

Node Localization in Wireless Sensor Networks using Trilateration and Multilateration

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ABSTRACT

Wireless Sensor Networks (WSNs) have become an essential technology for monitoring and collecting environmental and physical data in various application domains such as environmental monitoring, industrial automation, healthcare, military surveillance, and smart systems. One of the most significant challenges in WSNs is accurate node localization, as the usefulness of sensed data largely depends on the precise geographical position of the sensor nodes. In large-scale deployments, sensor nodes are often distributed randomly in inaccessible or hazardous environments, making manual position configuration impractical. Therefore, efficient localization techniques are required to estimate the positions of unknown nodes using a limited number of reference nodes with known coordinates. This project presents a MATLAB-based simulation framework for node localization in Wireless Sensor Networks using Trilateration and Multilateration techniques. The proposed system utilizes pre-stored datasets containing anchor node coordinates and distance measurements between anchor nodes and unknown nodes. Trilateration estimates the position of an unknown node using distance information from at least three anchor nodes, while Multilateration improves localization accuracy by considering multiple reference nodes and minimizing estimation errors. The simulation model developed in MATLAB performs mathematical computations to determine the estimated coordinates of unknown sensor nodes and provides graphical visualization of the localization process. The project also analyzes the effectiveness of both localization methods in terms of accuracy, error tolerance, and computational performance. The results demonstrate that Multilateration generally provides higher localization accuracy compared to Trilateration, especially in the presence of measurement uncertainties. The proposed work highlights the importance of geometric localization techniques in Wireless Sensor Networks and provides a foundation for future research in advanced localization systems using optimization algorithms, hybrid approaches, and machine learning techniques. The developed simulation framework can further be extended for real-time localization applications and performance evaluation in complex WSN environments.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) have emerged as one of the most important technologies in modern communication and sensing systems due to their extensive applications in environmental monitoring, industrial automation, healthcare, military surveillance, precision agriculture, and disaster management. A Wireless Sensor Network consists of a large number of spatially distributed sensor nodes capable of sensing environmental conditions, processing collected information, and communicating wirelessly with other nodes in the network. Each sensor node generally contains four essential components: a sensing unit, a processing unit, a communication module, and a power supply. These sensor nodes collaboratively monitor physical or environmental parameters such as temperature, humidity, pressure, vibration, gas concentration, motion, and light intensity within a specific Region of Interest (ROI). The collected data from sensor nodes is transmitted to a central unit known as the Base Station (BS) or Sink Node, where the information is processed, analyzed, and forwarded to remote systems or cloud platforms for

decision-making and visualization. The effectiveness of a WSN not only depends on the accuracy of sensed data but also on the precise location of the sensor nodes from which the data originates. Without accurate localization information, sensor readings lose practical significance because the system cannot identify the exact geographical position where an event has occurred. Therefore, node localization is considered one of the most critical aspects of Wireless Sensor Networks. In many practical WSN applications, accurate node positioning is essential for meaningful interpretation of data. In environmental monitoring systems, sensors deployed over forests, oceans, or agricultural fields must report their exact positions to analyze spatial variations in environmental conditions. In military surveillance systems, localization helps identify the precise location of detected intrusions or enemy movements. Similarly, in industrial automation, accurate node positioning enables efficient equipment monitoring, fault detection, and maintenance scheduling. Consequently, reliable localization techniques are necessary for ensuring the efficiency, reliability, and usability of Wireless Sensor Networks. One of the major challenges in WSN deployment is the random distribution of sensor nodes in inaccessible or hazardous environments such as disaster zones, mountainous regions, battlefields, or remote terrains. In such cases, manually configuring the position of each node becomes difficult, expensive, and often impossible. To address this issue, localization algorithms are developed to estimate the coordinates of unknown sensor nodes using a few nodes with known positions, commonly referred to as anchor nodes or reference nodes. These algorithms enable self-configuring and autonomous network operations, allowing nodes to determine their own locations after deployment.

Localization techniques in Wireless Sensor Networks are generally classified into two major categories: range-based and range-free methods. Range-based localization techniques estimate node positions using physical measurements such as distance or angle between nodes. These measurements are obtained through methods such as Received Signal Strength Indicator (RSSI), Time of Arrival (ToA), Time Difference of Arrival (TDoA), and Angle of Arrival (AoA). In contrast, range-free localization techniques estimate positions without direct distance measurements and rely mainly on connectivity information, hop counts, or neighborhood relationships between nodes. Among the range-based localization methods, Trilateration and Multilateration are widely recognized geometric approaches for estimating unknown node positions. Trilateration determines the location of a node using distance information from at least three anchor nodes with known coordinates. Geometrically, the unknown position is calculated as the intersection point of three circles in two-dimensional space or spheres in three-dimensional space. Multilateration extends this principle by utilizing more than three anchor nodes to improve localization accuracy and reduce estimation errors caused by noise or uncertainty in measurements. These methods form the foundation of many modern positioning systems, including GPS and indoor localization systems. The concept of Wireless Sensor Networks evolved from advancements in wireless communication, sensing technologies, and microelectronics during the late 1990s and early 2000s. Initial research in WSNs was primarily motivated by military applications such as battlefield monitoring and surveillance. Projects like Smart Dust, developed at the University of California, Berkeley, introduced the idea of tiny autonomous sensor nodes capable of wireless communication and environmental sensing. As technology advanced, WSN applications expanded into healthcare, industrial systems, smart homes, environmental monitoring, and Internet of Things (IoT) applications. During the early stages of WSN development, Global Positioning System (GPS) modules were used for node localization. However, GPS-based solutions were unsuitable for large-scale deployments because of high cost, increased power consumption, and limited performance in indoor or obstructed environments. This limitation encouraged researchers to develop algorithmic localization methods such as Trilateration and Multilateration, which estimate node positions mathematically using inter-node distances and geometric computations. The simulation model in this project uses pre-stored dataset values that include anchor node coordinates and measured distances between anchor nodes and unknown nodes. Based on these parameters, the MATLAB system calculates the estimated positions of unknown nodes and visualizes the localization process through graphical representations. Since the implementation uses stored datasets instead of real-time sensor readings, the project represents a

simulation-oriented localization framework rather than a real-time hardware deployment. The importance of this project lies in demonstrating how fundamental geometric principles can be effectively applied to solve localization problems in Wireless Sensor Networks. The implementation of Trilateration and Multilateration provides a clear understanding of the relationship between inter-node distances and spatial coordinates, enabling accurate estimation of unknown node positions. Furthermore, the project serves as a foundational framework for future research in advanced localization techniques involving optimization methods, machine learning algorithms, and hybrid localization models.

The main objectives of this project are to study the architecture and working principles of Wireless Sensor Networks, implement Trilateration and Multilateration algorithms for node localization, develop a MATLAB-based simulation framework using stored datasets, analyze the localization accuracy and computational performance of both methods, and visualize the localization process through graphical representations. Additionally, the project aims to provide insights into future improvements and advanced research opportunities in WSN localization systems.

II. LITERATURE SURVEY

Wireless Sensor Network (WSN) localization has gained significant attention in recent years due to its importance in applications such as environmental monitoring, industrial automation, military surveillance, healthcare, and smart city systems. Accurate localization of sensor nodes is essential because the usefulness of sensed data depends on the precise geographical position of the node generating the information. Since manual node configuration and GPS-based positioning are costly and impractical for large-scale deployments, researchers have developed various algorithmic localization techniques to improve accuracy, reduce computational complexity, and minimize energy consumption. Several studies have focused on range-based localization methods such as Trilateration and Multilateration. Abdelhady Naguib proposed a multilateration-based localization framework using the NS-2 simulator and compared atomic and iterative multilateration approaches. The study concluded that multilateration provides higher localization accuracy than trilateration by utilizing multiple anchor nodes and reducing localization error. Similarly, Akhigbe- Mudu developed a multilateration technique for Doppler shift sensor networks, introducing correction factors and Geometric Reference Triangulation (GRT) to improve positioning accuracy while maintaining low computational cost. Research on RSSI-based localization in LoRa networks also demonstrated that multilateration achieves lower localization error compared to trilateration, making it more suitable for large-scale and real-time WSN applications.

Researchers have also explored different range-based localization techniques such as Received Signal Strength Indicator (RSSI), Time of Arrival (ToA), Time Difference of Arrival (TDoA), and Angle of Arrival (AoA). Oguejiofor et al. proposed an RSSI-based trilateration localization algorithm that achieved high localization precision with low implementation cost, making it suitable for static and small-scale WSN deployments. Other studies highlighted that ToA and TDoA methods provide higher localization accuracy but require strict synchronization and additional hardware support. AoA-based techniques offer accurate positioning with fewer anchor nodes but are sensitive to environmental interference and multipath effects.

In addition to range-based methods, range-free and hybrid localization techniques have been widely investigated. Range-free approaches such as Centroid Localization, DV-Hop, and APIT estimate node positions using connectivity information and hop counts rather than physical distance measurements. These methods are more energy-efficient and cost-effective but generally provide lower localization accuracy. To overcome these limitations, modern research has focused

on hybrid localization approaches that combine geometric techniques with optimization algorithms and machine learning models. Suresh Sankaranarayanan et al. introduced a hybrid localization method combining the Crow Search Algorithm (CSA) with Weighted Centroid Localization (WCL), resulting in reduced localization error and improved energy efficiency. Recent studies indicate that optimization-based and intelligent localization systems are highly effective for improving scalability, robustness, and positioning accuracy in dynamic Wireless Sensor Network environments.

III. SYSTEM DEVELOPMENT

3.1 System Overview

The proposed system is designed to simulate node localization in a Wireless Sensor Network (WSN) using MATLAB. The main objective of the system is to estimate the coordinates of unknown sensor nodes using the measured distances from anchor nodes with known positions. Localization is an important process in WSNs because sensor data becomes useful only when the exact physical location of the sensor node is identified. In the proposed system, anchor nodes are deployed with predefined coordinates, while unknown nodes are randomly placed within the sensing area. The distances between anchor nodes and unknown nodes are either generated synthetically or taken from stored datasets. Using these distance values, the system applies Trilateration and Multilateration algorithms to estimate the positions of unknown nodes. MATLAB is used for simulation, mathematical computation, and graphical visualization. The system also evaluates localization accuracy, computation efficiency, and the effect of anchor density on overall performance.

Components of the System

The proposed localization system consists of the following major components:

1. **Anchor Nodes** - Anchor nodes are sensor nodes with known coordinates. These nodes act as reference points for estimating the position of unknown nodes. The localization accuracy depends on the number and placement of anchor nodes.
2. **Unknown Nodes** - Unknown nodes are randomly deployed sensor nodes whose positions are not known initially. Their coordinates are estimated using distance information from anchor nodes.
3. **Distance Data** - Distance measurements between anchor nodes and unknown nodes are used as input for localization. In this project, the distance values are generated using datasets for simulation purposes.

The Euclidean distance formula is used for distance calculation:

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$$

System Functionality

The system estimates unknown node positions using geometric localization techniques.

Network Initialization - A two-dimensional network area is created in MATLAB where anchor nodes and unknown nodes are deployed.

Localization Process -

- Trilateration is used when three anchor nodes are available.
- Multilateration is used when four or more anchor nodes are available for improved accuracy.

Position Estimation - The system calculates the estimated coordinates of unknown nodes based on distance measurements.

Visualization -

MATLAB graphical tools are used to display:

- Anchor nodes
- Unknown nodes
- Estimated positions
- Network topology

3.2 MATLAB Implementation

Trilateration Implementation - Trilateration estimates the position of an unknown node using three anchor nodes. Each anchor forms a circular region, and the intersection point of the circles represents the estimated position of the unknown node. MATLAB performs the geometric calculations required for coordinate estimation. Multilateration improves localization accuracy by using four or more anchor nodes. The method applies least squares optimization to minimize localization error and determine the best estimated position. This method provides higher accuracy compared to Trilateration, especially when measurement noise is present.

Visualization of Results

MATLAB visualization tools are used to plot:

- Anchor node positions
- Actual unknown node positions
- Estimated node positions

Different markers and colors are used for easy interpretation of localization results.

3.3 Performance Evaluation

Localization Accuracy - Localization accuracy is measured by comparing estimated coordinates with actual node positions. Lower localization error indicates better performance.

The localization error is calculated using:

$$LE = \sqrt{(x_{true} - x_{est})^2 + (y_{true} - y_{est})^2}$$

Computation Efficiency - Computation efficiency measures the time required by the localization algorithms.

- Trilateration requires less computation time.

- Multilateration requires slightly higher computation due to optimization calculations.

Effect of Anchor Density -Increasing the number of anchor nodes improves localization accuracy but also increases computation complexity. The system analyzes the impact of anchor density on localization performance.

3.4 Tools and Technologies

Software - The project is implemented using MATLAB software for simulation, computation, and visualization.

Programming Language - MATLAB scripting language (.m files) is used for implementing localization algorithms.

Input Data - The input data includes:

- Anchor node coordinates
- Distance measurements

Output Data - The output generated by the system includes:

- Estimated coordinates
- Localization error
- Graphical visualization plots

3.5 Algorithms

Algorithm 1: Trilateration

1. Initialize the WSN environment in MATLAB.
2. Input coordinates of three anchor nodes.
3. Input measured distances.
4. Calculate circle intersections.
5. Estimate unknown node coordinates.
6. Display results and localization error.

Algorithm 2: Multilateration

1. Initialize the WSN simulation.
2. Input coordinates of multiple anchor nodes.
3. Input distance measurements.
4. Apply least squares optimization.
5. Estimate unknown node coordinates.
6. Display localization results and performance analysis.

IV. RESULTS

The proposed Wireless Sensor Network (WSN) localization system was successfully implemented and simulated in MATLAB using both Trilateration and Multilateration techniques. The simulation results demonstrate the effectiveness of geometric localization methods in estimating

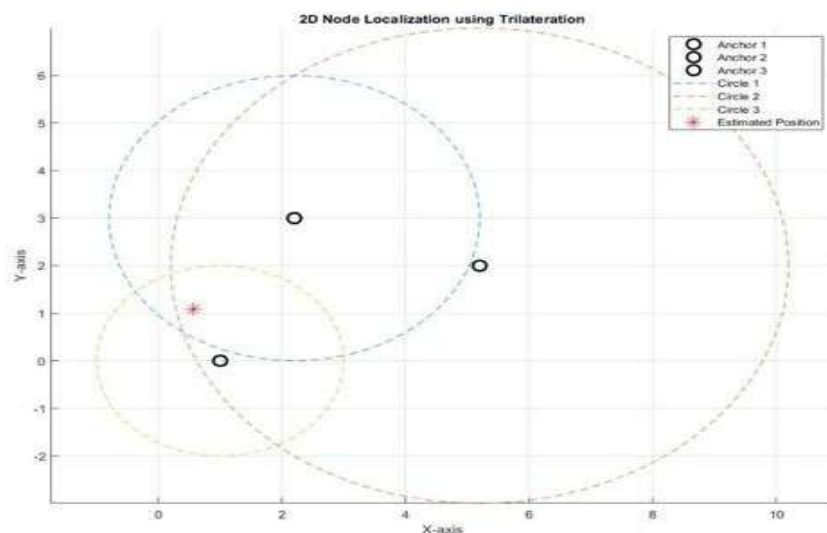
the coordinates of unknown sensor nodes using anchor node information and distance measurements.

Trilateration Result Analysis - The first simulation was performed using the Trilateration technique, where three anchor nodes were used to estimate the position of a single unknown node. In this method, each anchor node generated a circular region centered at its known coordinates, with the radius equal to the measured distance between the anchor and the unknown node. The MATLAB visualization shows that the three circles intersect near a common region, and the estimated node position is represented by the red marker. The obtained result confirms that trilateration can successfully determine the approximate coordinates of the unknown node using only three reference anchors. The graphical output also demonstrates the geometric behavior of localization. Small deviations among circle intersections indicate the presence of minor estimation errors, which commonly occur due to imperfect distance measurements or limited anchor coverage. Despite these deviations, the estimated position remains reasonably close to the actual node location.

The trilateration approach provides:

- Simple mathematical implementation
- Faster computation time
- Acceptable localization accuracy for small-scale networks

However, because only three anchors are considered, the localization accuracy is comparatively lower when measurement noise or irregular anchor placement exists.

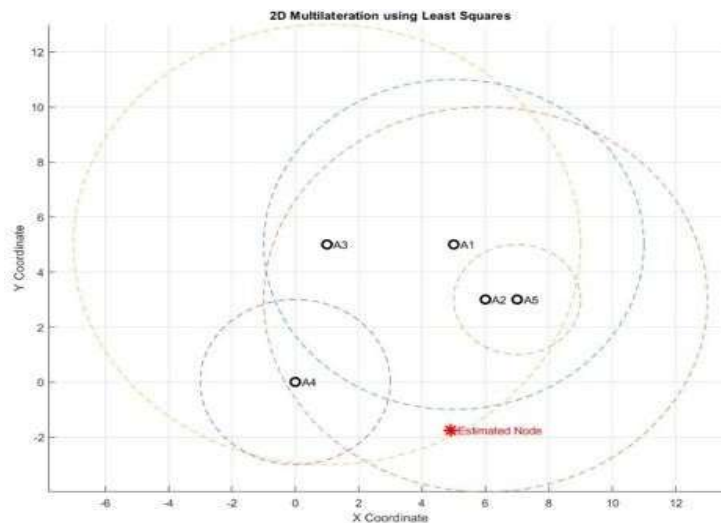


Multilateration Result Analysis - The second simulation implemented the Multilateration technique using five anchor nodes. Unlike trilateration, multilateration considers multiple anchor references simultaneously and applies a Least Squares Optimization method to minimize the cumulative localization error. The MATLAB plot illustrates multiple circular distance boundaries corresponding to different anchors. Since all circles do not intersect perfectly at one point, the optimization algorithm computes the best possible coordinate estimate that minimizes the total distance mismatch. The estimated node position obtained through multilateration is shown by the red marker in the graph. Compared to trilateration, the estimated position is more stable and mathematically optimized because additional anchor information improves the reliability of localization.

The results indicate that multilateration offers:

- Higher localization accuracy
- Better resistance to measurement noise
- Improved estimation stability
- Greater robustness in irregular network environments

The use of additional anchors significantly enhances coordinate estimation, especially in dense wireless sensor deployments.

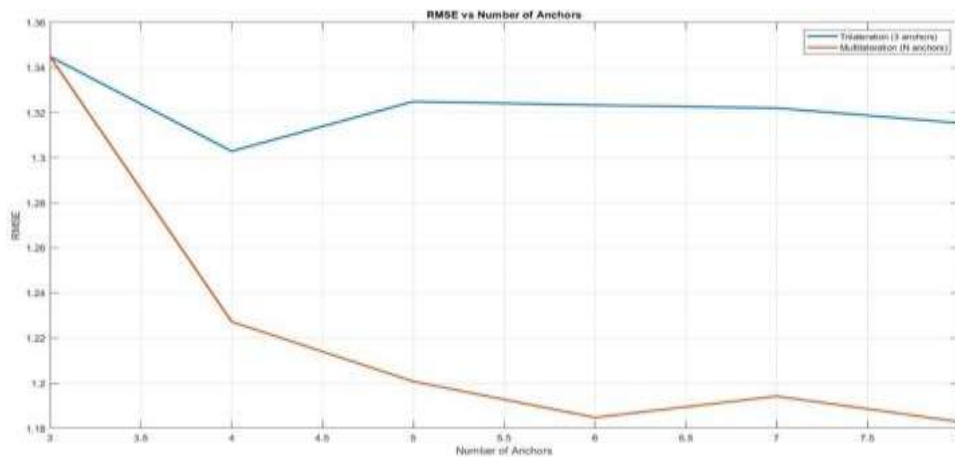


RMSE Performance Analysis - To evaluate the performance of both localization methods, Root Mean Square Error (RMSE) analysis was performed by varying the number of anchor nodes from 3 to 8. The generated graph clearly shows the relationship between anchor density and localization accuracy.

Observations from the RMSE Graph:

1. When only 3 anchors are used, both Trilateration and Multilateration exhibit nearly similar RMSE values, approximately 1.34.
2. As the number of anchors increases, the RMSE of Multilateration decreases significantly.
3. The minimum RMSE for Multilateration is observed near 8 anchors, reaching approximately 1.18.
4. Trilateration maintains relatively stable RMSE values around 1.30–1.32 because it fundamentally relies on only three anchors for computation.
5. Multilateration consistently outperforms Trilateration in terms of localization accuracy as anchor density increases.

The graph confirms that increasing the number of anchors improves localization precision because additional geometric constraints reduce uncertainty in coordinate estimation.



Effect of Anchor Density - The simulation results strongly indicate that anchor density has a direct impact on localization performance.

- With fewer anchors, the system has limited geometric reference information, resulting in higher localization errors.
- As more anchor nodes are introduced, the localization algorithm gains additional reference points, enabling more precise coordinate estimation.
- Multilateration benefits greatly from higher anchor density because the optimization process uses redundant measurements to reduce overall estimation error.

However, increasing the number of anchors also slightly increases computational complexity due to additional mathematical operations and optimization calculations. Therefore, a balance between accuracy and computational efficiency must be maintained in practical WSN deployments. Therefore, the proposed system demonstrates that multilateration-based localization is more efficient and accurate for practical WSN applications, particularly in environments where high precision and robustness are required.

V. CONCLUSION

The study and analysis presented in this Phase-1 report focused on the conceptual understanding and system design of node localization in Wireless Sensor Networks (WSNs) using Trilateration and Multilateration techniques. Localization is an essential aspect of WSNs because the usefulness of sensed data depends on the accurate determination of sensor node positions. Without proper localization, monitoring and tracking applications cannot provide meaningful results. During this phase, a detailed literature survey was conducted to study different localization techniques, including range-based, range-free, and hybrid approaches. The survey indicated that geometric localization methods such as Trilateration and Multilateration provide a good balance between localization accuracy, computational efficiency, and implementation simplicity. These techniques are highly suitable for small and medium-scale Wireless Sensor Network applications. Based on the theoretical study, a MATLAB-based simulation framework was proposed for node localization. The system design includes anchor nodes with known coordinates, unknown nodes requiring localization, and distance measurements used for position estimation. Trilateration is used for basic geometric localization, while Multilateration improves localization accuracy using multiple anchor nodes and optimization methods. Performance evaluation parameters such as Localization Error, Computation Time, and Anchor Density were also identified for analyzing system efficiency. Although this phase mainly focused on theoretical analysis and system planning, the developed methodology and simulation structure provide a strong foundation for future implementation. The mathematical models, workflow design, and algorithmic approaches

have been clearly defined for the next phase of the project. Therefore, the Phase-1 work successfully establishes the conceptual and methodological base for developing an efficient Wireless Sensor Network localization system using MATLAB simulation.

VI. REFERENCES

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