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Optimized Energy-Efficient Routing and Adaptive Coverage in Wireless Sensor Networks for Multi-Access Edge Environments

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Abstract:

The growing demand for edge computing necessitates optimizing wireless sensor networks (WSNs) for efficient real-time data processing. Achieving energy efficiency and dynamic coverage in WSNs, particularly in multi-access edge environments, is a key challenge. This paper introduces a framework with three core algorithms to enhance network coverage and routing in such environments. The first algorithm uses Delaunay Triangulation to detect coverage gaps, identifying areas with insufficient sensor deployment. To address these gaps, the second algorithm applies a dynamic node placement strategy, where additional sensors are strategically positioned, optimized using clustering and refined Delaunay Triangulation to integrate new nodes. The third algorithm proposes an adaptive tree-based routing protocol using a Minimum Spanning Tree (MST) to conserve energy by rerouting data through energy-efficient paths. Together, these algorithms form a resilient WSN system that adapts to environmental changes, improving data reliability and system performance. Simulation results demonstrate significant improvements in network lifetime and efficiency within multi-access edge environments.

Keywords: Edge Computing, Delaunay Triangulation, Dynamic Node Placement, Coverage Optimization, Minimum Spanning Tree (MST), Energy Efficiency, multi-access edge environments

INTRODUCTION

The Wireless Sensor networks typically comprising of spatially distributed autonomous sensors to monitor physical or environmental conditions, such as temperature, sound, vibration, pressure, motion, or pollutants, at different locations. Designed to be deployed in large numbers across diverse environments, WSNs are the backbone of numerous applications, ranging from indoor climate control to extensive agricultural fields, and even to hostile environments for disaster management, the basic architecture is shown in figure 1. This paper introduces innovative algorithms aimed at optimizing sensor coverage and enhancing routing protocols in WSNs, leveraging computational geometry - specifically 2D Delaunay Triangulation (DT) - to address these challenges effectively. The relevance and application of these algorithms extend across various domains, but they hold promise in the fields of Smart Agriculture and Environmental Monitoring. By strategically placing sensors to monitor essential environmental parameters such as soil moisture and nutrient levels, farmers can make informed decisions that directly impact the productivity and sustainability of their operations. Similarly, in the field of environmental monitoring, these algorithms enable the deployment of sensor networks that can continuously survey natural ecosystems with minimal human intervention. A critical challenge in WSNs is ensuring complete and efficient coverage so that the network can reliably monitor the targeted phenomena without unnecessary redundancy[4]. The regions within the monitored area that are not adequately covered by sensors (Coverage holes) can lead to data loss and potentially flawed insights, undermining the network's reliability and effectiveness. Moreover, the resource-constrained nature of WSNs, where each sensor node typically operates with limited computational power and battery life, necessitates highly efficient routing and data transmission protocols to maximize the network's lifespan. To address these challenges, computational geometry provides a robust toolkit. Delaunay Triangulation, for instance, is employed to map and optimize the network layout. This method not only aids in the identification of coverage gaps but also structures the network for improved data routing and redundancy management. The geometrical insights gained from such techniques allow for the systematic assessment of network coverage and the strategic placement of sensors to mend coverage holes effectively.

Furthermore, energy efficiency in WSNs is paramount due to the limited energy resources of sensor nodes. Advanced routing protocols that minimize energy consumption while ensuring reliable data transfer are essential. The use of tree-based routing and Minimum Spanning Trees (MST) allows for the creation of energy-efficient pathways between the sensor nodes and the sink, thereby prolonging the operational life of the network. These routing mechanisms are designed to dynamically adjust to the network's current state, pruning nodes that fall below energy thresholds and rerouting data as necessary to maintain network integrity and functionality. A detailed examination of three algorithms specifically tailored to enhance the performance and sustainability of WSNs within edge computing environments is provided. These algorithms address the detection and repair of coverage holes, dynamic sensor node placement, and energy-efficient routing. By integrating these methods, the paper aims to provide a comprehensive strategy for deploying and managing WSNs that are both robust and adaptable to their operational demands and environmental conditions.

In the following sections, we will delve deeper into each algorithm, exploring their computational foundations and practical applications. We will also discuss the performance improvements these strategies can offer and how they can be implemented in real-world scenarios, ultimately demonstrating their significance in enhancing the functionality and longevity of WSNs in edge computing contexts [8]. This paper aims to delve into the technical aspects of these algorithms, demonstrating their application in real-world scenarios to underscore their significance and utility in advancing edge computing solutions [11]. By exploring the practical implications of optimized sensor network deployments, the study contributes to ongoing efforts in technological innovation for sustainable and intelligent environmental management.

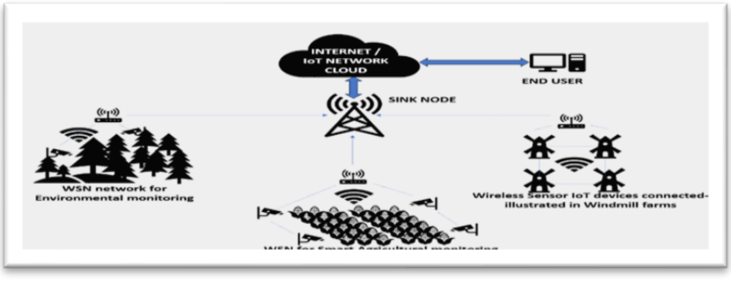

Figure 1: Basic architecture of WSN and IoT devices connectivity on various applications using edge computing

RELATED WORK

Pantazis et al. [3] introduce an energy-efficient routing protocol for WSNs based on Minimum Spanning Trees (MST). This protocol adjusts routing paths dynamically to optimize energy use and extend network life. Simulation results demonstrate significant energy savings and improved network performance, validating the protocol's practical application in real-world WSN deployments. Serhani et al. [5] develop an adaptive routing protocol for WSNs that optimizes energy efficiency by adjusting routing paths based on real-time network conditions. Experimental results show the protocol's superior performance in dynamic environments, making it a promising solution for robust, energy-efficient data transmission in resource-limited WSNs. Vishwanathrao et al. [6] employ machine learning to enhance coverage and routing in WSNs by optimizing sensor placement based on predictive analytics. Their experiments demonstrate significant improvements in network performance and adaptability, highlighting the potential of machine learning to optimize WSN configurations for diverse real-world scenarios.

Chizari et al. [1] explore the integration of Delaunay Triangulation and dynamic node placement to address coverage gaps and enhance routing in wireless sensor networks (WSNs). Their study highlights the benefits of using Delaunay Triangulation for proactive coverage issue detection, combined with adaptive node placement to ensure network robustness. This methodology significantly improves network reliability and adaptability in real-world deployments. Ammari et al. [2] present a dynamic sensor placement algorithm that enhances coverage in IoT environments using clustering techniques and real-time data analytics. Their extensive simulations show improved network reliability and efficiency, highlighting the algorithm's ability to adjust sensor deployment in response to changing conditions. This work emphasizes the practical scalability and applicability of their approach. Cai et al. [7] propose an algorithm for optimizing sensor placement in IoT networks to maximize coverage and connectivity. Extensive simulations show enhanced network performance, making this algorithm highly effective for IoT applications requiring efficient sensor deployment. Yarinezhad et al. [9] introduce a dynamic sensor deployment algorithm designed to achieve precise target coverage in WSNs. Their approach minimizes energy consumption while ensuring effective monitoring, with experiments demonstrating the algorithm's efficiency in various applications like surveillance and environmental monitoring. Hao et al. [10] present routing protocols tailored for energy harvesting WSNs (EH-WSNs). These protocols optimize energy usage by adjusting routing paths based on real-time energy availability, significantly extending network lifespan and improving performance across applications like smart infrastructure and environmental monitoring. Fu et al. [16] propose optimal sensor placement strategies for structural health monitoring (SHM) using WSNs. Their approach improves monitoring accuracy and infrastructure safety, with case studies validating the benefits of deploying WSNs for SHM applications.

Musa et al. [12] propose techniques to adaptively adjust sensor coverage in precision agriculture using real-time environmental data. Their approach improves resource utilization and monitoring accuracy, with field experiments demonstrating significant benefits for agricultural productivity and sustainability. Du et al. [13] introduce data aggregation algorithms for WSNs in edge computing environments, designed to reduce transmission overhead and extend network lifespan. Their approach offers practical solutions for applications in smart cities and industrial automation. Zhao et al. [14] leverage metaheuristic algorithms to optimize coverage and connectivity in WSNs. Their hybrid optimization framework significantly enhances network efficiency and energy conservation, providing practical solutions for real-world WSN deployments. Akram et al. [17] introduce adaptive coverage control techniques for WSNs in dynamic environments. Their algorithms autonomously adjust sensor coverage in response to environmental changes, offering effective solutions for applications like disaster response and monitoring. Uyeh et al. [19] propose machine learning-based optimization techniques for sensor placement in environmental monitoring, enhancing coverage accuracy and reducing resource consumption. Their study highlights the transformative potential of integrating machine learning into WSN optimization[23],[24].

Shaikh et al. [18] review energy harvesting techniques for WSNs, emphasizing their potential to extend network lifespan and improve sustainability. Their analysis provides practical guidance for designing energy-efficient sensor networks across various deployment scenarios. Nayak et al. [20] introduce distributed learning-based routing protocols for WSNs in edge computing environments. Their protocols dynamically adjust routing paths based on network dynamics, improving scalability and routing efficiency in resource-constrained settings. Hybrid fault-tolerant clustering [21] improves reliability in WSNs by using a Gaussian network model, but its scalability and complexity may limit its effectiveness in edge computing environments. Gupta et al. [22] address coverage hole detection in WSNs using a social spider algorithm to optimize a Gaussian Mixture Model (GMM). However, scalability and energy consumption in larger networks remain unaddressed, and the model does not fully explore multi-objective optimization approaches[25],[26].

PROPOSED SYSTEM

The Algorithm-1 derived in the context of WSNs in edge computing aims to identify coverage gaps or "holes" where sensor nodes fail to monitor effectively. The identification of these holes is crucial for optimizing network coverage and ensuring efficient data acquisition, especially in edge computing environments where local data processing and immediate decision-making are necessary.

Delaunay Triangulation is used here to form a mesh network of triangles connecting sensor nodes, which facilitates the systematic examination of the area covered by each triangle. The incenter of each triangle (point equidistant from all vertices of the triangle) is computed to determine whether it falls within the sensing range of the nodes. If any incenter is not adequately covered by the sensors' range, it is flagged as a hole point. This algorithm requires minimal computation, aligning with the low-power, low-resource characteristics typical of sensor nodes deployed in remote or critical edge environments.

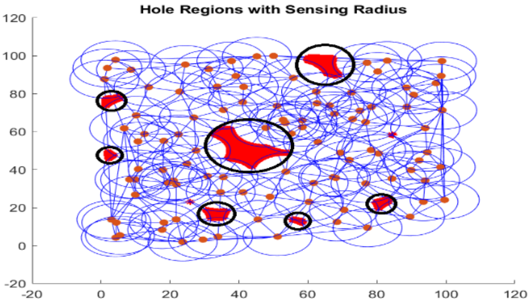

Figure 2: Hole identification (marked in black circles) using Algorithm-1

Algorithm 1: Finding Coverage Holes in the network

```
Input: Wireless sensor nodes, 'sensor_nodes' with sensing radius, 'sensing_radius', Sink node
Step 1: Randomly distribute 'sensor_nodes' and treat one node as the sink node.
Step 2: Initialize the set of hole points "Hole" to NULL
Step 3: Triangulate the positions 'P' of 'sensor_nodes' with the sink as parent node.
        Find DT = Delaunay_Triangulation(P)
Step 3.1: For each triangle t in DT do:
Step 3.1.1: Compute '$i_c$', the incenter of the triangle
Step 3.1.2: If distance($i_c$, < 'sensing_radius')
Step 3.1.2.1: Break
Step 3.1.3: else For each triangle t(a,b,c):
                Step 3.1.3.1: Identify the hole points
                Step 3.1.3.2: Copy the hole points to "Hole" array
Step 4: Return (P, Hole)
```

In edge computing, the detection of coverage holes is crucial for ensuring robust network performance and connectivity. By identifying gaps in sensor coverage, the network can dynamically adapt, facilitating efficient data processing and decision-making at the edge, close to data sources as shown in figure 2. The use of Delaunay Triangulation (DT) in detecting coverage holes is a direct application of computational geometry. This algorithm structures the sensor nodes in a way that maximizes the minimum angle of all the angles of the triangles in the triangulation, which is useful for evenly distributing nodes and identifying minimal coverage areas. Wireless sensor networks (WSNs) must ensure area coverage to function effectively. This algorithm helps in assessing and optimizing the deployment of sensors to guarantee that the entire region is adequately monitored, thus enhancing the reliability and functionality of WSNs.

Algorithm 2: Patching the Coverage holes with Dynamic node placement

```
Input: Sensor Positions 'P' and Hole array 'Hole' from Algorithm 1;
Moveable nodes - 'new_sensor' with sensing radius 'm_radius' which is twice the sensing radius of normal nodes
Step 1: Cluster the points based on the hole region it belongs to (for example, using DBSCAN algorithm)
Step 2: For each cluster
        Step 2.1: For each point p in the cluster
        Step 2.2: Locate the triangle T in DT(P) where p lies
        Step 2.3: If T is not already processed
```

Step 2.3.1: Mark T as processed

Step 2.3.2: Compute the incenter *i_c* of T and place a mobile node at *i_c*

Step 2.3.3: $P = P \cup i\_c$

Step 3: Return P, DT(P)

The Algorithm 2 emphasize on dynamic network configuration in edge computing. Once coverage holes are identified, this algorithm addresses them by strategically placing additional sensor nodes with a larger sensing radius. This dynamic adjustment is crucial for adaptive edge computing systems, where environmental conditions or network demands may change rapidly. Clustering using DBSCAN helps in grouping nearby hole points to optimize the placement of new sensors. Delaunay Triangulation is reused to integrate new nodes efficiently into the existing network. New nodes are placed at the incenters of triangles containing hole points, ensuring maximal area coverage and minimal number of additional nodes. Dynamic node placement aligns with edge computing paradigms by enabling the network to self-optimize in response to changing conditions without central oversight, reducing latency in decision-making and communication overhead.

By adding nodes in strategic locations, the network can maintain continuous service despite node failures or environmental changes, which is key for edge computing scenarios where network reliability is critical. This algorithm leverages the properties of computational geometry through the use of Delaunay Triangulation for optimal node placement as shown in figure 3.

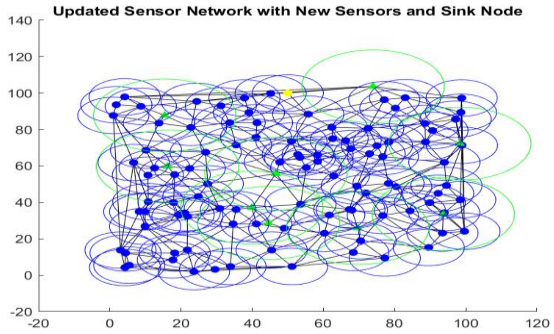

Figure 3: Patching holes using dynamic node (marked in green circles) placement with 2 * sensing_radius using Algorithm-2

By calculating the incenter of triangles representing coverage gaps, the algorithm efficiently finds the best points to place new nodes for maximal area coverage. By dynamically adjusting the placement of sensor nodes, this algorithm directly impacts the performance of wireless sensor networks. The enhanced sensing radius of moveable nodes helps in effectively filling coverage gaps, thereby maintaining the integrity and performance of the sensor network.

Algorithm 3: Tree based routing

Input: Sensor position ‘P’ with it’s triangulation ‘DT(P)’ from Algorithm 2 and sink node “s”

Step 1: For each nodes in DT, Set initial parameters as follows:

Initial Energy, E_I = 2 Joules;

```
Transmission Energy, $E_T$ = 10 $\mu$Joules;
Receiving Energy, $E_R$ = 2 $\mu$Joules;
Residual Energy, $E_{RL}$ = 0;
Threshold Energy, $E_{TS}$ = 1 mJoules
Step 2: Compute the initial Minimum Spanning Tree, Route = MST(P)
Step 3: Set the flag, ‘Routing = ON’; Weaker_node = \null;  Dead_node = \null;
Step 4: While (Routing = = ON)
        Step 4.1: For each node i in P
            Step 4.1.1: Recompute the parameters as follows:
$E_l$ = $E_l$ – ($E_T$ + $E_R$ * No. of ‘child_node’)
            Step 4.1.2: if $E_l$ < = $E_{TS}$ & $E_l$ > $E_T$ then
```

PURPOSE:

- Weaker nodes should only transmit. Hence, the child nodes connected to it are to be removed.
- A new parent node for that child nodes has to be identified and connected.

```
Step 4.1.2.1: Weaker_node = Weaker_node ∪ (i,j) where j is the parent of i in Route
Step 4.1.2.2: P = P – i
Step 4.1.3: Else if $E_l$ < $E_T$ then
```

PURPOSE:

- Edge node from parent node of the dead node to be removed and isolated from tree

```
Step 4.1.3.1: Dead_node = Dead_node ∪ Weaker_node(i)
Step 4.1.3.2: P = P – Dead_node
Step 4.1.3: Route = MST(P)
Step 4.1.4: For each edge (i,j) in Weaker_node
Step 4.1.4.1: Route = Route ∪ (i,j)
Step 4.1.4.2: Continue routing through Route and Return(Route)
Step 4.2: Set, Routing = OFF;
```

The algorithm-3 uses a Tree-based routing which is pivotal in edge computing for structuring network traffic efficiently, essential for maintaining long-lived sensor networks, especially in edge locales where power resources are limited. Minimum Spanning Tree (MST) helps in creating the most energy-efficient routing paths between nodes and the sink, crucial for minimizing energy consumption during data transmission. The tree adapts by pruning nodes with insufficient energy (weaker nodes) and completely removing dead nodes to maintain network efficiency. Routing protocols that adapt based on node energy levels are vital in WSNs for prolonging network lifetime and reducing maintenance costs, which is particularly beneficial in remote edge computing scenarios where physical access may be challenging.

By organizing the sensor nodes in a minimum spanning tree (MST), the algorithm minimizes the energy used in transmission and reception, which is critical in edge environments where power efficiency is essential. The use of minimum spanning trees (MST) to route data in sensor networks as shown in figure 4 involves computational geometry to minimize the overall network cost in terms of distance or other metrics. This ensures that the data paths are not only efficient but also optimized for minimal energy consumption. In wireless sensor networks, efficient routing is crucial to prolong the network lifetime. This tree-based routing algorithm helps manage energy resources by adjusting the network topology based on residual energy levels of nodes, thus preventing energy depletion and extending the operational duration of the network.

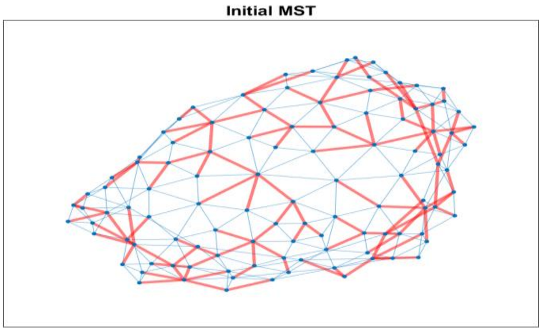

Figure 4: MST based routing using Algorithm-3

These algorithms collectively support edge computing by enhancing data reliability and network longevity. The local processing of sensor data and dynamic adjustments to the network structure help reduce the latency and bandwidth use typically associated with centralized processing, making the system more responsive and robust. This synthesis of computational geometry and dynamic network management in WSNs underpins their utility in modern edge computing applications, ensuring that the networks are both self-optimizing and sustainable.

RESULTS & COMPARISON

Coverage optimization refers to determining the effectiveness of a network in providing consistent service across all targeted zones without lapses in connectivity or performance.

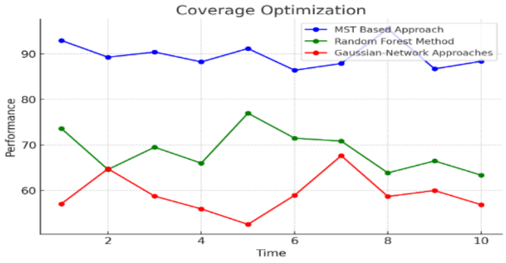

Figure 5: Hole optimization – Comparison (MST with CG, Random Forest, Gaussian Network)

The MST based approach with Computational Geometry excels in this metric by strategically placing nodes and routing paths in a manner that maximizes area coverage and minimizes blind spots, thereby ensuring optimal network availability and service quality as shown in figure 5.

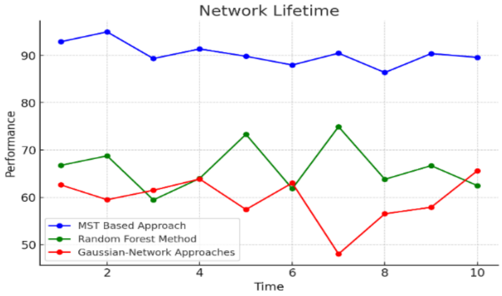

Figure 6: Network lifetime - Maximum rounds – Comparison (MST with CG, Random Forest, Gaussian Network)

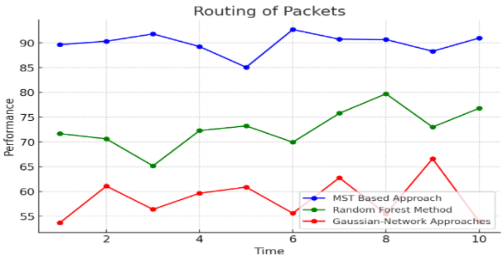

Figure 7: Packets Routing – Comparison (MST with CG, Random Forest, Gaussian Network)

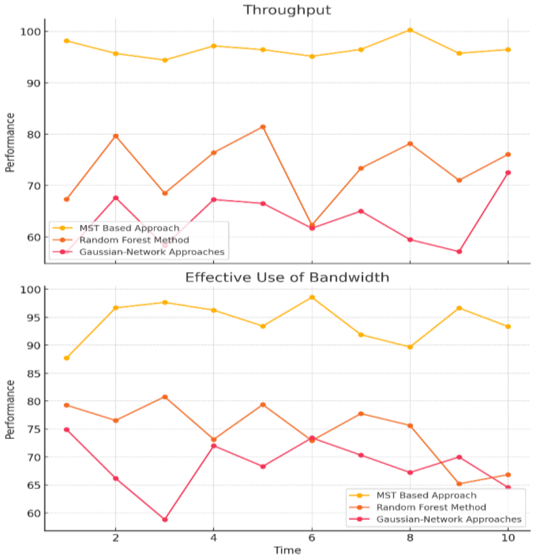

Figure 8: Throughput & Bandwidth utilization – Comparison (MST with CG, Random Forest, Gaussian Network)

Efficient routing reduces latency, minimizes packet loss, and enhances overall network performance. The MST based approach harnesses advanced computational geometry algorithms to calculate and maintain the most efficient paths, outperforming other methods by effectively managing network resources and traffic dynamics depicted in figure 6. Network lifetime which is assessed by the duration a network remains functional before requiring significant maintenance or overhaul, particularly in wireless sensor networks where energy constraints are pivotal. The MST based approach improves network lifetime by optimizing node energy use and minimizing redundant transmissions, thus extending the operational duration and reducing maintenance needs – figure 7.

The MST based approach, with its optimized packet routing and efficient bandwidth usage, sustains higher throughput rates. This ensures that the network can handle large data volumes effectively, making it particularly suitable for high-demand environments. The proposed approach maximizes bandwidth utilization by preventing bottlenecks and optimizing data flow, which not only enhances the performance but also reduces operational costs by avoiding wasteful bandwidth expenditure shown in figure 8.

These detailed evaluations illustrate why the MST based approach with Computational Geometry consistently outperforms the other considered methods across various crucial metrics. This superiority stems from its advanced algorithmic foundation, which intelligently addresses both theoretical and practical challenges in network design and operation.

CONCLUSION

The framework proposed in this paper effectively addresses the challenges of optimizing wireless sensor networks (WSNs) for edge computing through a novel integration of computational geometric algorithms and a Minimum Spanning Tree (MST)-based routing protocol. This approach markedly enhances the network's ability to adapt to dynamic environments and operational demands, ensuring robust and efficient data handling. The paper's first significant contribution is the utilization of Delaunay Triangulation for the detection and remediation of coverage holes, a pivotal aspect of maintaining data integrity across the network. The geometric precision of this method allows for precise identification of under-covered areas, ensuring no critical data is missed due to gaps in sensor deployment. Following this, the framework employs a dynamic node placement strategy that not only patches these identified coverage holes but does so in a manner that optimizes network connectivity and sensor utility. By using clustering techniques like DBSCAN for the initial grouping of nodes and refining placements through updated Delaunay Triangulation, the framework ensures seamless integration of new nodes while maximizing the coverage area and maintaining the network’s structural integrity. The third key element of the proposed framework is the MST-based adaptive routing protocol, which enhances network longevity and energy efficiency. This algorithm adjusts routing paths in real-time, based on the operational status of nodes, thereby minimizing energy waste and extending the network's operational lifespan. This dynamic adaptation also means that the network can maintain high levels of data transmission fidelity and timeliness, critical for real-time processing in edge computing scenarios. Comparative analyses have demonstrated that this integrated approach significantly outperforms traditional methods like Random Forest and Gaussian network models under specific constraints such as energy efficiency, network longevity, and data reliability. This research has practical implications for industries where real-time data processing and decision-making are critical, showcasing significant advancements over existing methodologies.

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