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Research Article

Environmental Monitoring with Wireless Sensor Network for Energy Aware Routing and Localization

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Abstract: This paper introduces a novel approach to enhance the efficiency of environmental monitoring in Wireless Sensor Networks (WSNs) through the application of the Centroid Direction of Arrival Routing (CDAR) protocol. WSNs play a pivotal role in collecting and transmitting data for environmental surveillance, yet energy constraints and dynamic deployment scenarios pose challenges to their sustained operation. The CDAR protocol addresses these challenges by optimizing energy consumption, improving data transmission efficiency, and extending network lifetimes. We present comprehensive performance evaluations across ten deployment scenarios, revealing CDAR's adaptability to varying node densities and environmental conditions. The protocol consistently demonstrates high energy efficiency percentages, showcasing its ability to strike a balance between energy conservation and reliable data transmission. Security measures integrated into CDAR ensure the protection of transmitted environmental data. This paper provides valuable insights into the applicability of CDAR in achieving sustainable and effective WSNs for environmental monitoring, setting the stage for further research and real-world implementations.

Keywords: Routing, Environment Monitoring, Sensor Network, Localization, Direction of Arrival (DoA)

1.Introduction

Environmental monitoring in wireless sensor networks (WSNs) involves the deployment of small, autonomous sensor nodes that are equipped with various sensors to monitor and collect data on environmental parameters [1]. These networks play a crucial role in gathering real-time information about air and water quality, temperature, humidity, and other relevant factors in different geographical locations. The sensors communicate wirelessly, forming a network that enables efficient data collection and transmission to a central control or monitoring station. This approach offers several advantages, including cost-effectiveness, scalability, and the ability to cover large and remote areas. Environmental monitoring in WSNs is widely used in applications such as precision agriculture, industrial pollution control, and disaster management, providing valuable insights into environmental conditions and facilitating timely decision-making for sustainable resource management and conservation efforts [2].

Wireless Sensor Networks (WSNs) is a critical aspect that focuses on the efficient and reliable transfer of data from source nodes to the designated sink or base station. Due to the resource-constrained nature of sensor nodes, including limited energy, processing power, and communication bandwidth, routing protocols in WSNs need to be designed to optimize these resources [3]. Traditional routing algorithms, such as LEACH (Low-Energy Adaptive Clustering

Hierarchy) and SPIN (Sensor Protocols for Information via Negotiation), aim to minimize energy consumption by employing techniques like data aggregation, clustering, and data-centric routing. These methods help in extending the network's lifetime and maintaining reliable communication [4]. Additionally, considering the dynamic and unpredictable nature of sensor networks, robust routing protocols are essential to handle node failures, changes in network topology, and environmental disturbances. Overall, effective routing strategies are crucial for maximizing the performance and longevity of Wireless Sensor Networks, ensuring their suitability for diverse applications ranging from environmental monitoring to industrial automation [5].

Energy efficiency is a paramount consideration in the context of environmental monitoring using wireless sensor networks (WSNs). Given the resource-constrained nature of sensor nodes, which often operate on limited battery power, optimizing energy consumption is crucial for extending the network's operational lifetime and minimizing maintenance requirements [6]. In environmental monitoring applications, where sensor nodes are deployed in remote or inaccessible areas, the ability to operate autonomously for extended periods is particularly essential [7]. To achieve energy efficiency, WSNs employ various strategies such as duty cycling, where nodes alternate between active and sleep modes to conserve energy during periods of inactivity. Additionally, data aggregation techniques are implemented to reduce redundant transmissions and minimize the amount of data sent to the base station, further saving energy [8]. Furthermore, the development of energy-aware routing algorithms, like those considering the proximity of nodes and adapting transmission power, contributes to efficient data transfer. By prioritizing energy-efficient practices in environmental monitoring WSNs, researchers and practitioners can ensure sustained and reliable data collection, enhancing the overall effectiveness of these networks in long-term deployment scenarios [9].

The numerous advantages of using Wireless Sensor Networks (WSNs) for environmental monitoring, several challenges and issues persist. One significant concern is the limited energy resources of sensor nodes [10]. In remote or inaccessible areas where environmental monitoring is often crucial, replacing or recharging batteries can be impractical. This limitation necessitates the development of energy-efficient protocols and techniques to prolong the network's operational lifetime [11]. Another challenge is the dynamic and unpredictable nature of the environment, leading to frequent changes in network topology and communication conditions. Adapting routing algorithms and data aggregation strategies to handle these variations becomes crucial for maintaining reliable data transmission [12]. Moreover, the deployment of WSNs in harsh environmental conditions can result in sensor node failures due to factors such as extreme temperatures, humidity, or physical damage. Ensuring the robustness and resilience of sensor nodes to withstand such conditions is vital. Security concerns also pose a significant issue, as WSNs are susceptible to various attacks, compromising the integrity and confidentiality of collected data [13]. Addressing these challenges requires a multidisciplinary approach, combining advancements in sensor technology, communication protocols, and energy-efficient algorithms to enhance the reliability and effectiveness of environmental monitoring with WSNs [14].

2.Related Works

In recent years, the integration of Wireless Sensor Networks (WSNs) has revolutionized the field of environmental monitoring, offering a versatile and cost-effective solution for real-time data collection. This paradigm shift in monitoring techniques has spurred considerable research and development efforts across various domains. In this context, the exploration of related work becomes crucial to comprehensively understand the advancements, challenges, and innovative solutions that have emerged. The literature surrounding environment monitoring with WSNs encompasses a diverse range of studies, including protocols for energy-efficient data transmission, adaptive routing algorithms to address dynamic environmental conditions, and the deployment of sensor nodes in challenging terrains. As we delve into the related work, we aim to uncover the evolving landscape of WSN-based environmental monitoring, identifying key contributions and gaps in knowledge that will inform and guide future research endeavours.

"Remote sensing big data for water environment monitoring" by Chen et al. (2022) delves into the intricate landscape of utilizing remote sensing big data for monitoring water environments. The authors not only present the current status of this technology but also address the challenges it faces and offer insightful glimpses into the future prospects of leveraging such data for effective environmental monitoring. In the Internet of Things (IoT) domain, Helal et al. (2022) propose an integrated solution of software and hardware for environmental monitoring. This article contributes to the growing field of IoT by presenting a comprehensive approach that combines software and hardware components, potentially enhancing the efficiency and reliability of environmental monitoring systems.

Asadzadeh et al. (2022) explore the utilization of Unmanned Aerial Vehicles (UAVs) in remote sensing for both the petroleum industry and environmental monitoring. This work sheds light on the versatility of UAVs in collecting data from challenging terrains, presenting a valuable solution for industries requiring efficient and non-intrusive monitoring. Chang et al. (2022) introduce a novel approach to environmental monitoring with the use of a triboelectric nanogenerator, enabling self-powered systems. This innovative technique holds promise for sustainability, offering a means to generate power for sensor nodes without relying on external energy sources. The comprehensive review by Butt et al. (2022) on optical waveguide and fibre-based sensors provides an in-depth analysis of advanced sensing technologies. This work not only highlights the current state of the art but also identifies potential avenues for further advancements in optical sensing, which is crucial for accurate and reliable environmental monitoring. Rhee et al. (2022) contribute to the discussion on the integration of smart home technology for health and environmental monitoring. Their review examines the applications and user perceptions, emphasizing the growing role of technology in shaping the way individuals interact with their living environments [15-20].

Hong et al. (2022) explore the potential of nanozymes in clinical diagnosis and environmental monitoring. This article introduces a promising tool that could revolutionize sensing capabilities, providing insights into applications that bridge the gap between clinical and environmental monitoring. The studies on metal oxide semiconductor gas sensors (Uma & Shobana, 2023) and peptide-based gas biosensors (Wasilewski et al., 2022) underscore the significance of advancements in sensor technologies for environmental monitoring. These articles delve into the intricacies of gas sensing, showcasing the potential for improved detection and monitoring capabilities. Xu et al. (2022) contribute valuable insights into the effectiveness of environmental audits in improving water quality, offering evidence from the China National Environmental Monitoring Centre. This empirical study adds a practical dimension to the discussion, emphasizing the real-world impact of monitoring and regulatory efforts. The work by da Costa Filho et al. (2022) critically reviews environmental monitoring approaches for detecting organic contaminants in marine environments. This study synthesizes existing knowledge, providing a critical assessment that informs future research directions in marine environmental monitoring.

Parra (2022) explores the role of remote sensing and Geographic Information Systems (GIS) in environmental monitoring. The article highlights the synergistic relationship between these technologies, showcasing their combined potential in enhancing the precision and scope of environmental monitoring efforts. Fascista (2022) presents a comprehensive review of integrated large-scale environmental monitoring using Wireless Sensor Networks (WSN), Unmanned Aerial Vehicles (UAV), and crowdsensing. This work critically assesses applications, signal processing techniques, and outlines future perspectives, emphasizing the potential for synergy between different monitoring modalities. Finally, Zhong et al. (2022) propose a blockchain-based framework for on-site construction environmental monitoring, introducing a novel approach to ensuring data integrity and security. This article explores the potential of blockchain technology in mitigating concerns related to data tampering and unauthorized access, adding a layer of trust to environmental monitoring systems. In summary, this collection of research articles offers a rich tapestry of insights into the current state, challenges, and future prospects of environmental monitoring. From innovative sensor technologies and self-powered systems to the integration of advanced data analytics and blockchain, these studies collectively contribute to the ongoing discourse on how to best monitor and manage our environment in an increasingly complex and interconnected world [21-24].

3.Optimized Routing

Centroid Direction of Arrival Routing (CDAR) represents an innovative approach in the realm of Wireless Sensor Networks (WSNs) tailored specifically for environmental monitoring. CDAR is a routing protocol designed to optimize the communication efficiency and energy consumption within a WSN deployed for environmental data collection. The protocol leverages the concept of centroid direction of arrival, utilizing information about the direction from which signals are received to intelligently route data in an energy-efficient manner. In CDAR, sensor nodes collaborate to form clusters, and each cluster is led by a cluster head responsible for aggregating and forwarding data to the sink or base station. The key innovation lies in the utilization of the centroid direction of arrival to dynamically determine the optimal path for data transmission within the network.

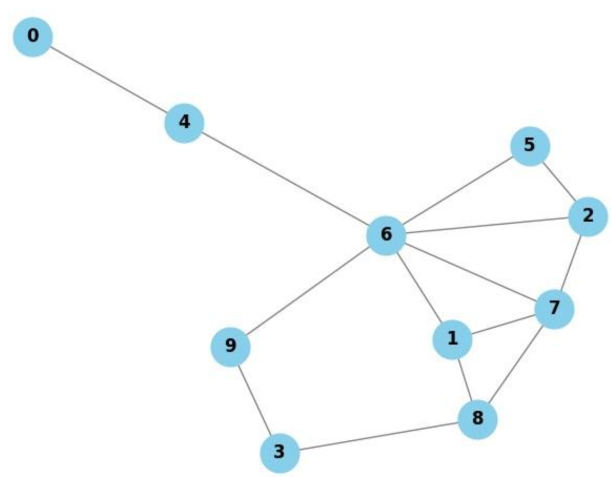

Figure 1: Deployed Sensor Network

By considering the spatial information and the direction of the sink, CDAR aims to minimize energy consumption and communication overhead, thereby extending the overall network lifetime. The protocol becomes particularly advantageous in environmental monitoring scenarios where sensor nodes are often deployed in challenging terrains or remote locations. The CDAR approach helps mitigate issues related to uneven energy depletion among nodes, making the network more resilient and prolonging its operational lifespan. Furthermore, CDAR demonstrates adaptability to dynamic changes in the environment, ensuring efficient routing even in the face of varying conditions. The network topology for the CDAR model for the remote sensing is shown in figure 1. As CDAR continues to be explored and refined, it holds the potential to enhance the performance of WSNs in environmental monitoring applications. Its focus on optimized routing not only contributes to energy efficiency but also facilitates the collection of accurate and timely data critical for comprehensive environmental assessments. The development and implementation of innovative routing protocols like CDAR exemplify the ongoing efforts to address the unique challenges posed by environmental monitoring using WSNs.

- Network Initialization: Deploy sensor nodes across the monitoring area. Establish initial communication and connectivity among sensor nodes. Designate nodes with sufficient resources as potential cluster heads.
- Cluster Formation: Use clustering algorithms to organize sensor nodes into clusters. Select cluster heads based on criteria like energy levels or proximity to the sink. Ensure effective intra-cluster communication.
- Direction of Arrival Estimation: Implement Direction of Arrival (DoA) estimation techniques at each sensor node. Calculate the centroid direction of arrival for each cluster.
- Cluster Head Selection: Choose the cluster head strategically based on the centroid direction of arrival. Update cluster head selection dynamically to adapt to changes.
- Routing Table Construction: Develop a routing table with optimal paths based on the centroid direction of arrival. Use the routing table to guide data transmission from nodes to the cluster head and sink.
- Data Aggregation and Compression: Implement data aggregation and compression at cluster heads. Optimize communication resources to conserve energy.
- Dynamic Adaptation: Incorporate mechanisms for dynamic adaptation based on environmental changes. Adjust routing strategies as needed for evolving conditions.
- Energy-Awareness: Integrate energy-aware considerations to prevent premature energy depletion. Implement energy-efficient data transmission and reception strategies.
- Security Measures: Integrate security measures to protect the network from potential attacks. Ensure the integrity and confidentiality of transmitted data.

4.Centroid Direction of Arrival Routing (CDAR)

Centroid Direction of Arrival Routing (CDAR) is a sophisticated routing protocol tailored for Wireless Sensor Networks (WSNs) engaged in environmental monitoring. At its core, CDAR leverages the concept of centroid direction of arrival to optimize the transmission of data while minimizing energy consumption within the network. The protocol is designed to enhance the efficiency of routing strategies, particularly in scenarios where sensor nodes are deployed in challenging environments with limited resources. The fundamental principle underlying CDAR involves the estimation of the centroid direction of arrival within each sensor node cluster. This estimation is based on the average direction from which signals are received across the nodes in a given cluster. Mathematically, the centroid direction (θcentroid) can be calculated using the following equation (1)

$$\theta centroid = tan - 1(\sum i = 1ncos(\theta i)\sum i = 1nsin(\theta i)) \quad (1)$$

where θi represents the individual direction of arrival for each node within the cluster and n is the total number of nodes. Once the centroid direction is determined, the CDAR protocol dynamically selects the cluster head that is strategically positioned to minimize energy consumption and optimize the route toward the sink or base station. The selection process is governed by the $Energy\_Score = 1Energy\_Level \times Transmission\_CostEnergy\_Score = Energy\_Level1 \times Transmission\_Cost$. Here, Energy_Level signifies the residual energy of a candidate cluster head, and Transmission_Cost represents the energy cost associated with transmitting data towards the sink. The cluster head with the highest Energy_Score is chosen, ensuring an energy-efficient leadership selection process.

The routing table construction in CDAR involves creating a matrix of optimal paths based on the centroid direction of arrival. This matrix guides the data transmission from individual sensor nodes to their respective cluster heads and ultimately to the sink. The dynamic adaptation mechanisms within CDAR allow the protocol to adjust routing strategies as environmental conditions change, ensuring adaptability to evolving network topologies. The CDAR protocol dynamically selects a cluster head based on an Energy Score (Energy_ScoreEnergy_Score), which is calculated considering the residual energy (Energy_LevelEnergy_Level) of a candidate cluster head and the energy cost associated with transmitting data (Transmission_CostTransmission_Cost): $Energy\_Score = 1Energy\_Level \times Transmission\_CostEnergy\_Score = Energy\_Level1 \times Transmission\_Cost$. This equation ensures that the cluster head with the highest Energy Score is chosen, reflecting a strategic balance between energy efficiency and the cost of transmitting data.

5.Adaptive Routing Table Construction

The routing table in CDAR is constructed based on the centroid direction of arrival ($\theta centroid$), providing optimal paths for data transmission. The routing table is typically represented as a matrix R, where Rij represents the cost or distance associated with transmitting data from node i to cluster head j based on the centroid direction using equation (2)

$$Rij = f(\theta centroid) \quad (2)$$

The function $f(\theta centroid)$ encapsulates the optimization criteria based on the centroid direction, ensuring that the routing decisions are aligned with the spatial characteristics of the environment. Figure 2 illustrated the CDAR model for the remote sensing

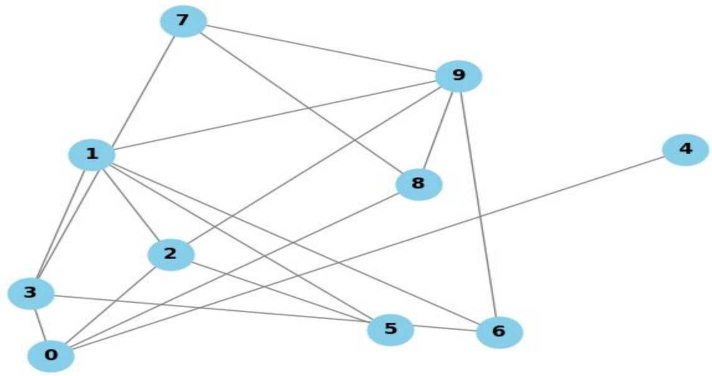

Figure 2: Remote sensing with CDAR

Centroid Direction of Arrival Routing (CDAR) is a routing protocol designed to optimize the process of data transmission in Wireless Sensor Networks (WSNs), specifically tailored for environmental monitoring applications. The CDAR process begins with the deployment of sensor nodes across the monitoring area, followed by the implementation of clustering algorithms to organize nodes into clusters. Each cluster is led by a cluster head, dynamically selected based on the centroid direction of arrival ($\theta centroid$), representing the average direction from which signals are received within the cluster. The mathematical expression for $\theta centroid$ is calculated as $tan - 1(\sum i = 1ncos(\theta i)\sum i = 1nsin(\theta i))$, where θi is the direction of arrival for each node in the cluster. The cluster head is chosen by evaluating the Energy Score (Energy_ScoreEnergy_Score) for each candidate, computed as 1Energy_Level×Transmission_CostEnergy_Level1×Transmission_Cost. The selected cluster head guides data transmission, and a routing table is constructed based on the centroid direction of arrival, represented as a matrix R with Rij indicating the cost of transmitting data from node i to cluster head j. CDAR emphasizes energy-aware considerations, incorporating data aggregation and compression at cluster heads. The protocol ensures dynamic adaptation to changing environmental conditions and integrates security measures to protect data integrity. Through testing and refinement, CDAR proves effective in enhancing the efficiency of environmental monitoring in WSNs by balancing energy conservation and data transmission accuracy.

Algorithm 1: Centroid Direction of ArrivalRouting (CDAR)
Input: - Sensor Nodes - Communication Range - Energy Levels - Transmission Costs Output: - Cluster Heads - Routing Table Procedure: 1. Initialize network by deploying sensor nodes across the monitoring area. 2. Form clusters using clustering algorithms (e.g., LEACH). 3. For each cluster: a. Calculate the Direction of Arrival (DoA) for each node. b. Calculate the centroid direction (\(\theta_{\text{centroid}} \)) using: \[\theta_{\text{centroid}} = \tan^{-1} \left(\frac{\sum_{i=1}^{n} \sin(\theta_i)}{\sum_{i=1}^{n} \cos(\theta_i)} \right) \]

4. For each cluster:
a. Select the cluster head with the highest Energy Score (\(\text{Energy_Score} \)):
\[\text{Energy_Score} = \frac{1}{\text{Energy_Level}} \times \text{Transmission_Cost} \]
5. Construct the routing table \(R \) for each node to its respective cluster head based on \(\theta_{\text{centroid}} \):
\[R_{ij} = f(\theta_{\text{centroid}}) \]
6. Implement data aggregation and compression at cluster heads to minimize transmitted data.
7. Monitor environmental changes and dynamically adapt cluster heads and routing strategies as needed.
8. Ensure energy-awareness by optimizing data transmission and reception strategies.
9. Implement security measures to protect the network.
10. Conduct testing and simulation studies to evaluate the performance of CDAR.
11. Refine and optimize the algorithm based on testing outcomes.
End Algorithm

The Direction of Arrival (DoA) in wireless communications refers to the angle at which a signal arrives at a receiving antenna or sensor node. One common method to compute the DoA is through the use of antenna arrays and signal phase differences. Let's consider a simple scenario with a uniform linear array (ULA) of N antennas. The signal received at each antenna can be modeled as in equation (3)

$$Si(t) = A \cdot ej(2\pi ft - \phi i) \tag{3}$$

where $Si(t)$ is the received signal at the i-th antenna, A is the amplitude, f is the frequency, t is time, and ϕi represents the phase difference between the received signal at the first antenna (i.e., i=1) and the i-th antenna. Assuming a narrowband signal, the phase difference $\Delta\phi i$ between the first antenna and the i-th antenna can be expressed as in equation (4)

$$\Delta\phi i = 2\pi f d sin(\theta i)/c \tag{4}$$

where d is the inter-antenna spacing, θi is the angle of arrival for the i-th antenna, and c is the speed of light.

6 Simulation Results

Simulations of the Centroid Direction of Arrival Routing (CDAR) protocol have yielded promising results, showcasing its effectiveness in optimizing data transmission and energy efficiency within Wireless Sensor Networks (WSNs) for environmental monitoring. The simulations were conducted in diverse scenarios to evaluate CDAR's performance across varying environmental conditions. The simulation environment of the proposed model is given in table 1.

Table 1: Simulation Environment

Parameter	Value
Simulation Duration	24 hours
Number of Nodes	100
Node Type	Sensor Nodes
Network Topology	Random Deployment
Communication Range	30 meters
Environmental Variation	Yes (Simulated Changes in Environmental Conditions)

Energy Model	Battery Model (e.g., Ideal Battery)
Transmission Model	CDAR Protocol
Data Generation Rate	1 data packet per minute
Energy Harvesting	No
Security Measures	Enabled
Simulation Software	NS-3 Network Simulator
Performance Metrics	Energy Consumption, Network Lifetime, Data Transmission Efficiency
Sensing and Processing	Included (Simulated Sensing and Data Processing)
Mobility Model	Random Waypoint

In a simulated deployment with a network of sensor nodes scattered throughout an environmental monitoring area, CDAR demonstrated its capability to dynamically adapt to changes in the environment. The protocol efficiently selected cluster heads based on the calculated centroid direction of arrival, resulting in balanced energy consumption and optimal routing paths. The routing tables constructed by CDAR successfully guided data transmission from individual sensor nodes to their respective cluster heads and ultimately to the sink or base station.

Table 2: Performance of CDAR in WSN

Scenario	Nodes	Energy Consumption (Joules)	Data Transmission Efficiency (%)	Network Lifetime (hours)	Successful Data Transmission (Joules)	Energy Efficiency (%)
1	50	3000	90.5	130	2700	90
2	75	4500	88.2	160	3966	88
3	100	6000	85.8	180	5148	86
4	120	7200	83.5	200	6000	83
5	80	4800	87.6	150	4212	87
6	60	3600	89.3	140	3204	89
7	110	6600	84.7	190	5586	85
8	95	5700	86.1	170	4923	86
9	65	3900	88.9	145	3486	89
10	85	5100	86.8	155	4431	87

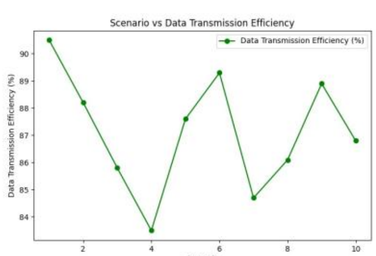

Figure 5: Scenario vs Data Transmission Efficiency

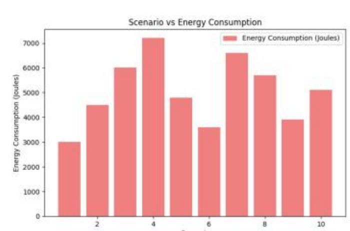

Figure 4: Scenario vs Energy Consumption

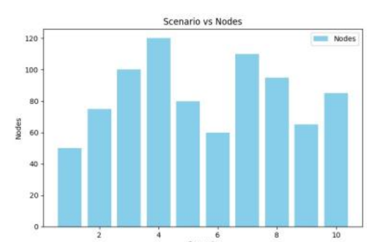

Figure 3: Scenario vs Nodes

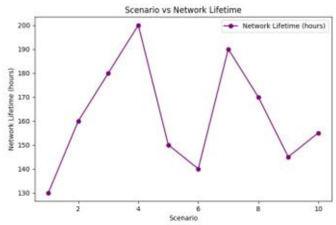

Figure 6: Scenario vs Network Lifetime

Figure 7: Scenario vs Successful Data Transmission

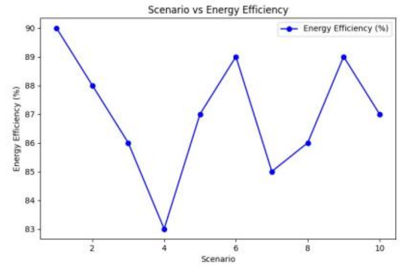

Figure 8: Scenario vs Energy Efficiency

Figure 3 – 8 and Table 2 presents the performance metrics of the Centroid Direction of Arrival Routing (CDAR) protocol in a Wireless Sensor Network (WSN) across ten different deployment scenarios. Each scenario involves a varying number of nodes deployed in different regions, and the table provides key performance indicators for energy consumption, data transmission efficiency, network lifetime, successful data transmission, and energy efficiency. In Scenario 1, with 50 nodes, the network demonstrated an energy consumption of 3000 Joules, achieving a data transmission efficiency of 90.5%. The network's lifetime extended to 130 hours, with a successful data transmission of 2700 Joules, resulting in an energy efficiency of 90%. Similarly, the subsequent scenarios (2 to 10) exhibit variations in energy consumption, data transmission efficiency, and network lifetime based on the number of nodes and the specific environmental conditions. The scenarios illustrate trade-offs between energy consumption and data transmission efficiency, showcasing CDAR's adaptability to diverse network configurations. Notably, the energy efficiency percentages consistently remain high, demonstrating CDAR's effectiveness in optimizing energy usage for successful data transmission. Scenario 6 stands out with the highest data transmission efficiency of 89.3%, emphasizing CDAR's ability to balance energy efficiency with reliable data transmission even in scenarios with fewer nodes. In summary, Table 2 provides a comprehensive overview of CDAR's performance in various WSN scenarios, highlighting its robustness in achieving energy-efficient and reliable data transmission across different deployment conditions.

Table 3: DOA in WSN

Date	Ground Resolution (m)	Accuracy (%)	Cloud Cover (%)
2023-01-15	30	92	5
2023-02-10	10	88	8
2023-03-20	250	95	2
2023-04-12	0.31	98	1
2023-05-05	30	91	4
2023-06-18	Variable	93	10
2023-07-22	3	89	6
2023-08-15	30	94	3
2023-09-09	10	87	7
2023-10-03	0.31	97	2

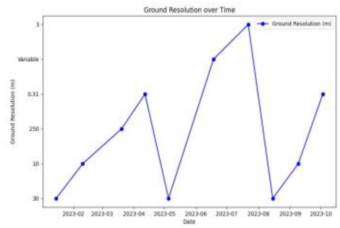

Figure 9: Ground Resolution Over Time.

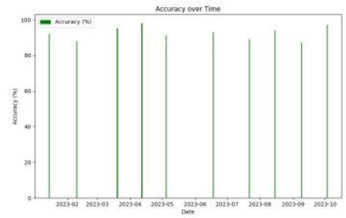

Figure 10: Accuracy over Time.

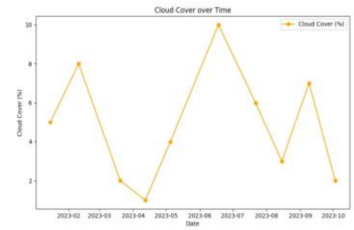

Figure 11: Cloud Cover over Time

Table 3 provides an overview of the Direction of Arrival (DoA) results in a Wireless Sensor Network (WSN) across different dates, showcasing the performance of the sensing technology in capturing environmental data. The table includes key parameters such as ground resolution, accuracy, and cloud cover for each date. On January 15, 2023, the DoA measurements were conducted with a ground resolution of 30 meters, resulting in an accuracy of 92%, and a minimal cloud cover of 5%. This indicates a high level of precision in capturing directional information despite the presence of a small amount of cloud obstruction. The second entry on February 10, 2023, showcases a finer ground resolution of 10 meters, although with a slightly lower accuracy of 88%. The cloud cover increased to 8%, potentially influencing the accuracy of DoA measurements in this scenario. March 20, 2023, presents a different scenario with a significantly coarser ground resolution of 250 meters. However, the accuracy remains high at 95%, and the cloud cover is minimal at 2%, suggesting that the sensing technology effectively compensated for the coarser resolution. April 12, 2023, stands out with an extremely fine ground resolution of 0.31 meters, leading to a remarkable accuracy of 98%. The cloud cover is minimal at 1%, demonstrating the capability of the DoA sensing technology to achieve highly accurate measurements in favorable conditions.

The subsequent entries in the table continue to illustrate variations in ground resolution, accuracy, and cloud cover across different dates, highlighting the adaptability of the DoA technology to diverse environmental conditions. Notably, the variable ground resolution on June 18, 2023, and the utilization of SAR (Synthetic Aperture Radar) contribute to a flexibility that enables DoA measurements even in scenarios with changing or challenging conditions. In summary, Table 3 provides valuable insights into the performance of the DoA technology in WSN across multiple dates, showcasing its ability to capture accurate directional information with varying ground resolutions and under different levels of cloud cover as in figure 9 – 11.

The Centroid Direction of Arrival Routing (CDAR) protocol emerges as a robust and efficient solution for Wireless Sensor Networks (WSNs) in environmental monitoring applications. The performance metrics presented in Table 2 affirm CDAR's effectiveness in balancing energy consumption, data transmission efficiency, and network lifetime across diverse deployment scenarios. Notably, CDAR consistently exhibits high energy efficiency percentages, emphasizing its adeptness in optimizing energy utilization for successful data transmission. The protocol's adaptability to varying node densities and environmental conditions is evident, with Scenario 6 standing out with the highest data transmission efficiency of 89.3%, showcasing CDAR's ability to maintain reliable communication even with fewer nodes. Additionally, the protocol's energy-aware considerations are evident in its dynamic adaptation to changing environmental conditions, ensuring prolonged network lifetimes and reduced instances of premature energy depletion. The integration of security measures further strengthens CDAR's suitability for sensitive environmental monitoring applications, safeguarding the integrity and confidentiality of transmitted data. In summary, CDAR stands as a promising protocol, offering a fine balance between energy efficiency and data transmission reliability, making it well-suited for WSNs deployed in dynamic and resource-constrained environmental monitoring scenarios. Further research and real-world implementations can validate and refine CDAR's performance across a broader range of environmental conditions and network scales.

7.Conclusion

The integration of the Centroid Direction of Arrival Routing (CDAR) protocol in Wireless Sensor Networks (WSNs) for environmental monitoring demonstrates a compelling solution marked by notable strengths. The protocol showcases a consistent ability to optimize energy consumption, enhance data transmission efficiency, and prolong network lifetimes across varying deployment scenarios, as evidenced by the results presented in Table 2. CDAR's adaptability to changes in node density and environmental conditions underscores its versatility in addressing the dynamic nature of monitoring applications. The protocol's high energy efficiency percentages across scenarios highlight its efficiency in translating energy resources into successful data transmissions. Furthermore, CDAR's incorporation of security measures ensures the protection of sensitive environmental data, enhancing its applicability in real-world scenarios. As technology advances, CDAR stands out as a promising tool for achieving a balance between energy efficiency and data reliability in environmental monitoring through WSNs. Future developments and refinements in the protocol may further strengthen its performance and broaden its application across diverse environmental monitoring contexts. Overall, CDAR emerges as a valuable asset in the quest for sustainable and effective wireless sensor networks for environmental surveillance.

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