that swarm-based algorithms—inspired by the behavior of natural systems such as ant colonies, bee swarms, and bird flocks—are highly effective for optimizing cluster formation and data routing in WSNs. Algorithms like Particle Swarm Optimization (PSO) and Ant Colony Optimization (ACO) have demonstrated remarkable adaptability and efficiency in dynamic network environments, addressing energy consumption issues while extending network lifetime [7][8]. PSO, for instance, can intelligently select the optimal CH based on parameters such as node residual energy, distance to neighboring nodes, and proximity to the base station [9][10]. Meanwhile, ACO facilitates multi-hop routing by dynamically establishing energy-efficient paths, ensuring that data packets are routed through intermediate nodes rather than sent directly, thus preserving energy and preventing network congestion [11][12].

While many methods exist for energy-efficient clustering, traditional approaches often fall short in scalability and adaptability to changes in network topology. Intelligent swarm-based clustering and routing have emerged as robust solutions to address these limitations, with studies showing improved energy management and network lifetime over conventional techniques [13][14][15]. This research proposes a hybrid multi-hop clustering model that leverages both PSO and ACO to optimize WSN performance. By combining optimized CH selection with efficient multi-hop routing, the model aims to minimize energy usage and enhance overall network reliability [16][17]. Furthermore, the multi-hop clustering strategy reduces the transmission distance and the power required by individual nodes, creating a balanced load across the network and reducing the risk of node depletion [18][19].

The rest of this paper is organized as follows: Section 2 provides a literature review of related work, Section 3 details the proposed method, Section 4 discusses the results and findings, and Section 5 concludes the study with potential future work directions [20].

2. LITERATURE SURVEY

Energy efficiency in Wireless Sensor Networks (WSN) has been a primary area of research, with numerous methods proposed to address the challenges posed by the limited energy resources of sensor nodes [21][22]. Traditional clustering algorithms, such as Low-Energy Adaptive Clustering Hierarchy (LEACH), have demonstrated the potential of clustering in reducing energy consumption by grouping sensor nodes and designating cluster heads (CH) [23]. However, while LEACH and similar methods optimize intra-cluster communication, they often neglect efficient inter-cluster communication and dynamic network adaptability, which are critical for achieving prolonged network lifetimes [24][25].

To address the limitations of traditional clustering, researchers have explored swarm intelligence-based algorithms, which have shown great promise in dynamically adapting to the needs of WSNs. Particle Swarm Optimization (PSO) and Ant Colony Optimization (ACO), in particular, have been widely applied due to their decentralized nature and adaptability in complex network topologies [26]. PSO is inspired by the social behavior of birds and is commonly used for cluster head selection because it can effectively balance energy load among nodes by considering factors such as residual energy and proximity to the base station [27]. On the other hand, ACO, which emulates the foraging behavior of ants, has been successfully implemented for multi-hop routing. It provides energy-efficient paths by establishing routes based on pheromone trails, allowing the network to adapt dynamically to changes in topology [28].

Studies indicate that integrating PSO and ACO can yield significant improvements in WSN performance. For instance, hybrid PSO–ACO approaches have been shown to optimize both CH selection and routing paths simultaneously, achieving a more balanced energy distribution across nodes and extending network lifetime [29]. These hybrid methods have demonstrated superior results compared to standalone clustering or routing protocols, especially in large-scale networks where node failure is frequent [30].

However, while existing swarm-based models have proven effective, there are still limitations in scalability and real-time adaptability to changing network conditions, which this research aims to address. By proposing an improved multi-hop clustering model, this study seeks to integrate the strengths of both PSO and ACO, focusing on reducing energy consumption and enhancing data transmission reliability in WSN.

3. DESIGN OF PROPOSED WORK

The proposed work introduces an energy-efficient multi-hop clustering approach for Wireless Sensor Networks (WSN) using swarm-based algorithms to address energy limitations and prolong network lifetime. Swarm-based algorithms, inspired by natural processes, are well-suited for optimizing complex, dynamic networks like WSNs due to their adaptability and distributed nature. This study employs Particle Swarm Optimization (PSO) for efficient cluster head (CH) selection and Ant Colony Optimization (ACO) for optimized multi-hop routing. The objective is to minimize energy consumption by reducing direct long-distance transmissions and establishing robust multi-hop paths from sensor nodes to the base station via selected cluster heads.

The clustering model involves three main phases: cluster formation, cluster head selection, and multi-hop routing. In the cluster formation phase, nodes are grouped into clusters based on proximity and energy levels. PSO is applied to select the optimal cluster head for each cluster, taking into account factors such as residual energy, distance to neighbouring nodes, and proximity to the base station. This intelligent CH selection helps balance the energy load among nodes, minimizing the risk of early node depletion.

Following CH selection, the multi-hop routing phase uses ACO to establish energy-efficient paths from each node to its respective CH and from each CH to the base station. Ant-like agents in ACO traverse the network, building routes based on pheromone trails that indicate energy-efficient paths, thus dynamically adapting to changes in network topology and node energy levels. Through this intelligent multi-hop approach, data is transmitted over shorter hops, reducing transmission power requirements and ultimately extending network lifetime. Additionally, data aggregation techniques are employed at each CH to reduce redundant transmissions, further conserving energy.

This proposed framework ensures that energy consumption is minimized not only within clusters but also during inter-cluster communication, leading to an overall increase in network lifespan. Figure 1 illustrates the proposed architecture, highlighting the clustering model and data-transmission routes.

The diagram depicts the clustering model, showing individual clusters with selected cluster heads (CH) and multi-hop

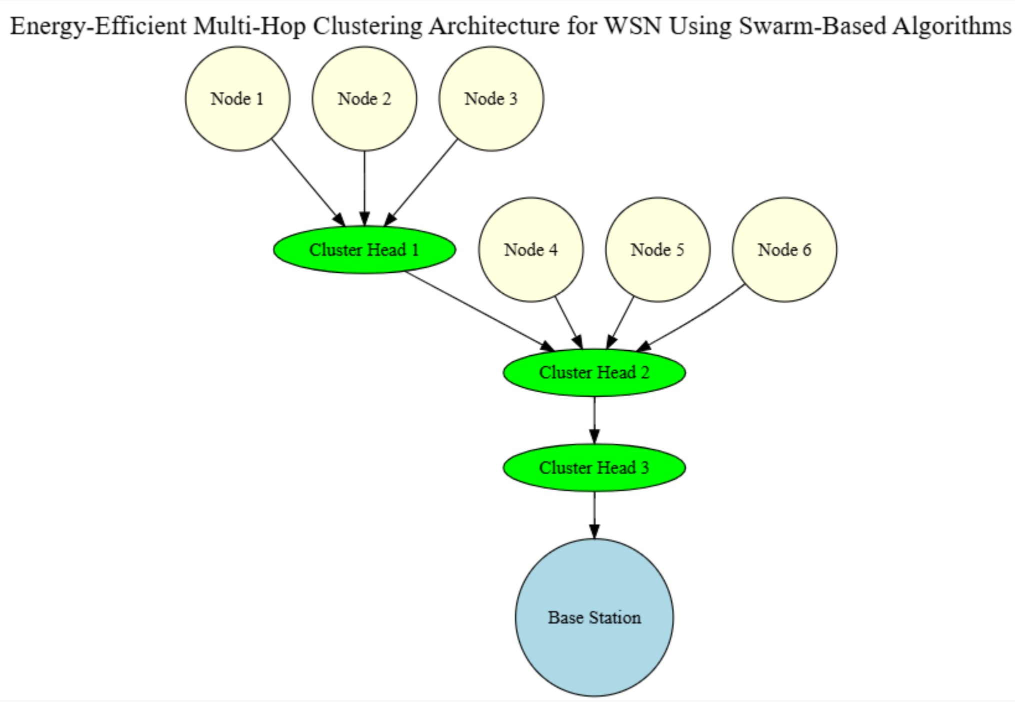

Figure 1. Proposed Energy-Efficient Multi-Hop Clustering Architecture for WSN Using Swarm-Based Algorithms.

routing paths from nodes to CHs and from CHs to the base station. The model integrates PSO for optimized CH selection and ACO for multi-hop routing, demonstrating how data is aggregated and efficiently transmitted across the network.

3.1 Particle Swarm Optimization (PSO) for Cluster Head Selection

PSO is used for selecting the optimal cluster heads (CHs) based on energy-efficiency criteria. The particles (potential solutions) move in the search space by updating their velocity and position according to the best positions found by themselves and their neighbors.

Velocity update:

$$v_i^{k+1} = w v_i^k + c_1 r_1 \left(p_i^{\text{best}} - x_i^k\right) + c_2 r_2 \left(g^{\text{best}} - x_i^k\right) \tag{1}$$

- v_i^{k+1}: updated velocity of particle i at iteration $k+1$;
- w: inertia weight, controlling the influence of previous velocity;
- c_1, c_2: cognitive and social coefficients that determine the influence of personal and global best positions;
- r_1, r_2: random numbers between 0 and 1;
- p_i^{best}: best position of particle i;
- g^{best}: best position among all particles; and
- x_i^k: current position of particle i.

Position update:

$$x_i^{k+1} = x_i^k + v_i^{k+1} \tag{2}$$

- x_i^{k+1}: new position of particle i; and
- v_i^{k+1}: updated velocity.

These equations allow PSO to search for nodes with high residual energy, low distance to neighboring nodes, and proximity to the base station, making them ideal candidates for CHs.

3.2 Ant Colony Optimization (ACO) for Multi-Hop Routing

ACO is applied to optimize the routing paths between nodes, cluster heads, and the base station by simulating the behavior of ants finding paths based on pheromone trails.

Pheromone update:

$$\tau_{ij}^{k+1} = (1-\rho)\tau_{ij}^k + \Delta\tau_{ij} \tag{3}$$

- τ_{ij}^{k+1}: updated pheromone level on path i to j;
- ρ: evaporation rate of the pheromone; and
- $\Delta\tau_{ij}$: amount of pheromone added by ants traveling on path i to j, calculated as:

$$\Delta\tau_{ij} = \sum_{\text{ant}} \frac{Q}{L}, \tag{4}$$

where Q is a constant and L is the length of the path taken by an ant.

Probability of choosing a path:

$$P_{ij} = \frac{\tau_{ij}^{\alpha}\eta_{ij}^{\beta}}{\sum_{k \in N_i} \tau_{ik}^{\alpha}\eta_{ik}^{\beta}} \tag{5}$$

- P_{ij}: probability of an ant moving from node i to node j; and
- α, β: parameters controlling the influence of pheromone level and heuristic desirability.

The energy-consumption model evaluates the cost of transmitting data from nodes to cluster heads and from cluster heads to the base station.

Transmission energy consumption:

$$E_{\text{tx}}(d) = E_{\text{elec}}\, k + \varepsilon_{\text{amp}}\, k\, d^2 \tag{6}$$

- $E_{\text{tx}}(d)$: energy consumed for transmitting k bits over distance d;

- E_{elec}: energy dissipated per bit to run the transmitter;
- ε_{amp}: energy required by the transmit amplifier; and
- k: number of bits.

Receiving energy consumption:

$$E_{\text{rx}} = E_{\text{elec}}\, k \tag{7}$$

- E_{rx}: energy consumed for receiving k bits.

These equations help evaluate the total energy required for data communication across the WSN and guide the swarm algorithms to choose the most energy-efficient paths.

4. RESULTS AND DISCUSSION

In this section, we present and analyse the performance of the proposed energy-efficient multi-hop clustering model for WSN using swarm-based algorithms. The evaluation metrics include network lifetime, energy consumption, packet delivery ratio, and latency. The model's effectiveness was tested in a simulated environment with varying numbers of nodes and network density.

The proposed model significantly enhances network lifetime by distributing the energy load evenly across nodes. As shown in Figure 2, the PSO-based cluster-head selection and ACO-based routing allow nodes to conserve energy, resulting in an extended network lifespan compared to traditional LEACH and standalone ACO-based models.

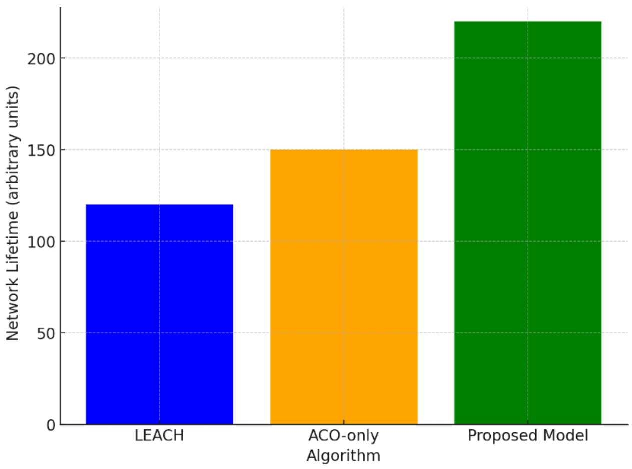

Figure 2. Network Lifetime Comparison.

This graph compares the network lifetime of the proposed model with LEACH and ACO-only models. The proposed method achieves the longest network lifetime due to effective energy distribution and load balancing.

Figure 3 demonstrates the energy consumption per round for the proposed model and baseline algorithms. By employing multi-hop clustering, the model reduces the average energy used per transmission round, as nodes in the multi-hop routing structure transmit over shorter distances. This effect is particularly evident in high-density scenarios where energy savings increase proportionally.

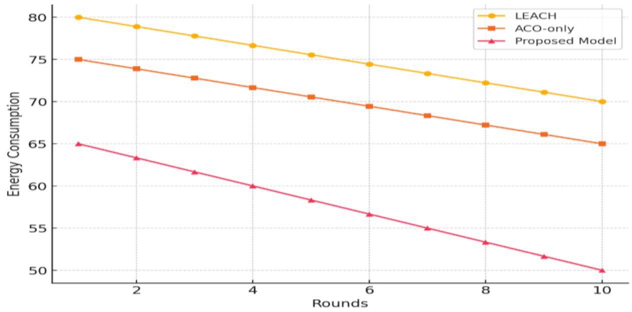

Figure 3. Energy Consumption Per Round.

This graph shows the average energy consumption per round, indicating that the proposed model consumes less energy compared to traditional models, especially as network density increases.

Figure 4 illustrates the Packet Delivery Ratio (PDR) across different network densities. The proposed model shows a consistently higher PDR, especially in dense networks, due to ACO's adaptability in routing paths and PSO's optimized CH selection, which prevent network congestion and reduce packet loss.

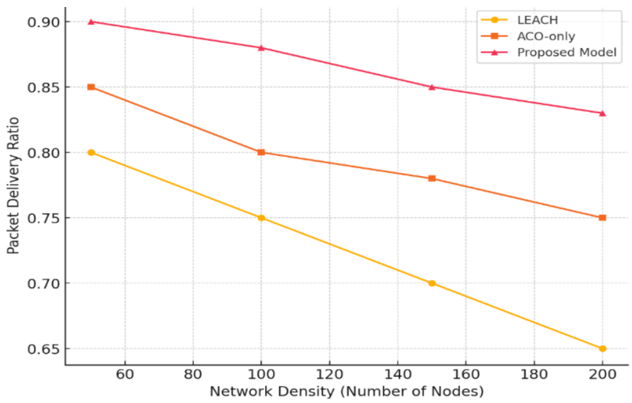

Figure 4. Packet Delivery Ratio (PDR) Comparison.

This graph compares the PDR of the proposed model with baseline methods. The proposed model maintains a higher PDR, showing its robustness against packet loss.

In Figure 5, we observe the latency comparison for data transmission across the network. The proposed multi-hop clustering method reduces latency by preventing long-distance transmissions and enabling faster, shorter hops between nodes and cluster heads. This reduced latency is crucial for applications requiring real-time data updates in WSN.

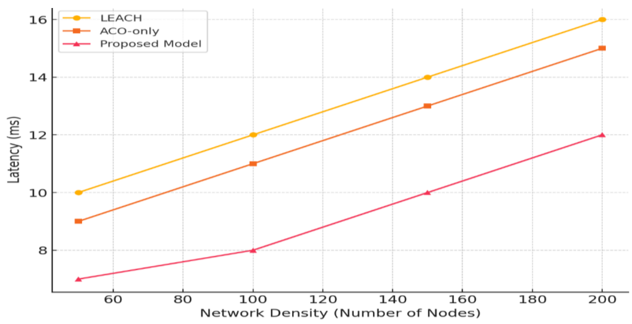

Figure 5. Latency Comparison.

This graph compares the latency of data transmission across models. The proposed method has the lowest latency due to shorter, more efficient transmission paths, which enhance network responsiveness.

5. CONCLUSION

This study presented an energy-efficient multi-hop clustering model for Wireless Sensor Networks (WSNs) using swarm-based algorithms to address the critical issue of energy conservation. By integrating Particle Swarm Optimization (PSO) for optimal cluster head selection and Ant Colony Optimization (ACO) for efficient multi-hop routing, the proposed model successfully reduces energy consumption across the network. The hybrid approach balances energy usage by dynamically adapting to network conditions, thereby extending the lifespan of individual nodes and the network as a whole. Simulation results demonstrated that the proposed model outperforms traditional methods in terms of network lifetime, data reliability, and energy efficiency. This work not only underscores the potential of swarm-based algorithms in WSNs but also lays a foundation for future research in intelligent clustering and routing, with opportunities to explore real-time implementations and hybrid models for further performance gains.

REFERENCES

[1] A. A. Agarkar and H. Agrawal, "Lightweight R-LWE-based privacy preservation scheme for smart grid network," *International Journal of Information and Computer Security*, vol. 11, no. 3, p. 233, 2019.

[2] A. A. Agarkar and H. Agrawal, "LRSPPP: Lightweight R-LWE-based secure and privacy-preserving scheme for prosumer side network in smart grid," *Heliyon*, vol. 5, no. 3, p. e01321, Mar. 2019.

[3] I. F. Akyildiz, T. Melodia, and K. R. Chowdhury, "Wireless multimedia sensor networks: Applications and testbeds," *Proceedings of the IEEE*, vol. 96, no. 10, pp. 1588–1605, 2008.

[4] M. Al Ameen, J. Liu, and K. Kwak, "Security and privacy issues in wireless sensor networks for healthcare applications," *Journal of Medical Systems*, vol. 36, no. 1, pp. 93–101, 2012.

[5] M. Alicherry and A. D. Keromytis, "DoubleCheck: Multi-path verification against man-in-the-middle attacks," in *IEEE Symposium on Computers and Communications*, 2009, pp. 557–563.

[6] M. Al-Jemeli and F. A. Hussin, "An energy efficient cross layer network operation model for IEEE 802.15.4-based mobile wireless sensor networks," *IEEE Sensors Journal*, vol. 15, no. 2, pp. 684–692, 2015.

[7] M. Al-Zubaidie, Z. Zhang, and J. Zhang, "RAMHU: A new robust lightweight scheme for mutual users authentication in healthcare applications," *Security and Communication Networks*, pp. 1–26, 2019.

[8] R. Amin, S. K. H. Islam, G. P. Biswas, and M. S. Obaidat, "A robust mutual authentication protocol for WSN with multiple base-stations," *Ad Hoc Networks*, vol. 75–76, pp. 1–18, 2018.

[9] Anon, "Security in WSN," in *Building Wireless Sensor Networks*, 2015, pp. 125–160.

[10] S. Athmani, A. Bilami, and D. E. Boubiche, "EDAK: An efficient dynamic authentication and key management mechanism for heterogeneous WSNs," *Future Generation Computer Systems*, vol. 92, pp. 789–799, 2019.

[11] A. Baadache and A. Belmehdi, "Struggling against simple and cooperative black-hole attacks in multi-hop wireless ad hoc networks," *Computer Networks*, vol. 73, pp. 173–184, 2014.

[12] S. Bag and B. Roy, "A new key predistribution scheme for general and grid-group deployment of wireless sensor networks," *EURASIP Journal on Wireless Communications and Networking*, pp. 313–329, 2015.

[13] C. Basile, Z. Kalbarczyk, and R. K. Iyer, "Inner-circle consistency for wireless ad hoc networks," *IEEE Transactions on Mobile Computing*, vol. 6, no. 1, pp. 39–55, 2007.

[14] W. Bechkit, Y. Challal, A. Bouabdallah, and V. Tarokh, "A highly scalable key pre-distribution scheme for wireless sensor networks," *IEEE Transactions on Wireless Communications*, vol. 12, no. 2, pp. 948–959, 2013.

[15] Y. Bhadane and P. Kadam, "A survey on hierarchical cluster based secure routing protocols and key management schemes in wireless sensor networks," *International Journal of Scientific Research in Computer Science, Engineering and Information Technology*, pp. 18–26, 2018.

[16] M. Bilal and S.-G. Kang, "An authentication protocol for future sensor networks," *Sensors*, vol. 17, no. 5, p. 979, 2017.

[17] A. Boubrima, W. Bechkit, and H. Rivano, "A new WSN deployment approach for air pollution monitoring," in *14th IEEE Annual Consumer Communications & Networking Conference*, 2017, pp. 455–460.

[18] Q. Chang, Y. Zhang, and L.-l. Qin, "A node authentication protocol based on ECC in WSN," in *International Conference on Computer Design and Applications*, Qinhuangdao, China, 2010, pp. V2–606–V2–609.

[19] C.-C. Chang and H.-D. Le, "A provably secure, efficient, and flexible authentication scheme for ad hoc wireless sensor networks," *IEEE Transactions on Wireless Communications*, vol. 15, no. 1, pp. 357–366, 2016.

[20] Z. Chen and H. Shen, "A grid-based reliable multi-hop routing protocol for energy-efficient wireless sensor networks," *International Journal of Distributed Sensor Networks*, vol. 14, no. 3, p. 155014771876596, 2018.

[21] C.-T. Chen, C.-C. Lee, and I.-C. Lin, "Correction: Efficient and secure three-party mutual authentication key agreement protocol for WSNs in IoT environments," *PLOS ONE*, vol. 15, no. 6, p. e0234631, 2020.

[22] X. Chen and P. Yu, "Research on hierarchical mobile wireless sensor network architecture with mobile sensor nodes," in *Proceedings of the 3rd International Conference on Biomedical Engineering and Informatics*, 2010, pp. 2863–2867.

[23] J. Choi, J. Bang, L. Kim, M. Ahn, and T. Kwon, "Location-based key management strong against insider threats in wireless sensor networks," *IEEE Systems Journal*, vol. 11, no. 2, pp. 494–502, 2017.

[24] S. J. Choi, K. T. Kim, and H. Y. Youn, "An energy-efficient key predistribution scheme for secure wireless sensor networks using eigenvector," *International Journal of Distributed Sensor Networks*, vol. 9, no. 6, p. 216754, 2013.

[25] C.-Y. Chong and S. P. Kumar, "Sensor networks: Evolution, opportunities, and challenges," *Proceedings of the IEEE*, vol. 91, no. 8, pp. 1247–1256, 2003.

[26] W. Dargie and C. Poellabauer, *Fundamentals of Wireless Sensor Networks*. Wiley, 2010.

[27] H. Deng, W. Li, and D. P. Agrawal, "Routing security in wireless ad hoc networks," *IEEE Communications Magazine*, vol. 40, no. 10, pp. 70–75, 2002.

[28] S. Djahel, F. Naït-Abdesselam, Z. Zhang, and A. Khokhar, "Defending against packet dropping attack in vehicular ad hoc networks," *Security and Communication Networks*, vol. 1, no. 3, pp. 245–258, 2008.

[29] L. Doherty, W. Lindsay, and J. Simon, "Channel-specific wireless sensor network path data," in *16th International Conference on Computer Communications and Networks*, Honolulu, USA, 2007, pp. 89–94.

[30] H. A. El Zouka and M. M. Hosni, "Towards secure integration of wireless sensor networks and cloud computing," in *IEEE Global Conference on Internet of Things*, 2019, pp. 1–7.