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Research Article

Optimizing Energy Efficiency and Network Performance in Wireless Sensor Networks: An Evaluation of Routing Protocols and Swarm Intelligence Algorithm

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Abstract:

The research explores advanced routing protocols and swarm intelligence algorithms to enhance energy efficiency in Wireless Sensor Networks (WSNs), focusing on optimizing network performance. It examines the performance of Hierarchical Energy-Efficient Distributed (HEED), Low-Energy Adaptive Clustering Hierarchy (LEACH), and Threshold-sensitive Energy Efficient sensor Network (TEEN) protocols, alongside swarm intelligence technique Chaotic Based Firefly Algorithm (CFA). Swarm Intelligence algorithms enhance WSNs by addressing routing challenges and cluster head selection. The study introduces a novel method for mitigating malicious routes and optimizing cluster heads using these algorithms. Evaluation measures include Latency, Packet Delivery Ratio, End-to-End Delay, Throughput, Energy Consumption, and Network Lifetime, aiming to identify strategies for enhancing network performance and sustainability.

1. Introduction

WSNs are networks composed of numerous sensor nodes distributed across various locations, capable of collecting, transmitting, and processing data wirelessly. These networks play a crucial role in diverse applications. The versatility and ability of WSN to provide real-time data make WSNs integral to modern technological solutions across multiple domains [1].The key challenges in WSNs, including high energy consumption, limited node lifespan, and their impacts on network performance, such as reduced coverage and efficiency.OMNeT++ is a powerful, discrete event simulation framework widely used for modeling and evaluating network systems. It offers a flexible and modular environment for designing and simulating complex network scenarios, including WSNs. OMNeT++ provides a range of tools and libraries to create detailed simulations, enabling researchers to test and optimize various network configurations, protocols, and performance metrics. Its relevance lies in its ability to accurately model network dynamics and evaluate the impact of different strategies on energy consumption, network performance, and overall efficiency. By using OMNeT++, researchers can gain valuable insights and make data-driven decisions to improve WSN design and operations. the objectives of this research paper listed below,

Network Data Simulation: Leverage OMNeT++ to model and simulate diverse WSN scenarios for comprehensive analysis.

Energy Efficiency Analysis: Investigate and optimize energy consumption across various routing protocols and swarm intelligence algorithms to extend node lifespan *and network sustainability.*

Performance Optimization: Enhance network performance by optimizing key metrics such latency, packet delivery ratio, end-to-end delay, throughput, and network lifetime to improve overall efficiency and reliability. This research focuses on mitigating malicious routes and optimizing cluster heads in

WSNs using swarm intelligence techniques. By leveraging OMNeT++ for simulation, it aims to enhance energy efficiency and network performance, applying detailed evaluation metrics to improve overall network reliability and resilience.

2. Research Methodology

The research utilizes OMNeT++ for simulating WSNs and applies various swarm intelligence algorithms to address routing challenges and optimize cluster heads.

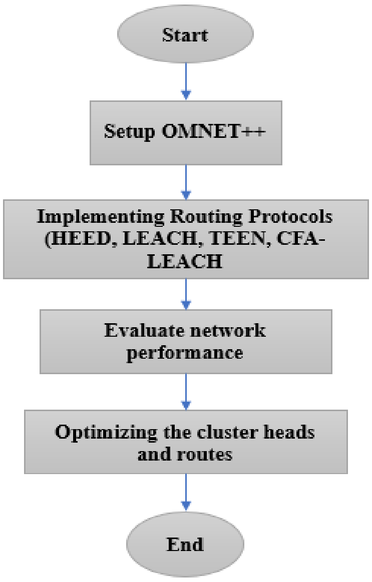

Figure 1. *Research Workflow for WSN Simulation and Optimization*

The flowchart provides an overview of the research process's various stages. Setting up a simulation environment with OMNET++ is the first step in the process. In the subsequent steps, different routing protocols are put into action, and swarm intelligence algorithms are utilised. Following this, the network's performance is analysed, which ultimately results in optimising the cluster heads and routes.

2.1 Routing protocols

Routing protocols in WSNs are designed to manage data transmission and network communication efficiently. They determine how data packets are routed from source to destination, aiming to optimize energy consumption, extend network lifetime, and enhance overall performance. Protocols may use various strategies, such as hierarchical clustering or energy-aware routing, to improve efficiency and ensure reliable data delivery[2,3,4].

Hierarchical Energy-Efficient Distributed (HEED):

The HEED algorithm is a clustering protocol for WSNs designed to improve energy efficiency and network lifetime [5].

a. Cluster Head Selection: Each node i has a probability of becoming a cluster head based on its residual energy: $p_i = \frac{E_i}{E_{max}}$

b. Cluster Formation: Nodes join the nearest cluster head based on distance:

$$d_{ij=\sqrt{(x_i-x_j)^2+(y_i-y_j)^2}}$$

c. Cluster Head Rotation: Cluster heads are periodically rotated based on residual energy, using: $P_i = \frac{E_i}{E_{avg}}$

d. Data Transmission: Energy for data transmission is calculated by:

$$E_{tx} = E_{trans} \times d^n{}_{ij}$$

Where $E_{trans}$is the energy per distance unit, is the distance, and n is the path loss exponent.HEED improves network lifetime by distributing energy use and optimizing cluster management.

Low-Energy Adaptive Clustering Hierarchy (LEACH):

LEACH algorithm is a widely-used protocol for WSNs aimed at reducing energy consumption and extending network lifetime [6-9].

a. Cluster Head Selection: Nodes decide to become cluster heads (CHs) based on a probability:

$$P(n) = \{\frac{p}{1 - p \times \left(rmod\frac{1}{p}\right)} ifn \in G$$

0 $otherwise$

b. Cluster Formation: Non-CH nodes join the nearest CH based on distance:

$$d_{ij} = \sqrt{(x_i - x_j)^2}+(y_i - y_j)^2$$

c. Data Transmission: Nodes send data to CHs, and CHs aggregate and send data to the base station (BS). Energy for transmitting k bits over distance d is:

$$E_{tx} = E_{elec} \times k + E_{amp} \times k \times d^2$$

d. Energy Dissipation: Energy consumed by CHs during data reception and aggregation:$E_{CH} = E_{elec} \times k \times N + E_{DA} \times k \times N$Where$\boldsymbol{E_{DA}}$ is the energy for data aggregation and N is the number of nodes in the cluster.

Threshold-sensitive Energy Efficient sensor Network (TEEN):
TEEN algorithm is designed for reactive networks in WSNs [10]. It focuses on reducing energy consumption and ensuring timely data reporting, especially in time-critical applications.

a. Cluster Formation:
Cluster Head (CH) Selection: Nodes are organized into clusters, with a CH responsible for aggregating and transmitting data to the base station (BS).

b. Thresholds Definition
Hard Threshold (HT): Minimum value of the sensed attribute (S) that triggers data transmission.$S \geq HT$

Soft Threshold (ST): The minimum change in the value of the sensed attribute (ΔS) that triggers the sensor to transmit new data.$\Delta S \geq ST$Where, $\Delta S = |S_{new} - S_{last}|$

c. DataTransmission:Nodes continuously sense the environment.
Transmission Condition: A node transmits data only if the sensed value exceeds the HT and the change from the last reported value exceeds the ST:

If $S \geq HT and \Delta S \geq ST,$

transmit data Once a node senses a value above the HT, it transmits the data and updates its last reported value [1].

2.2 Swarm Intelligence algorithms:

Swarm intelligence algorithms are well-suited for optimizing energy efficiency and network performance in wireless sensor networks (WSNs).To mitigate malicious routes, they analyse and adjust routing paths based on collective intelligence, improving the robustness and security of data transmission. To optimize cluster heads, the algorithm evaluate various configurations and adaptively select the most efficient nodes to act as cluster heads, thereby enhancing energy efficiency and network performance[11-13].

Choatic-based firefly (CFA) algorithm (Proposed):
Enhances the Firefly Algorithm with chaotic mapping to improve exploration and avoid local optima.The CFA integrates chaotic sequences into the traditional FA to enhance its optimization capabilities[14].
Initialization:Generate initial population of fireflies with random positions.X_i
Calculate initial brightness I_i based on the objective function $f(X_i)$

Chaotic Sequence:Use a chaotic map (e.g., Logistic map) to generate chaotic sequences.

$$x_{n+1} = r x_n (1 - x_n)$$

Where r is a parameter (commonly set to 4 for the Logistic map) and x_n is the current value in the sequence.

Brightness and Attractiveness:Brightness I_i is related to the objective function value: $I_i = f(x_i)$Attractiveness β decreases with the square of the distance r_{ij}: $\beta = \beta_0 e^{-\gamma r_{ij}^2}$
Whereβ_0 is the attractiveness at $r_{ij} = 0$ and γ is the light absorption coefficient

Position Update with Chaotic Influence: If firefly ***j***is brighter than firefly ***i***, update the position of firefly ***i*:**

$$x_i = x_i + \beta(x_j - x_i) + \alpha(choticsequence)$$

Here,α is a randomization parameter influenced by the chaotic sequence.

3. Result and Discussion

OMNeT++ provides a comprehensive and modular environment for simulating complex network scenarios, including WSNs. It equips researchers with the tools to accurately model network behaviours, configure simulation parameters, and analyse the performance of various network protocols.

3.1 WSN Simulation Parameters in OMNeT++

The OMNeT++ simulation framework utilizes IEEE802.11ac for MAC, simulates 20 nodes in a 2000m³ area with a 500m transmission range. Key settings include a random direction mobility model, 5 GHz carrier frequency, and a maximum speed of 20 m/s. The simulation runs for 1200 seconds with 2048-byte packets, employing a network layer setup, 60 km/h movement speed, 10 Mbps data rate, and protocols like TEEN, HEED, and LEACH. The energy model is based on extended battery and radio/CPU consumption, with constant bit rate (CBR) traffic. The table 1 represents the parameters used to set the Omnet+ The figure 1 illustrates the node distribution scenario in a WSN with 20 nodes using the CFA-LEACH (proposed) protocol. The nodes are strategically positioned to ensure complete coverage of the target area while maintaining network connectivity.

Table.1. *Parameters in OMNeT++*

Parameter	Value
Simulator	OMNeT++ (Advanced)
MAC Protocol	IEEE802.11ac
Number of Nodes	20
Simulation Area	2000m x 2000m x 1000m
Transmission Range	500m
Mobility Model	Random Direction Model
Carrier Frequency	5 GHz
Max Speed	20 m/s
Simulation Duration	1200 s
Packet Size	2048 bytes
Layer Type	Network Layer
Movement Speed	60 km/h
Data Rate	10 Mbps
Routing Protocols	TEEN, HEED, LEACH
Energy Model	Extended Battery Model
Energy Consumption	Radio and CPU based
Traffic Type	Constant Bit Rate (CBR)

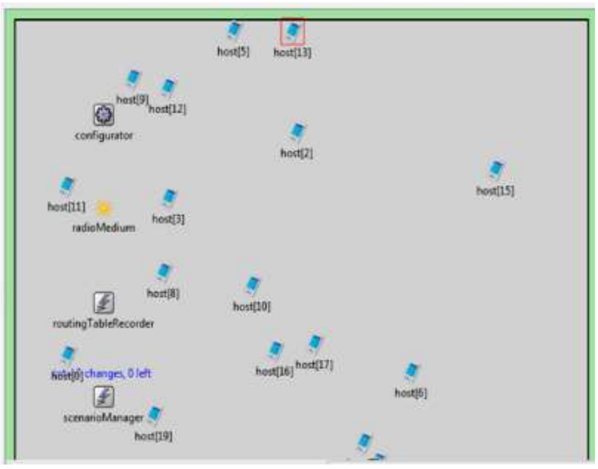

Figure 2.*(a). Node distribution of the proposed protocol before data transmission.*

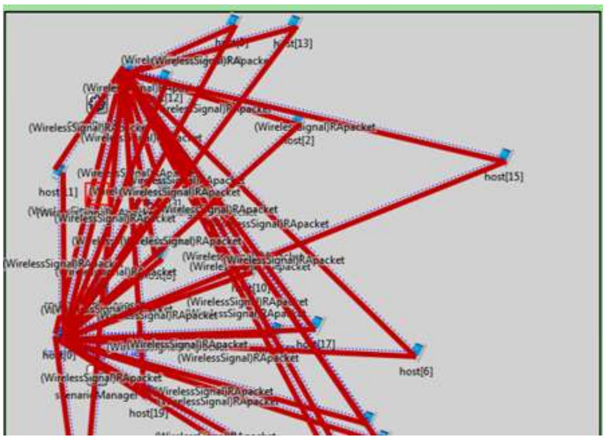

Figure 2.*(b). Node distribution during data transmission with the proposed protocol.*

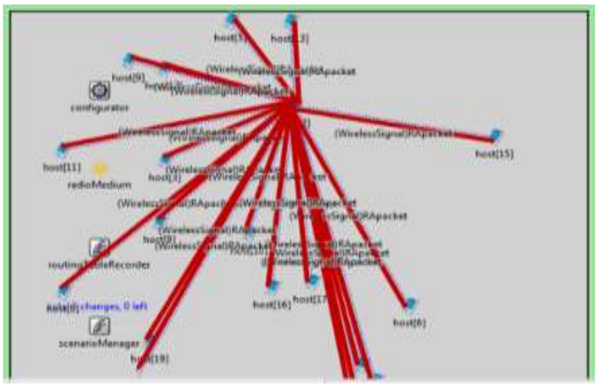

Figure 3.*(c) Node distribution during data transmission with the proposed protocol.*

The arrangement depicted in figure 2 is designed to optimize data transmission and enhance network performance.

3.2 Evaluation Measures

To gauge the energy efficiency of the FCWW (Fuzzy Clustering and Weighted Watermarking) algorithm, the following metrics are employed [12]:

Latency (L)

Latency represents the time taken for a data packet to travel from the source node to the destination node. It provides insight into the speed of data transmission within the network.

As the transmission duration increases to 200, 300, 400, and 500 seconds, latencies rise for all methods. Throughout all durations, the proposed method consistently achieves the lowest latency, indicating superior performance in data transmission speed compared to TEEN, HEED, and LEACH Protocols. Figure 3 shows latency comparison of protocols and figure 4 is impact of transmission duration. Table 2 is latency (Seconds) vs. rounds.

Packet Delivery Ratio (PDR)

The Packet Delivery Ratio measures the effectiveness of the network in delivering packets to their intended destination. A higher ratio indicates better network performance and reliability. Table 3 shows PDR (%) vs. rounds on throughput.

While transmission duration increases to 200, 300, 400, and 500 seconds, the PDR decreases for all methods, with the proposed method consistently maintaining the highest PDR values: 89.50% at 200 seconds, 87.00% at 300 seconds, 85.75% at 400 seconds, and 84.00% at 500 seconds. Overall, the proposed method outperforms other protocols in packet delivery efficiency throughout all durations.

End-to-End Delay (EED)

End-to-End Delay assesses the total time required for a packet to travel from the sender to the receiver.

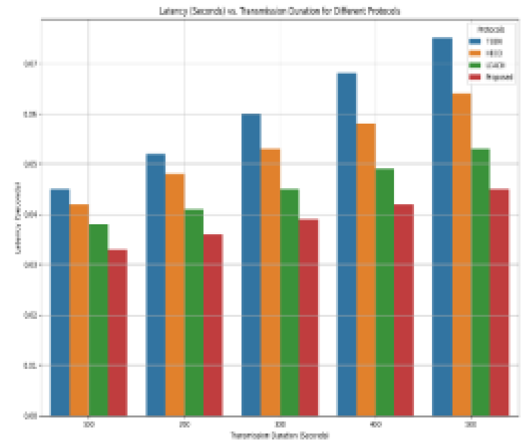

Figure 3. *Latency Comparison of Protocols*

Table 2*. Latency (Seconds) vs. Rounds*

Transmission Duration	TEEN	HEED	LEACH	PROPOSED
100	0.045	0.042	0.038	0.033
200	0.052	0.048	0.041	0.036
300	0.060	0.053	0.045	0.039
400	0.068	0.058	0.049	0.042
500	0.075	0.064	0.053	0.045

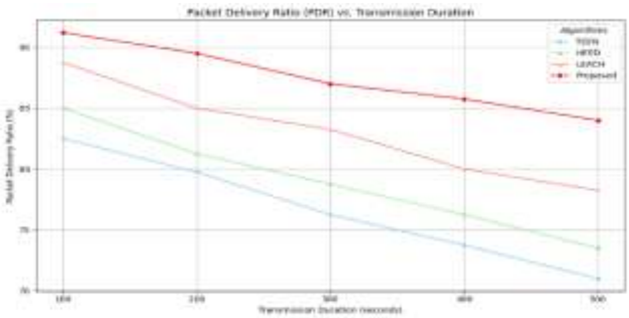

Figure 4. *Impact of Transmission Duration*

Table 3. *PDR (%) vs. Rounds on Throughput*

Transmission Duration	TEEN	HEED	LEACH	PROPOSED
100	82.50	85.00	88.75	91.20
200	79.75	81.25	85.00	89.50
300	76025	78.75	83.25	87.00
400	73.75	76.25	80.00	85.75
500	71.00	73.50	78.25	84.00

This metric encompasses all delays, including processing, queuing, and transmission times. Figure 5 shows comparison of End-to-End Delay. Table 4 is End-to-End Delay(milliseconds) vs. Rounds. By the time the duration reaches 500 milliseconds, the proposed method's delay increases to 5.5 ms, still the lowest among the compared methods, which range from 8.0 ms for TEEN to 6.8 ms for LEACH. This indicates that the proposed algorithmCFA-LEACH consistently exhibits the lowest end-to-end

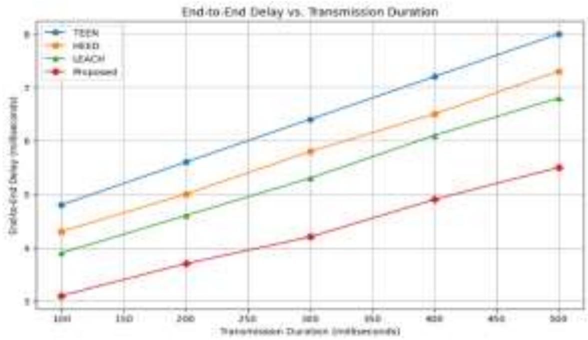

Figure 5*. Comparison of End-to-End Delay*

Table 4*. End-to-End Delay(milliseconds) vs. Rounds*

Transmission Duration	TEEN	HEED	LEACH	PROPOSED
100	4.8	4.3	3.9	3.1
200	5.6	5.0	4.6	3.7
300	6.4	5.8	5.3	4.2
400	7.2	6.5	6.1	4.9
500	8.0	7.3	6.8	5.5

delay compared to the other three algorithms across different transmission durations.

Throughput ($E_{throughput}$)

Throughput measures the efficiency of data transfer within the network, reflecting the rate at which packets are successfully transmitted over a specified period. Figure 6 shows throughout comparison and figure 7 and 8 are comparison of protocols. Table 5 shows throughput (bps) vs. rounds of protocols. And table 6 is energy consumption (µ Joules) with energy consumption vs. rounds. For transmission duration of 100 milliseconds, the proposed algorithm achieves the highest throughput of 30.20 bps, outperforming LEACH at 26.50 bps, HEED at 23.00 bps, and TEEN at 21.50 bps. The x-axis shows the transmission duration in milliseconds, and the y-axis displays throughput in

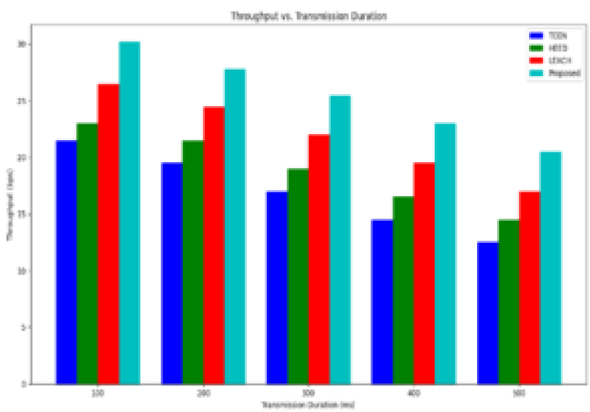

Figure 6. *Throughout Comparison*

Table 5. *Throughput (bps) vs. Rounds of Protocols*

Transmission Duration	TEEN	HEED	LEACH	PROPOSED
100	21.50	23.00	26.50	30.20
200	19.50	21.50	24.50	27.80
300	17.00	19.00	22.00	25.50
400	14.50	16.50	19.50	23.00
500	12.50	14.50	17.00	20.50

bits per second (bps). The Proposed protocolCFA-LEACH consistently outperforms TEEN, HEED, and LEACH in throughput across all evaluated transmission durations.

Energy Consumption

Energy Consumption evaluates the total energy utilized by all nodes during data transmission, providing insight into the network's power efficiency. Lower energy consumption indicates a more efficient network [2]. The x-axis represents the transmission duration in microjoules (µJ), while the y-axis represents the energy consumption in microjoules (µJ). CFA-LEACH consistently shows the lowest energy

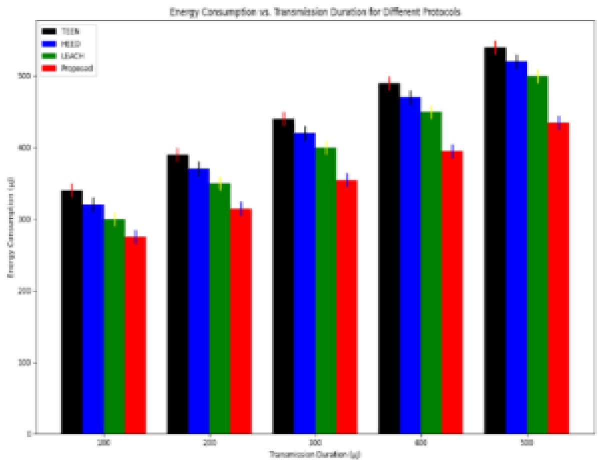

Figure 7. *Comparison of Protocols*

Table 6*. Energy Consumption (µ Joules) with Energy Consumptionvs. Rounds*

Transmission Duration	TEEN	HEED	LEACH	PROPOSED
100	340.00	320.00	300.00	275.00
200	390.00	370.00	350.00	315.00
300	440.00	420.00	400.00	355.00
400	490.00	470.00	450.00	395.00
500	540.00	520.00	500.00	435.00

consumption across all transmission durations, indicating its superior efficiency in energy management compared to the other protocols.

Network Lifetime

Network Lifetime measures the duration the network remains functional before any node runs out of

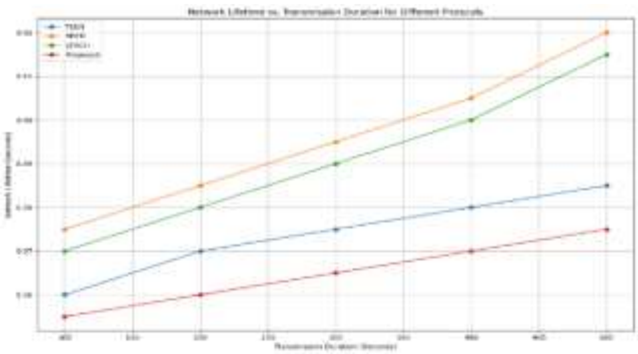

Figure 8. *Comparison of Protocols*

Table 7. *Network Lifetime (seconds) with network lifetimevs. Rounds*

Transmission Duration	TEEN	HEED	LEACH	PROPOSED
100	0.3600	0.3750	0.3700	0.3550
200	0.3700	0.3850	0.3800	0.3600
300	0.3750	0.3950	0.3900	0.3650
400	0.3800	0.4050	0.4000	0.3700
500	0.3850	0.4200	0.4150	0.3750

energy. Table 7 is network lifetime (seconds) with network lifetime vs. rounds. As the transmission duration increases, the network lifetime generally decreases for all protocols. The proposed protocol consistently demonstrates a longer network lifetime compared to the other three protocols across various transmission durations.

4. Conclusion

This research demonstrates significant advancements in optimizing energy efficiency and network performance in WSNs through the application of both traditional routing protocols and swarm intelligence algorithms. By evaluating TEEN, HEED, and LEACH protocols alongsideChaotic-Based Firefly algorithms, the research highlights the effectiveness of these approaches in reducing latency, improving packet delivery ratio, minimizing end-to-end delay, enhancing throughput, and lowering energy consumption. The proposed method performs better in maintaining lower latency, higher packet delivery ratios, and extended network lifetime, providing a robust solution for energy-efficient WSNs. The integration of swarm intelligence technique CFA and advanced routing protocols offer promising avenues for further enhancing network efficiency and resilience. Wireless Sensor Networks studied in literature and reported [15-18].

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.

- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
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