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Title

Collaborative technique for wireless sensor network localization

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This thesis is dedicated to *my family, encompassing both the living and the deceased, as well as to my friends, for their unwavering support throughout my academic journey.*

Abstract

The thesis explores sensor networks, focusing on distributed algorithms for localization challenges. It addresses the need to determine node positions after random deployment, crucial for event localization. The proposed solution involves employing a mobile anchor with GPS units, moving within the area of interest, periodically broadcasting its location to assist unknown nodes in self-localization. A novel path planning model for mobile-based localization in WSNs is introduced, incorporating beacon points from five established paths (SCAN, HILBERT, S-type, Z-curve, and Îĉ-Scan) on the widely used square grid decomposition. Unknown sensor nodes estimate positions using APT and WCWCL-RSSI techniques. The simulation results demonstrate that the proposed model achieves exceptional accuracy, leading to a significant reduction in error rates when compared to alternative models. Moreover, it ensures maximum coverage with a lower path resolution value, indicating its effectiveness in optimizing localization outcomes. The thesis underscores the impact and importance of path parameterization in enhancing the quality of a localization system with a mobile anchor node.

Keywords: *Localization ;Mobile anchor; Path planning model; Wireless sensor network; Square grid decomposition; Beacon points*

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Praise be to God, by whose grace good deeds are accomplished, great praise, as befits the majesty of His face and the greatness of His power.

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I also dedicate this thesis to the souls of my dear sisters, Fouzia and Salima, whose memories will remain engraved in my heart. They were the best supports; may God have mercy on them.

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To my dear friends, my childhood companions, I send all my love and appreciation

ملخص

تستكشف هذه الرسالة مسألة تحديد الموقع في شبكات الاستشعار اللاسلكية باستخدام الخوارزميات الموزعة. بعد النشر العشوائي للمستشعرات هنالك حاجة ماسة لمعرفة موقعها وخاصة من أجل معرفة مكان الأحداث. نقترح استخدام مستشعر خاص يكون متحركاً و مزوداً بوحدة GPS، يسمى مرساة، تتحرك المرساة داخل منطقة الاهتمام وفق مسار معد مسبقاً وتبث موقعها بانتظام لمساعدة المستشعرات غير معرفة الموقع في التحديد الذاتي لإحداثياتها. تقوم المستشعرات الغير معرفة الموقع بتقدير إحداثياتها باستخدام تقنيات APT و WCWCL-RSSI. السؤال الذي حاولنا الإجابة عليه في هذه الرسالة هو ما هو أحسن مسار يمكن أن تسلكه المرساة. قمنا في البداية باقتراح مجموعة من المعايير التي تسمح لنا بقياس جودة المسار. قمنا كذلك بدراسة و تحليل خمسة مسارات معتمدة على تقسيم منطقة الاهتمام الى مربعات : Σ -Scan, Z-curve, S-type, SCAN HILBERT. اقترحنا في النهاية مساراً جديداً سميناه Union-curve الذي يجمع جميع نقاط البث للمسارات الخمسة السابقة. تظهر نتائج محاكاة النموذج المقترح أنه يحقق دقة استثنائية، مما يؤدي إلى تقليل كبير في معدلات الخطأ مقارنة بالنماذج البديلة، علاوة على ذلك، يضمن تغطية كاملة مع دقة مسار أقل.

كلمات مفتاحية: تحديد الموقع؛ مرساة متحركة؛ نموذج تخطيط مسار؛ شبكة الاستشعار اللاسلكية؛ تقسيم الشبكة المربعة؛ نقاط البث

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List of Abbreviations and Symbols

Abbreviations

WSN	Wireless Sensor Network
ROI	region of interest
APT	Accuracy-Priority Trilateration
RSSI	Received Signal Strength Indicator
WCL	Weighted Centroid Localization algorithm
WCWCLRSSI	Weight-Compensated Weighted Centroid Localization Based on RSSI
LNSM	Log-Normal Shadowing Model
TDoA	Time Difference of Arrival
ToA	Time of Arrival
AoA	Angle of Arrival

CHAPTER 1

Introduction

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1.1 Background

In research, analysis, observation, and the control of physical phenomena, real-time data collection is essential. This task is performed by sensors, which play a crucial role in acquiring information about observed phenomena. Recent technological advancements, particularly in miniaturization and communication, have led to the development of a new generation of micro-sensors. These affordable devices efficiently integrate sensing, processing, radio communication functionality, and power components [5], transforming measured physical or environmental conditions into output signals for processing or display [6]. Wireless Sensor

Networks (WSNs) consist of strategically deployed sensors across a designated geographical area, referred to as the area of interest. These networks function autonomously, possessing self-configuring and self-managing capabilities, thus eliminating the need for human intervention. Data collected by the sensors are transmitted through wireless multi-hop communications [5], allowing communication from node to node. This data is then relayed to a base station (or sink), serving as the network's entry point responsible for aggregating and exploiting the collected data. The primary objective of WSNs is to establish a system that enables precise remote monitoring and control of the physical environment. WSNs are utilized in various fields, including environmental monitoring, military operations, industrial applications, biodiversity studies, healthcare, and urban management [7, 8].

In WSNs, the identification of information sources and the computation of event locations are essential tasks that impact various network operations, including routing and data broadcasting schemes [9]. The deployment of a large number of sensors is typically random, influenced by factors like the hostility or vastness of the monitored area. This randomness poses challenges for manual sensor localization, contributing to broader issues within WSN localization. Localization, defined as the process of determining the geographical locations of sensor nodes [10], is indispensable not only for network operation in terms of geographical routing but also for effectively exploiting the collected data. The question of "where" immediately arises following an event in the monitored area, underscoring the importance of achieving precise localization for all nodes within the network. Despite extensive research efforts, the challenge of sensor localization in WSNs remains an open problem. Hardware solutions such as the Global Positioning System (GPS) for lo-

calization are often cost-prohibitive. Consequently, various localization algorithms have been developed over the last decade to address this challenge. These algorithms leverage a set of statically deployed nodes called landmarks or anchors, possessing known coordinates, to transmit their coordinates to other unknown sensors and assist them in self-localization. The use of GPS-equipped nodes as anchors is a common approach in these algorithms [11–17].

A promising approach involves utilizing mobile anchor nodes equipped with GPS units, replacing fixed landmarks to provide unknown sensor nodes with their locations. This concept, explored in recent literature on mobile anchor node-based localization algorithms in WSNs [18, 19].

Mobile anchor-based localization offers several advantages over other techniques in WSNs:

- **Improved Accuracy:** Achieves higher accuracy using mobile anchor nodes with known positions.
- **Cost-Effective:** More cost-effective than deploying multiple static anchor nodes.
- **Adaptability:** Adapts to changes in network topology and environmental conditions using path planning algorithms.
- **Efficiency:** Reduces the number of exchanged packets between nodes, minimizing computational load.
- **Flexibility:** Applicable in various WSN applications, including target tracking, environmental monitoring, and disaster response.

Selecting the optimal path model for mobile anchors is a critical aspect of mobile anchor-based localization in WSN [20]. The literature presents various path models, and conducting a comparative analysis can assist in choosing the most suitable one for a specific application with its specified criteria [21]. The objective is to determine the best trajectory for mobile anchors, achieving high accuracy and comprehensive coverage in Wireless Sensor Networks. Identifying an optimal path for mobile anchors poses a complex problem. The authors of the paper [22] were the first to highlight this issue, initiating a discussion without providing a specific solution. In [4], path planning is categorized into static and dynamic classifications. This work specifically focuses on static paths, encompassing SCAN [9], HILBERT [9], Z-curve [23], Σ -Scan [24], and S-type [25].

1.2 Objectives

The optimization of path planning for mobile anchor-based localization in WSNs encompasses the following objectives:

1. The trajectory should pass as close as possible to numerous node positions to locate a maximum number of unknown nodes.
2. The trajectory must be designed in a manner that fully covers all possible unknown nodes, ensuring a singular estimation of their positions.
3. The trajectory should be as short as possible to conserve the energy consumption of mobile anchors and minimize localization time.
4. The movement of the mobile anchor should be carefully planned to maximize the number of beacon points, thereby enhancing location accuracy.

1.3 Contribution

To achieve the previously mentioned objectives, this thesis aims to contribute to this area of research by proposing a path planning model for mobile anchor-based localization. These contributions are summarized as follows:

1. Examines well-established trajectories in the literature that rely on area decomposition into squares, considering beacon points (broadcast points).
2. We propose an enhanced path planning model called Union-curve. This model integrates all beacon points from five previously developed paths: SCAN, HILBERT, S-type, Z-curve, and Σ -Scan, on the commonly used square grid decomposition of the area. To assess and validate the efficacy of the proposed model, five crucial analysis metrics are employed. The evaluation includes the calculation of unknown node positions using two localization techniques: APT (range-based) and WCWCL-RSSI (range-free). Simulation results indicate that the proposed model exhibits higher accuracy, demonstrating a significant difference in error rate compared to other models.
3. We investigate the impact of essential parameters on the performance metrics of path planning models for mobile anchor-based localization. This study aims to aid in configuring the localization system for improved results.

Consequently, parts of this thesis have been published in the following publications:

- Boukhari, Nawel, Salim Bouamama, and Adel Moussaoui. "Path Parameters Effect on Localization Using a Mobile Anchor in WSN." International

Journal of Informatics and Applied Mathematics 3.2 (2020): 12-22.

- Boukhari, Nawel, and Salim Bouamama. "Square grid Path Planning for Mobile Anchor-Based Localization in Wireless Sensor Networks." Computer Science 24.4 (2023).

1.4 Thesis Organization

This thesis is structured into five chapters, outlined as follows:

- **Chapter 2: Wireless Sensor Networks: Overview:** This chapter provides an overview of the expansive field of sensor networks. It covers various concepts related to sensor network implementation, explores its characteristics, diverse application areas, and outlines the primary research issues in sensor networks.
- **Chapter 3: Localization in WSNs: Motivation and Background:** addresses the issue of localization in sensor networks. It delves into various existing methods for determining the positions of nodes, introducing an approach centered around the utilization of a mobile anchor.
- **Chapter 4: Proposed approach: Union-curve algorithm for mobile anchor-based localization:** We present an innovative path planning model for mobile anchor-based localization in Wireless Sensor Networks called Union-curve. The main contribution is the development of a competitive path planning model, which outperforms earlier approaches in terms of performance.

- **Chapter 5: Performance Evaluation and Simulation Results:** We study the effect of path parameters on localization and evaluate the Union-curve model's performance using five analysis criteria. The Union Curve represents a static path planning model that yields lower localization error and a higher localization ratio compared to certain static path planning models.
- **Chapter 6: Conclusions and Future Works:** The thesis concludes with a summary of its contributions and explores potential future directions for research.

CHAPTER 2

Wireless Sensor Networks: Overview

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2.1 Introduction

This chapter presents a thorough literature review on WSNs, offering a comprehensive overview of existing literature. It encompasses various aspects, including WSNs architecture, topology, characteristics, constraints, applications, and research challenges. Furthermore, as illustrated in the Figure figure 2.1, this chapter provides an overview to improve understanding of its subsequent chapter on localization in WSNs, which includes mobile-based localization.

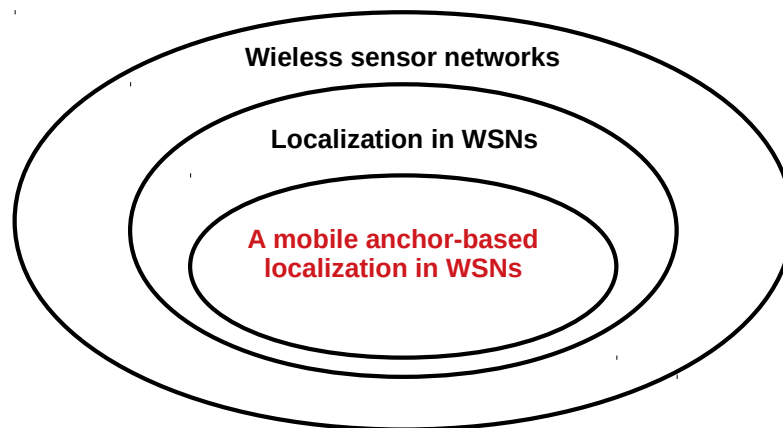


Figure 2.1: Hierarchy of literature review.

2.2 What is WSNs ?

The evolution of computer science has been characterized by various stages of miniaturization. In recent times, highly compact micro-electromechanical systems have emerged as affordable devices that integrate sensing, processing, radio

communication functionality, and power components [5]. These devices are deployed in significant numbers within a specific geographic area known as the ROI, forming a sensor network that enables enhanced precision in remote monitoring and control of the physical environment. They transfer measured physical or environmental conditions such as temperature, sound, vibration, pressure, or even luminosity into an output signal that can be processed or displayed [6]. WSNs are comprised of thousands of sensor nodes. They offer an intriguing perspective, that of networks capable of self-configuration and self-management without requiring human intervention.

2.3 The sensor node

A sensor is a device or module that detects and responds to physical or environmental changes, converting them by a transducer into measurable signals or data [26] as show in Figure 2.2. Sensors have the ability to detect a wide range of physical quantities, such as temperature, pressure, humidity, light intensity, motion, proximity, sound, gas concentration, bacteria, proteins, and more [27]. They are designed to measure specific properties or phenomena and are often specialized for particular applications. There exists a variety of sensor types, including optical sensors, pressure sensors, temperature sensors, proximity sensors, accelerometers, gyroscopes, and many others. Each type of sensor operates on different principles and technologies to detect and measure specific physical quantities.

The main advantages of sensor nodes are their small size as depicted in Figure 2.3, very low power consumption, and especially their ability to communicate

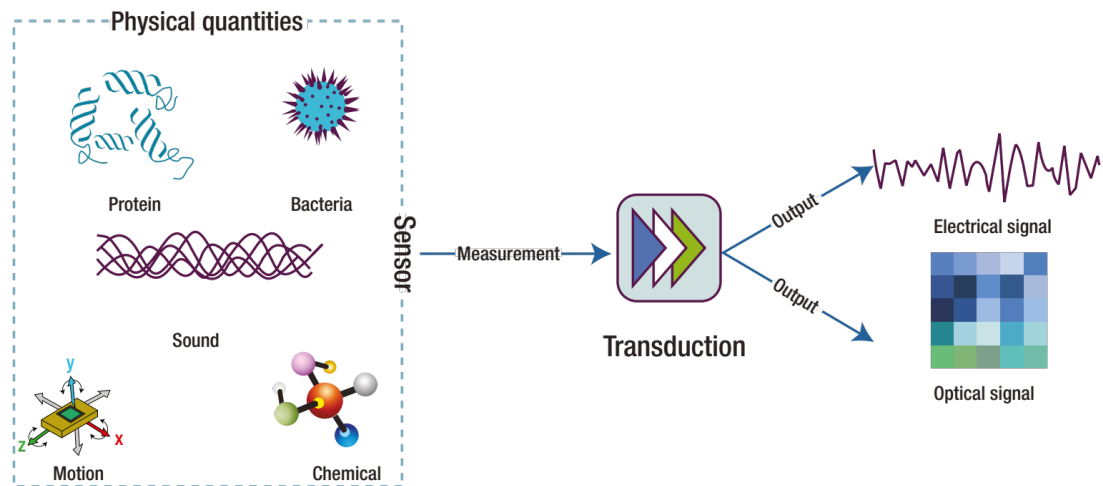


Figure 2.2: The process of sensing.

wirelessly. Sensor nodes have hardware and software components.

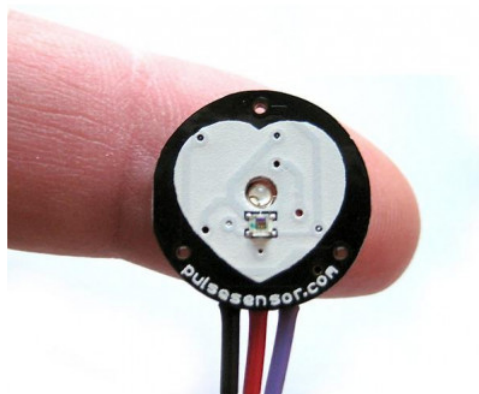


Figure 2.3: Example of a sensor.

The hardware components of a sensor can vary depending on the specific type and application. However, as depicted in Figure 2.4, a typical sensor may consist of the following components:

- 1) Sensing Element: This is the core component of the sensor that directly interacts with the physical phenomenon being measured. It could be a material,

device, or mechanism that undergoes changes in response to the environmental parameter being sensed, such as temperature, pressure, or light.

- 2) **Transducer:** The transducer is responsible for converting the physical changes detected by the sensing element into an electrical signal or another form of measurable output. It can be based on various principles, such as resistive, capacitive, inductive, piezoelectric, or optical.
- 3) **Signal Conditioning Circuitry:** The signal conditioning circuitry processes and amplifies the electrical signal from the transducer to make it suitable for further processing or analysis. It may include components such as amplifiers, filters, and analog-to-digital converters.
- 4) **Power Supply:** Sensors require a power source to operate. This can be in the form of batteries, external power supplies, or energy harvesting systems that convert ambient energy (such as light or vibration) into electrical power.
- 5) **Output Interface:** The output interface allows the sensor to communicate its measured data or signals to external devices or systems. It can be in various formats, including analog voltage, digital signals, or wireless communication protocols.
- 6) **Control and Processing Unit:** In some advanced sensors, there may be a control and processing unit that handles tasks such as calibration, data processing, and decision-making based on the sensor's inputs and programmed algorithms.

It's important to note that these components can vary significantly depending on the specific sensor and its application. Some sensors may have additional compo-

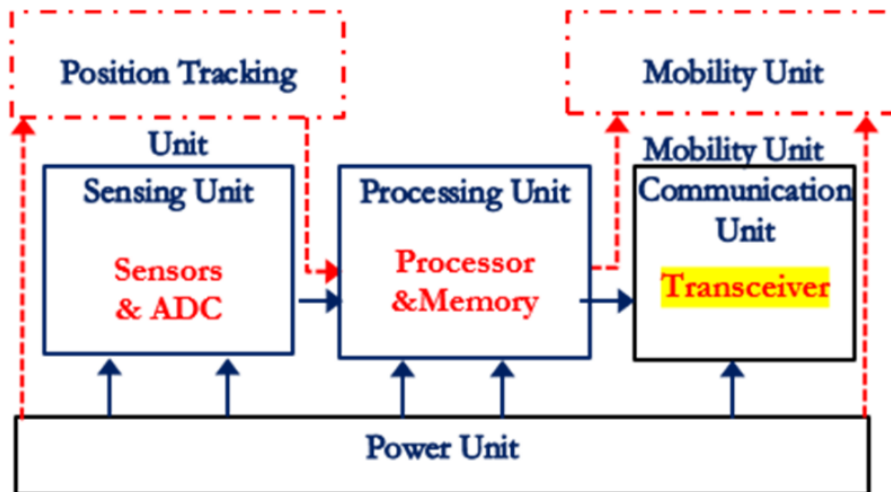


Figure 2.4: The hardware components of a sensor.

ponents, such as memory for data storage, onboard microcontrollers for local processing, a localization system (GPS: Global Positioning System, which is a globally functioning geolocation system based on the exploitation of radio signals emitted by dedicated satellites) or specialized components for specific functionalities.

The software components of a sensor can vary depending on the specific application and system architecture. However, some common software components found in sensor systems include:

- 1) Operating systems for sensors are typically lightweight and optimized to run on devices with limited resources. These operating systems are specifically designed to manage hardware resources, schedule tasks, and handle communication protocols. Some examples of such operating systems include TinyOS, Contiki, MantisOS, as well as other proprietary or custom operating systems[28].
- 2) Programming language: Sensors often use specific programming languages

tailored for efficient resource management and low-power operation, such as NesC for TinyOS or C for Contiki [29].

- 3) Device drivers: are software components that enable the sensor to interact with and control its hardware components. They provide an interface between the operating system and the specific sensors, enabling the software to communicate with and utilize the sensor's capabilities.
- 4) Sensor APIs: Application Programming Interfaces (APIs) provide a set of software functions and protocols that allow developers to interact with the sensor's functionalities. These APIs provide a standardized way to access and control the sensor's data acquisition, processing, and communication capabilities.
- 5) Communication Protocols: Sensors often need to communicate with other devices or systems, either directly or through a network. Various communication protocols, such as Bluetooth, Wi-Fi, Zigbee, or LoRaWAN, can be utilized depending on the requirements of the application.
- 6) Data Processing and Analysis: Sensors may incorporate software components for data processing and analysis. This can include algorithms for filtering, aggregating, or analyzing the collected sensor data to extract meaningful information or detect specific events or patterns.
- 7) Firmware and Over-the-Air Updates: Sensors often require firmware, which is low-level software embedded in the sensor's hardware. Firmware is responsible for booting the device, managing its operations, and providing essential functionalities. Additionally, over-the-air update mechanisms allow remote

updating of the sensor's software or firmware to introduce bug fixes, feature enhancements, or security patches.

2.4 The architecture and functionality of WSNs

The architecture of a WSNs typically comprises spatially distributed sensors and one or more sink nodes, also referred to as base stations [30], the following components as show in Figure 2.5:

- 1) Sensor Nodes: Each sensor node is equipped with one or more sensors to collect data from the environment.
- 2) Base Station (Sink Node): The base station, also known as the sink node, acts as a central hub or gateway within the WSNs. It is responsible for collecting, processing, and storing the data received from the sensor nodes [31]. The base station is usually connected to a higher-level network or a data center for further analysis and decision-making. In WSNs, a base station serves as a node with significantly greater computational, energy, and communication capabilities compared to other sensor nodes. Primarily, the base station functions as a pivotal link between sensor nodes and end-users by facilitating the transmission of data from the WSN to a designated server[32].

WSNs utilize wireless communication technologies to enable data transmission between sensor nodes and the base station. Common wireless communication protocols used in WSNs include Zigbee, Bluetooth, Wi-Fi, or custom-designed protocols optimized for low-power and low-data-rate communication. The collected data is

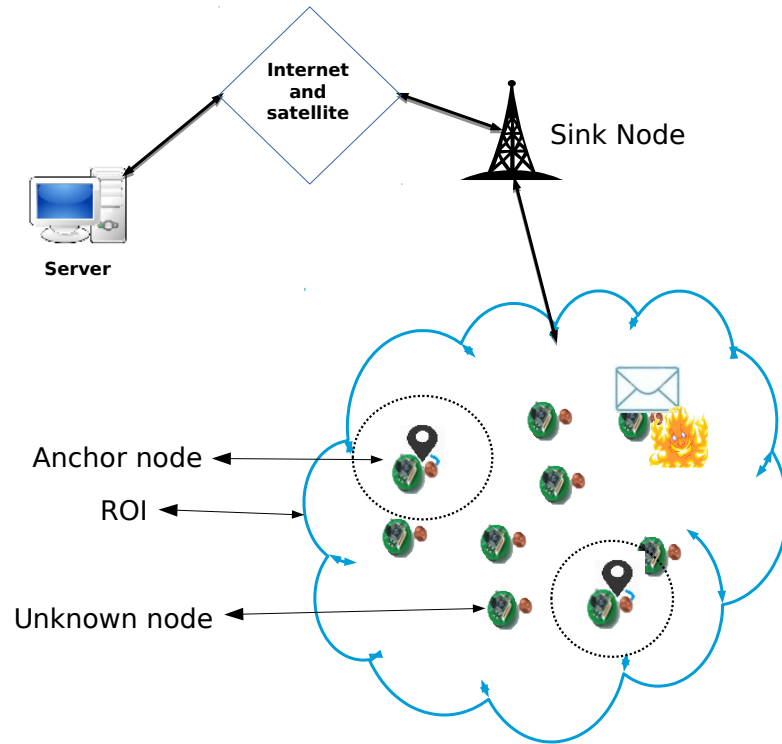


Figure 2.5: Architecture of a sensor network.

transmitted through wireless communications in multiple hops (i.e., from node to node) to a base station (or sink)[5]. A sensor node can directly communicate with its neighbors, those within its communication range, and acts as a router for other nodes. For example, in figure 2.6, node B can relay messages from sensor D to sensor A. In this scenario, the sensor nodes engage in multi-hop communication, where messages are routed through multiple nodes to reach their destination [33].

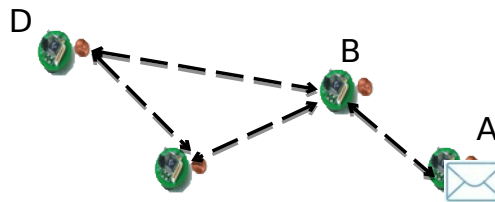


Figure 2.6: Example of multi-hop communication in a sensor network..

Interaction patterns between sensors and sinks play a crucial role in classifying application types in Wireless Sensor Networks (WSNs). There are two main methods

for collecting information:

- **Event-driven data collection:** When an event is detected, such as a temperature change or movement, the node processes the event locally and transmits it to the base station using multi-hop communication (as shown in Figure 2.7).
- **Periodic data collection:** When the sink node needs to obtain the current state of the coverage area, it broadcasts messages, prompting the sensors to send their latest readings back (as shown in Figure 2.8). This information is also transmitted through multi-hop communication.

The optimal interaction pattern depends on several factors, including network topology and size, power consumption constraints, data communication requirements (real-time vs. periodic), and network traffic density.

2.5 The Topology of WSNs

The network topology in a WSNs refers to the arrangement and connectivity of the sensor nodes. WSNs can employ various topologies depending on the specific requirements of the application. they are some commonly used topologies in WSNs [32] as show in figure 2.9:

Bus topology: arranges sensor nodes in a linear fashion, where each node connects to a central shared communication line (like a bus) as illustrated in Figure 2.9. Signals travel in both directions along this bus until they reach their designated recipient node. This approach offers simplicity and ease of installation. However, a key drawback is the presence of a single point of failure: if the

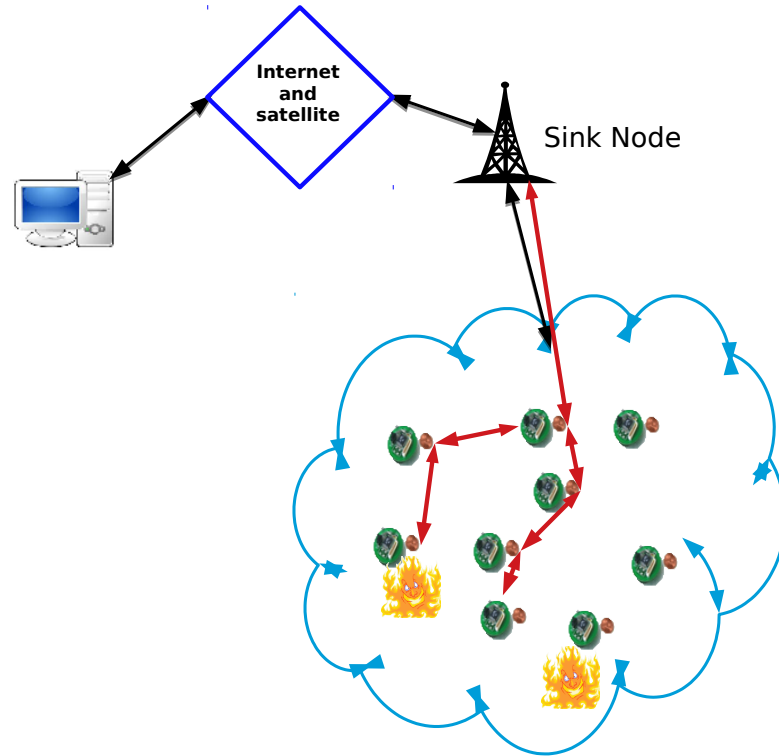


Figure 2.7: Following an event.

central bus malfunctions, the entire network collapses. To prevent data collisions when multiple nodes attempt to transmit simultaneously, bus networks require a mechanism for collision avoidance.

Linear topology: The linear topology features a bidirectional link between adjacent nodes, illustrated in Figure 2.9. At each end of the network, there are two terminating nodes with single connections to nearby nodes, while all other nodes are connected to two other nodes. In this setup, nodes rely on each other to relay messages to the next node. If a node malfunctions, any nodes linked to it become isolated from the network.

Star Topology: In a star topology, all sensor nodes communicate directly with a central base station or sink node. The base station collects data from the sensor nodes, and the nodes do not communicate with each other. This topology offers

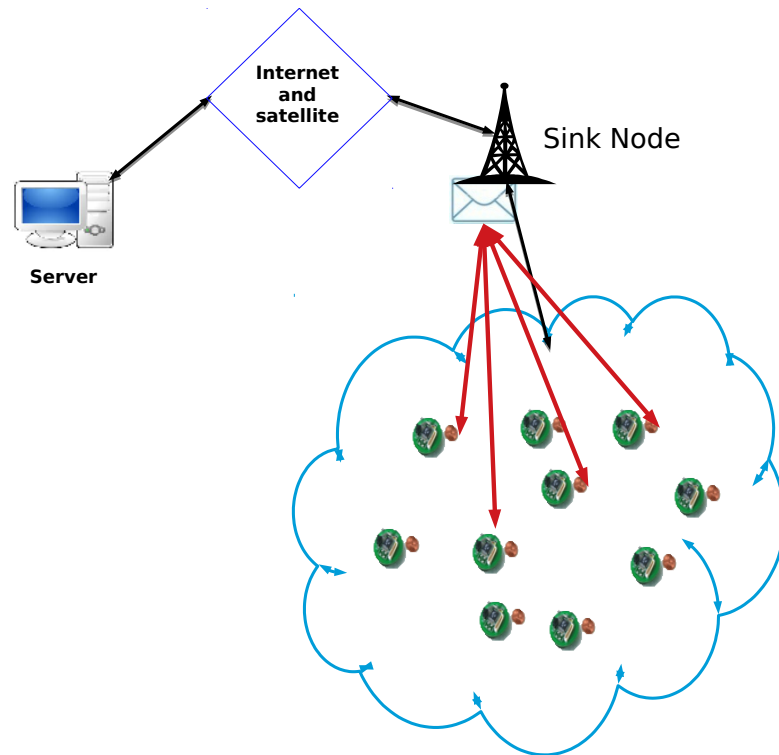


Figure 2.8: Upon request.

simplicity and low power consumption but may have limited coverage range. All data traffic flows through the central node, necessitating the need for an intelligent central node. If this node fails, the entire network will fail. The star network topology is one of the most common sensor network topologies.

Tree Topology: The tree topology represents a hierarchical structure of nodes, with the highest level being a single "root node" connected to one or more nodes in the level below, as illustrated in Figure 2.9. It can comprise multiple levels of nodes. As data traverses from the branches of the tree towards the root node, the processing power in nodes typically increases, enabling data processing closer to its source. This topology offers scalability, and its simple structure facilitates the identification and isolation of faults. However, as tree networks grow larger, they become progressively challenging to manage.

Mesh Topology: In a mesh topology, sensor nodes can communicate directly with multiple neighboring nodes within their radio transmission range. Its advantages include self-healing capabilities, allowing data rerouting in case of node failure, high scalability, and robustness for large and complex deployments. However, managing and routing data in mesh topologies is more complex compared to simpler topologies, leading to higher power consumption due to multi-hop communication.

Hybrid Topology: Hybrid topologies combine multiple topologies, such as star, tree, or mesh, to meet specific requirements. They offer flexibility and can be customized based on the application's needs. For example, a hybrid topology may include clusters of star networks connected in a mesh configuration [34].

2.6 Sensor Network Applications

The concept of WSNs is based on a simple equation [35]: "Sensing + CPU + Radio = Thousands of potential applications"

The decreasing size and cost of micro-sensors, along with the availability of diverse sensor types (thermal, optical, vibrations, etc.) and the use of wireless communication support, have enabled sensor networks to penetrate various application domains. These domains include environment, military [36], industrial, flora and fauna, health[37], and urban applications [?]. Sensor networks can be classified into these six categories [7, 8] based on their specific use and have found numerous applications in each category as show in figure 2.10.

- 1) **Environmental Monitoring:** WSNs are extensively used for monitoring environmental parameters such as temperature, humidity, air quality, water

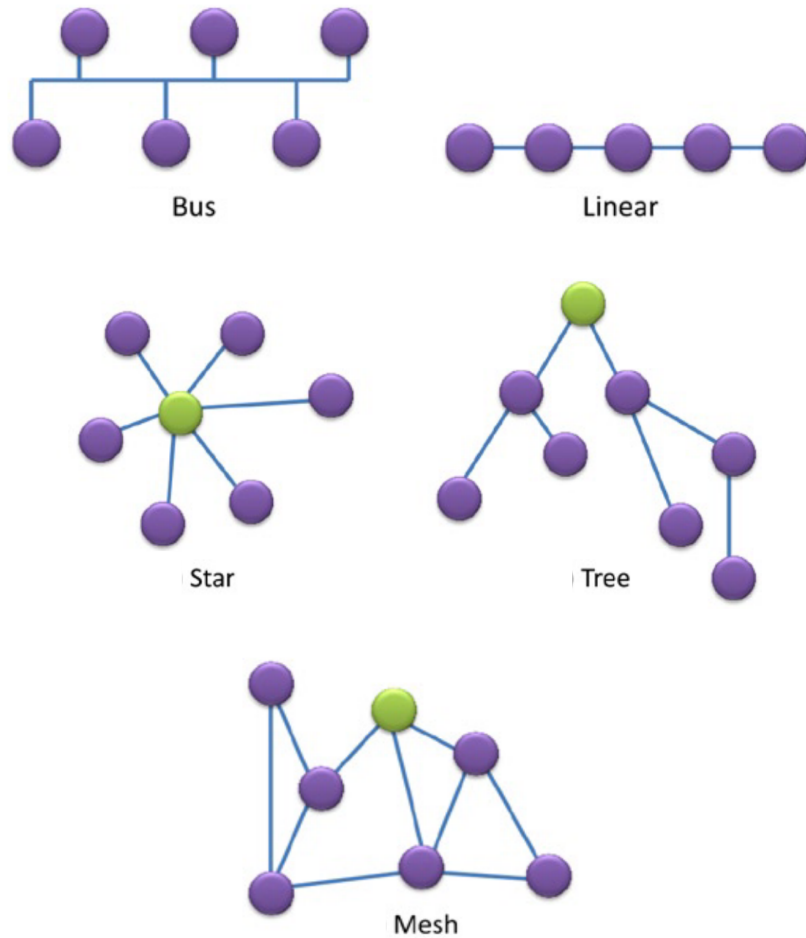


Figure 2.9: topologies of a sensor network.

quality, and soil conditions. These networks help in assessing environmental changes, detecting natural disasters, and managing natural resources. WSNs play a crucial role in safeguarding our environment. They help us monitor various aspects like water and air quality, and even provide early warnings for natural disasters. In [7] dives deeper into these environmental applications, showcasing specific areas like water monitoring, air pollution detection, and emergency alerts. It also details the types of sensors typically used in each of these applications.

2) **Military and Surveillance:** WSNs are integral to military operations,



Figure 2.10: Sensor Network Applications.

significantly bolstering situational awareness, intelligence gathering, and operational effectiveness. Deployed for battlefield surveillance, target tracking, and perimeter security, WSNs offer real-time intelligence, elevate situational awareness, and refine military strategies, thereby enhancing overall operational outcomes.

- 3) **Healthcare Applications:** WSNs revolutionize healthcare by facilitating remote patient monitoring, including tracking vital signs like heart rate, blood pressure, and blood sugar levels. This enables early detection of potential health issues and enhances healthcare management. WSNs also support various healthcare applications such as telemedicine consultations, emergency response systems, and rehabilitation monitoring, empowering both patients and healthcare providers. With their ability to provide real-time data on vital signs, medication adherence, and sleep patterns, WSNs improve patient safety, treatment outcomes, and overall healthcare delivery. Their versatile applications, ranging from remote patient care to wellness moni-

toring, demonstrate their transformative impact on healthcare, promoting access and fostering preventive healthcare practices

- 4) **Industrial Applications:** WSNs are pivotal in industrial operations, facilitating real-time monitoring, predictive maintenance, and enhanced efficiency. These networks are instrumental in asset tracking, predictive maintenance strategies, and environmental monitoring, ensuring regulatory compliance and safe working conditions. Moreover, WSNs streamline supply chain management, automate processes, and optimize energy usage, leading to cost savings and improved productivity. Additionally, they bolster safety and security measures, enable quality control processes, and enhance overall operational effectiveness. Through their multifaceted applications, WSNs revolutionize industrial operations, driving innovation, and sustainable growth.

- 5) **Flora and Fauna Applications:** WSNs play a pivotal role in the monitoring and conservation of flora and fauna, offering a range of applications to safeguard biodiversity and ecosystems. These applications include wildlife tracking, habitat monitoring, species population assessment, and detection of illegal activities like poaching and logging. WSNs also aid in invasive species management, pollution monitoring, and assessing ecosystem resilience to environmental changes. By providing real-time data on environmental variables and species behavior, WSNs empower conservation efforts, enabling timely interventions and informed decision-making for the protection and preservation of natural habitats and wildlife populations.

- 6) **Urban Applications:** WSNs are pivotal in transforming urban environ-

ments, offering solutions to various challenges and enhancing the quality of life for residents. These applications include monitoring smart infrastructure, managing traffic flow, monitoring air and noise pollution, optimizing waste management, and ensuring water quality. Additionally, WSNs contribute to energy efficiency, public safety, and security through real-time monitoring and surveillance systems. By leveraging advanced sensor technologies and real-time data, WSNs play a crucial role in creating smarter, more sustainable, and resilient cities.

2.7 Characteristics and constraints of WSNs

WSNs have several characteristics and constraints that define their operation and limitations. they are some key characteristics and constraints of sensor networks[1, 38]:

Energy Efficiency: Sensor nodes in a network typically operate on limited energy sources such as batteries. Therefore, energy efficiency is a crucial characteristic, and sensor nodes are designed to minimize power consumption in order to maximize network lifetime. After discussing energy efficiency, understanding the concept of clustering is important [39]. Clustering refers to the process of dividing a WSNs into smaller groups called clusters. Each cluster consists of a cluster head (CH) and a set of sensor nodes. The cluster head acts as a local coordinator for the nodes within its cluster. Clustering helps in organizing and managing the network by reducing energy consumption, improving scalability, and facilitating efficient data aggregation and communication within the network. It plays a crucial role in achieving energy efficiency and prolonging the network's overall lifetime.

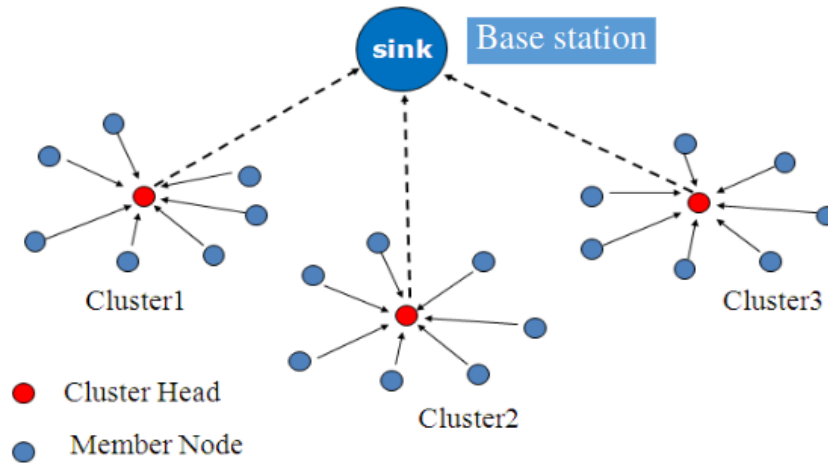


Figure 2.11: Clustering in WSNs[1].

Scalability: WSNs are capable of scaling up to accommodate a large number of sensor nodes. The network should be able to handle the addition or removal of nodes without affecting its overall performance.

Self-Organization: WSNs are designed to self-organize and self-configure. This means that the nodes can autonomously form a network and adapt to changes in the network, such as node failures or additions.

Limited Resources: Sensor nodes have limited resources in terms of processing power, memory, and storage capacity. These constraints necessitate the use of lightweight protocols and algorithms optimized for resource-constrained environments.

Wireless Communication: Sensor nodes communicate with each other wirelessly using radio frequency or other wireless communication technologies. This wireless communication allows for flexible deployment and data exchange between nodes.

Data-centric: WSNs are focused on collecting and transmitting data from the physical environment. The network is designed to efficiently handle data aggrega-

tion, filtering, and routing to ensure effective data transmission and retrieval.

Fault Tolerance: Sensor networks should be able to tolerate node failures or network disruptions. The network should have mechanisms in place to handle node failures and maintain continuous operation.

Security and Privacy: WSNs may transmit sensitive data, making security and privacy concerns essential. The network should employ secure communication protocols and mechanisms to protect the integrity and confidentiality of the data.

Environmental Constraints: Sensor nodes are often deployed in harsh or remote environments, such as outdoor areas or underground. The network design should consider environmental factors such as temperature, humidity, and physical obstacles.

Cost Constraints: WSNs are often deployed on a large scale, requiring cost-effective solutions. The design and implementation of the network should consider cost constraints to ensure practical and affordable deployment.

Distributed sensing and processing: In a WSNs, a large number of sensor nodes are distributed uniformly or randomly. Each node is capable of collecting, sorting, processing, aggregating, and sending data to the sink. This distributed sensing approach provides robustness to the system.

Dynamic network topology: WSNs are generally dynamic networks. Sensor nodes can fail due to battery exhaustion or other circumstances, communication channels can be disrupted, and additional sensor nodes may be added to the network, resulting in frequent changes in the network topology. Therefore, WSNs nodes need to be embedded with reconfiguration and self-adjustment functions.

Multi-hop communication: Due to the large number of sensor nodes deployed

in a WSNs, the most feasible way to communicate with the sink or base station is through intermediate nodes along a routing path. If a node needs to communicate with another node or base station beyond its radio frequency range, it must do so through a multi-hop route using intermediate nodes.

Application-oriented: WSNs differ from conventional networks due to their nature. They are highly dependent on specific applications ranging from military to environmental and health sectors. Nodes are deployed randomly and spanned according to the specific application requirements.

2.8 Research issues in WSNs

WSNs provide an effective method for distributed sensing and data collection across numerous applications. Despite their potential, WSNs face several significant research challenges. Key areas of focus include:

- 1) **Energy Efficiency:** Sensor nodes are often battery-powered and deployed in remote locations. Minimizing energy consumption is crucial for extending network lifetime and reducing maintenance needs. Research areas include:
 - Energy-efficient communication protocols: Developing protocols that minimize data transmission overhead and optimize routing strategies.
 - Energy-harvesting techniques: Exploring ways to harvest energy from the environment (e.g., solar, vibration) to power sensor nodes.
 - Duty cycling and sleep modes: Optimizing sleep schedules for sensor nodes to minimize active time while maintaining data collection requirements.

2) **Scalability and Coverage:** WSNs can be deployed with a large number of nodes spread over a wide area. Research focuses on:

- Network architecture and self-organization: Developing algorithms for efficient network formation, node addition/removal, and maintaining connectivity as the network grows.
- Coverage and connectivity: Ensuring complete sensing coverage within the deployment area while maintaining communication paths between nodes.
- Localization techniques: Enabling sensor nodes to determine their location for accurate data interpretation and routing.

3) **Data Management and Security:** Sensor data can be sensitive and needs to be processed and transmitted efficiently. Research areas include:

- In-network processing and aggregation: Performing preliminary data processing and filtering within the network to reduce data volume and communication overhead.
- Data security and privacy: Protecting data from unauthorized access, modification, or eavesdropping, especially in critical applications.
- Fault tolerance and reliability: Developing mechanisms to handle sensor node failures, data loss, and network disruptions to ensure reliable data collection.

4) **Emerging Challenges:** With the increasing complexity of WSN applications, new research issues are emerging:

- Integration with other networks: Enabling seamless interoperability

and data exchange between WSNs and other network infrastructures (e.g., cloud computing, internet of things).

- Real-time data analytics: Developing efficient algorithms to analyze sensor data in real-time for timely decision making and anomaly detection.
- Mobile sensor networks: Addressing the challenges of dynamic network topologies where sensor nodes can move or change location.

Overall, research in WSNs continues to address these challenges to improve efficiency, scalability, reliability, and security. As these advancements progress, WSNs will become even more versatile and impactful in various applications.

Our work in this thesis revolves around the localization problem, and initially, we clarify the concept of deployment.

2.8.1 Deployment:

Deployment in WSNs refers to the strategic placement of sensor nodes in a specific area to achieve effective coverage and efficient data collection. The chosen deployment strategy plays a crucial role in determining the network's performance and its ability to meet the desired application requirements. they are some commonly used deployment strategies in WSNs[39, 40]:

- Random Deployment: Sensor nodes are dropped randomly, often from aircraft, across the target area. This method assumes a uniform random distribution of nodes over a finite area.

- **Regular Deployment:** Sensor nodes are deployed in a well-planned and fixed manner. While not necessarily following a geometric structure, regular deployment is often assumed for convenience.
- **Mobile Sensor Nodes:** In this approach, sensor nodes have the ability to move. They can compensate for deployment shortcomings by adjusting their positions. They can also be passively moved by external forces such as wind or water. Furthermore, they can actively navigate to interesting areas based on specific criteria.

2.9 Conclusion

In this chapter, an overview of WSNs and their components, architecture, applications, characteristics, constraints, and research issues have been presented. Wireless Sensor Networks are a promising and recent technology, benefiting from reduced sensor manufacturing costs, increased autonomy, extended battery life, miniaturization, and application expansion. Despite making significant strides in wireless networks, WSNs face challenges like energy consumption, hardware costs, topology changes, and environmental adaptation, impeding widespread deployment. Essential for overcoming these hurdles is the development of new network management techniques to encourage broader adoption of this technology.

CHAPTER 3

Localization in WSNs: Motivation and Background

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3.1 Introduction

Localization in WSNs refers to the process of determining the spatial positions of sensor nodes within the network after they are deployed. It plays a crucial role in many WSNs applications and network operations where the accurate location of nodes is essential for various tasks such as event detection, target tracking, and environmental monitoring[41]. However, GPS-based localization schemes are not always feasible due to their cost and non-availability of GPS signals in indoor environments [42]. In this chapter, we present a novel approach to localization in sensor networks based on the use of a mobile anchor. The novelty of this approach lies in defining a predefined trajectory coupled with a very low-complexity algorithm.

The rest of this chapter is organized as follows: Firstly, we introduce the localiza-

tion problem, different methods for distance estimation between nodes, and some existing algorithms. Secondly, we present localization in sensor networks based on the use of a mobile anchor.

3.2 Why is localizing sensor nodes important?

Localization in WSNs is important for several reasons:

- 1) **Target Tracking:** Sensor nodes are deployed in order to monitor and track the movements of specific objects or individuals within a given area. By accurately localizing the sensor nodes, the WSNs can precisely determine the location of the target object or individual.
- 2) **Surveillance and Security:** Localization of sensor nodes enables efficient surveillance and security applications. By knowing the exact locations of the sensor nodes, it becomes possible to detect intrusions or unauthorized activities in a protected area, allowing for prompt response and effective security measures.
- 3) **Environmental Monitoring:** Localization in WSNs is crucial for environmental monitoring applications. By accurately determining the positions of sensor nodes, it becomes possible to track environmental phenomena such as pollution levels, wildlife movements, or natural disasters. This information aids in data analysis and decision-making for environmental management.
- 4) **Resource Optimization:** Localization helps optimize resource allocation and utilization in WSNs. By knowing the precise locations of sensor nodes, it

becomes possible to efficiently allocate resources such as energy, bandwidth, and storage based on the requirements and demands of the network.

- 5) Network Performance and Management: Localization information contributes to the overall performance and management of the WSNs. It aids in route planning, data aggregation, and network maintenance tasks. Knowing the locations of sensor nodes allows for efficient data routing and dissemination, leading to improved network efficiency and reduced communication overhead.
- 6) To enable mobility: In some WSNs applications, the sensor nodes may be mobile. Localizing the sensor nodes can help to track their movement and enable efficient data processing [41].

Overall, localizing sensor nodes in WSNs enhances the accuracy, efficiency, and effectiveness of various applications and contributes to better decision-making and resource management.

An example of target tracking using WSNs is in wildlife monitoring. In this application, sensor nodes are deployed in natural habitats to track and monitor the movements of wildlife species. Each sensor node is equipped with various sensors, such as motion sensors or sound sensors, to detect the presence of animals.

By accurately localizing the sensor nodes and collecting data from multiple nodes, the WSNs can track the movements of individual animals within the monitored area. This information is valuable for studying animal behavior, migration patterns, and habitat usage. For instance, in a wildlife conservation project, researchers may deploy a WSNs in a national park to monitor the movements of endangered species, such as tigers or elephants. The sensor nodes can detect the presence of

these animals and relay the information to a central monitoring station. The localization of the sensor nodes allows researchers to precisely determine the location of each animal, track their movement patterns, and analyze their behavior. This information can help in making informed decisions for wildlife conservation efforts, such as identifying critical habitats, designing protected areas, or implementing measures to prevent human-wildlife conflicts.

3.3 Components of Localization

The theory of WSNs localization is described as follows [43]. WSN is represented as a standard network graph $G = (V, E)$, where $V = \{v_1, v_2, \dots, v_i, \dots, v_n\}$ is the set of sensors, and $E = \{e_1, e_2, \dots, e_i, \dots, e_m\}$ denotes the edges connecting pairs of sensors. The set V is categorized into four types based on their status:

- $V_u \subseteq V$ is the set of unknown sensors that need to be localized.
- $V_b \subseteq V$ consists of beacons, representing sensors with known locations obtained through GPS or other means.
- $V_s \subseteq V$ is the set of settled sensors. As an unknown sensor (V_u) finds its location through the algorithm, it is transformed from V_u to V_s .
- $V_r \subseteq V$ is a set of reference sensors, which can be either V_b or V_s , depending on the specific algorithm. They provide location information as a reference for V_u .

The localization problem for WSNs can be stated as follows: Given graph G and $|V_b| < |V|$, the objective is to determine the location of $V_u = V - V_b$. In the localization process, some sensors in V_u will be transformed into V_s or V_r .

3.3.1 Beacon or anchor:

A beacon node is a specialized node in a network that serves as a reference point for determining the positions of other nodes. It broadcasts its own location information, which is typically obtained from a GPS or other means.

Beacon nodes are important in localization algorithms as they provide known positions that help estimate the positions of other nodes. Some localization algorithms use beacons to establish a relative map of node coordinates and then determine a transformation to convert relative coordinates to global coordinates [44]. Other algorithms start with the positions of beacons and calculate the positions of non-beacon nodes in a global system [45].

3.3.2 Mobile beacon(mobile anchor):

The mobile anchor serves as a specialized node equipped with a known location or coordinates, and it moves within the network's coverage area. It communicates with other nodes to assist in their localization process. By collecting and transmitting location information during its movement, the mobile anchor enables other nodes to estimate their positions relative to the anchor's known location.

3.4 Classification of Localization Methods:

Localization techniques can be classified based on various criteria. They differ in terms of assumed localization accuracy, hardware capabilities, measurement and computation methods, computational organization, presumed network configuration, architecture, node properties, and deployment, among others. they are some

common classification approaches:

1) **Localization method (Range-based vs. Range-free Localization)**[46]:

Range-based localization relies on distance or range measurements between sensor nodes. Range-free localization, on the other hand, does not require explicit range measurements and instead uses connectivity or proximity information between sensor nodes.

2) **Localization Processing (Centralized vs. Distributed Localization)**:

In centralized localization, a central entity or base station collects measurement data from sensor nodes and performs the localization computation.

Distributed localization involves local computations among sensor nodes, where each node collaboratively estimates its own position based on available information from neighboring nodes.

3) **Presence of anchor (Anchor-based vs. Anchor-free Localization)**:

Anchor-based localization relies on the presence of anchor nodes with known positions. These anchor nodes serve as reference points to estimate the positions of other unknown nodes.

Anchor-free localization does not require anchor nodes and instead relies on connectivity patterns, statistical inference, or other algorithms to estimate node positions.

4) **Hybrid Localization**: Hybrid localization combines multiple localization techniques, such as range-based and range-free approaches, to improve accuracy, robustness, or energy efficiency in WSNs.

- 5) **Mobility of nodes:** Classification of localization methods based on the mobility of nodes can be categorized as follows:
- **Static Nodes:** In this category, all nodes within the network are stationary and do not change their positions over time. Localization techniques for static nodes typically involve range-based or range-free methods using fixed anchors or reference points.
 - **Mobile Nodes:** This category includes nodes that have the capability to move within the network. Localization techniques for mobile nodes involve tracking their movement and estimating their positions based on mobility patterns, sensor measurements, or the use of mobile anchors.
 - **Mixed Nodes:** This category encompasses networks where both static and mobile nodes coexist. Localization techniques for mixed nodes take into account the different characteristics and behaviors of both static and mobile nodes, combining range-based or range-free methods with mobility tracking and anchor-based localization.
- 6) **Deployment Area (Two-Dimensional vs. Three-Dimensional):** The deployment of WSNS can be classified as either 2D or 3D, depending on the spatial dimension in which the sensor nodes are placed. The search results indicate that 3D deployment is relevant in various applications, such as structural health monitoring of bridges and towers, underwater surveillance networks, and mountain environments. In contrast, 2D deployment is suitable for open areas or indoor environments. The choice between 2D and 3D deployment depends on the specific application requirements and the need to monitor and cover the designated area effectively.

3.5 Range-based localization

Range-based localization is a technique used to estimate the positions of nodes in a WSNs based on the measurement of distances or ranges between nodes. It relies on the ability to accurately measure the physical distance between nodes, typically using techniques such as received signal strength (RSSI), time of arrival (TOA), time difference of arrival (TDOA), or angle of arrival (AOA).

3.5.1 Distance Measurement techniques

Received Signal Strength Indicator [47–49]: The Received Signal Strength Indicator (RSSI) is a measurement used to quantify the power level of a received radio signal. In the context of wireless communication, RSSI is often used to assess the strength of the signal between a transmitter and a receiver. RSSI is typically represented as a numerical value, usually in decibels (dBm), which indicates the signal strength. A higher RSSI value generally corresponds to a stronger signal, while a lower value indicates a weaker signal. In wireless systems, RSSI can be used for various purposes. One of its primary applications is in estimating the distance between the transmitter and receiver nodes. The relationship between RSSI and actual distance is a fundamental concept in many localization approaches for Wireless Sensor Networks. By leveraging RSSI measurements, it becomes possible to estimate the distance between nodes and enable localization algorithms in WSNs.

Radio wave propagation occurs when a wireless signal is transmitted through the air. During propagation, the transmitted signal undergoes attenuation caused by various factors, including reflection, deflection, scattering, shadowing, and diffrac-

tion. These mechanisms significantly impact the wireless channel's propagation characteristics. Wireless channel models are typically developed using a combination of analytical and practical methods. The practical approach is advantageous as it considers all relevant propagation parameters within the channel. Many Zig-Bee modules used in wireless systems support RSSI, allowing for the measurement of received power for each received packet. The power or energy of a signal traveling between two nodes, such as a mobile node and a coordinator node, contains information that reflects the distance between them. This signal parameter, along with the Log-Normal Shadowing Model (LNSM) and path loss, can be utilized for distance estimation. The LNSM equation captures the impact of path loss and random shadowing effects on the received signal strength [50].

$$PL(d) = PL(d_0) + 10n \log_{10}(d/d_0) + X_\sigma \quad (3.5.1)$$

Where:

$PL(d)$: Path Loss at distance d

$PL(d_0)$: Path Loss at reference distance d_0

n : Path Loss Exponent

d : Distance between transmitter and receiver

d_0 : Reference Distance

X_σ : Log-Normal Shadowing term with standard deviation σ

The RSSI (Received Signal Strength Indicator) in dBm of the mobile node at the coordinator node can be calculated using the following equation.

$$RSSI = P_T - PL(d) \quad (3.5.2)$$

Where:

P_T : the mobile node transmitted power in dBm

Then, the RSSI values at the coordinator node are [12, 15, 24-26].

$$PL(d) = P_T - PL(d_0) - 10n \log_{10}(d/d_0) + X_\sigma \quad (3.5.3)$$

Therefore, the distance between the mobile node and the coordinator node can be estimated based on Equation 3.5.4, which is derived from Equation 3.5.3.

$$d = d_0 10^{((RSSI - P_T + PL_0 - X_\sigma)/10n)} \quad (3.5.4)$$

Time of Arrival (ToA) or Time of Flight (ToF) [51, 52] is a technique commonly used in the localization of Wireless Sensor Networks. It involves measuring the time it takes for a signal to travel from a transmitter node to a receiver node in order to estimate the distance between them.

In ToA-based localization, the transmitter node sends a signal, and the receiver node measures the time it takes for the signal to reach it. Since the signal travels at a known speed, such as the speed of light, the distance can be calculated by multiplying the time of flight by the speed of the signal.

Time Difference of Arrival (TDoA) [53, 54] is a technique used in the localization of WSNS to estimate the position of a node based on the differences in the arrival times of signals from multiple reference nodes.

In TDOA-based localization, the reference nodes known as anchors transmit signals at precisely synchronized times. The target node receives these signals and measures the differences in arrival times. By comparing the arrival times of the signals at the target node, along with the known positions of the reference nodes, the target node can determine its position.

Angle of Arrival(AoA) [55] is a technique used in wireless communication and localization to estimate the direction or angle from which a signal is received. It refers to the measurement of the angle between a reference direction and the direction from which a signal arrives at a receiving antenna. In WSNs localization, AoA is used to determine the position of a node by analyzing the angles at which it receives signals from multiple reference nodes. By measuring the angles of arrival from different reference nodes. The measurement of AoA can be achieved using various methods, including antenna arrays, beamforming techniques, or the comparison of signal phase differences at different receiving antennas. These techniques allow for the determination of the signal's incident angle with respect to the reference direction.

AoA measurements can be used in combination with other distance measurement techniques such as RSSI to improve the accuracy of localization in WSNs [56].

3.5.2 Methods for calculating sensor nodes' location using ranging-based measurements

Ranging-based measurements are commonly used to estimate the positions of sensor nodes in a wireless network. These measurements involve determining the distances or ranges between nodes. Various methods are employed to calculate

the locations of sensor nodes based on these ranging measurements. they are some basic methods:

Trilateration [4, 57] Trilateration is a method used to determine the position of an unknown node based on its distances to three known anchor nodes. It is based on the same principle as a GPS system. Each node, knowing the positions of three of its neighbors, can localize itself by finding the intersection point of three circles. These circles are formed using the distances between the node and its neighboring nodes. As illustrated in Figure 3.1, let S represent an unknown node

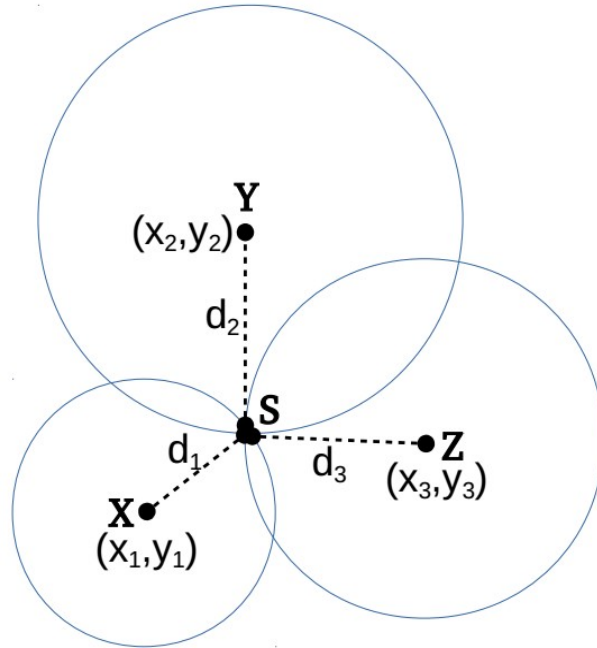


Figure 3.1: An example of the trilateration[2].

to be localized, and its position is denoted as $S(x, y)$. Assume that S receives three packets, each containing the positions of anchor nodes, for example, as $X(x_1, y_1)$, $Y(x_2, y_2)$, and $Z(x_3, y_3)$. Subsequently, S calculates the distances d_1 , d_2 , and d_3 between its current position and the positions of anchor nodes X , Y , and

Z , respectively, each time it receives a packet. The position of S can then be determined by solving the following system of equations:

$$\begin{cases} (x - x_1)^2 + (y - y_1)^2 = d_1^2 \\ (x - x_2)^2 + (y - y_2)^2 = d_2^2 \\ (x - x_3)^2 + (y - y_3)^2 = d_3^2 \end{cases} \quad (3.5.5)$$

We can expand out the squares in each one:

$$x^2 - 2x_1x + x_1^2 + y^2 - 2y_1y + y_1^2 = d_1^2$$

$$x^2 - 2x_2x + x_2^2 + y^2 - 2y_2y + y_2^2 = d_2^2$$

$$x^2 - 2x_3x + x_3^2 + y^2 - 2y_3y + y_3^2 = d_3^2$$

If we subtract the second equation from the first, we get:

$$(-2x_1 + 2x_2)x + (-2y_1 + 2y_2)y = d_1^2 - d_2^2 - x_1^2 + x_2^2 - y_1^2 + y_2^2$$

Likewise, subtracting the third equation from the second, we get:

$$(-2x_2 + 2x_3)x + (-2y_2 + 2y_3)y = d_2^2 - d_3^2 - x_2^2 + x_3^2 - y_2^2 + y_3^2$$

This is a system of two equations in two unknowns:

$$Ax + By = C$$

$$Dx + Ey = F$$

which has the solution:

$$x = \frac{CE - FB}{AE - BD}$$

$$y = \frac{CD - AF}{BD - AE}$$

where:

$$A = -2x_1 + 2x_2$$

$$B = -2y_1 + 2y_2$$

$$C = d_1^2 - d_2^2 - x_1^2 + x_2^2 - y_1^2 + y_2^2$$

$$D = -2x_2 + 2x_3$$

$$E = -2y_2 + 2y_3$$

$$F = d_2^2 - d_3^2 - x_2^2 + x_3^2 - y_2^2 + y_3^2.$$

Accuracy-Priority Trilateration (APT): The APT technique is utilized to localize unknown sensor nodes by considering the three nearest received messages from a mobile beacon. This method focuses on the three strongest RSSI values, which enables a higher level of accuracy in estimating the node's location. In studies such as [23, 24], the APT technique has demonstrated excellent results compared to the Time-Priority Trilateration (TPT) technique. The TPT technique determines the position of unknown sensors based on previously received messages. On the other hand, the Cosine Rule based Localization (CRL) algorithm proposed in [58] exhibits superior performance compared to APT.

Triangulation [3, 4, 59] Triangulation is a versatile technique employed to estimate the position of an unknown node by measuring its angles or distances relative to known reference points. It entails forming triangles with the known reference points and the unknown node. The process involves measuring the angles between the known reference points and the unknown node. By applying trigonometric principles such as the law of sines and cosines, the position of the unknown node can be determined based on the positions of the known reference points and the measured angles. Unlike trilateration, which relies solely on dis-

tance measurements, triangulation utilizes angular measurements between three different pairs of anchor nodes to compute the position of the unknown node. This flexibility allows triangulation to be applicable in scenarios where precise distance measurements may be challenging or impractical, such as in environments with obstacles or irregular terrain. The computation process of triangulation is visually depicted in figure 3.2.

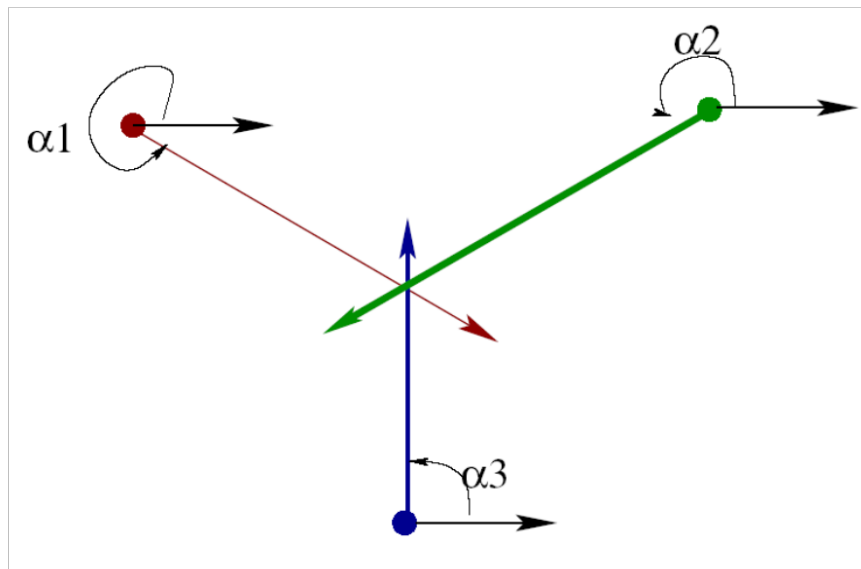


Figure 3.2: An example of the triangulation[3].

Multilateration [4, 60] Multilateration is the process of determining the position of an unknown node by using the distances measured from multiple reference points. It is used to locate the unknown node based on the measured distances between it and the reference points. The reference points are set at known locations, and the distances between the unknown node and each reference point are measured using techniques such as Received Signal Strength Indicator (RSSI), Time of Arrival (TOA), or Time Difference of Arrival (TDOA). Based on these measured distances and the known locations of the reference points, the position

of the unknown node can be calculated. In the case where the number of anchor nodes is greater than 3 ($n > 3$), the maximum likelihood estimation is employed to calculate the coordinates of the unknown node $D(x, y)$. The anchor nodes are denoted by their respective coordinates $A(x_1, y_1)$, $B(x_2, y_2)$, $C(x_3, y_3)$, ..., $C(x_n, y_n)$, and the distances between D and the anchor nodes are represented as d_1 , d_2 , d_3 , ..., d_n , respectively, as illustrated in Figure 3.3. Hence, the unknown node D will calculate its position by solving the equation Equation 3.5.6.

$$\begin{cases} (x - x_1^2) + (y - y_1^2) = d_1^2 \\ (x - x_2^2) + (y - y_2^2) = d_2^2 \\ (x - x_3^2) + (y - y_3^2) = d_3^2 \\ \vdots \\ (x - x_n^2) + (y - y_n^2) = d_n^2 \end{cases} \quad (3.5.6)$$

By subtracting the last equation from the first $n - 1$ equations, we can obtain a system of linear equations:

$$\begin{bmatrix} 2(x_1 - x_n) + 2(y_1 - y_n)y = \\ d_n^2 - d_1^2 + x_1^2 - x_n^2 + y_1^2 - y_n^2 \\ \vdots \\ 2(x_{n-1} - x_n)x + 2(y_{n-1} - y_n)y = \\ d_n^2 - d_{n-1}^2 + x_{n-1}^2 - x_n^2 + y_{n-1}^2 - y_n^2 \end{bmatrix} \quad (3.5.7)$$

With some proper transformations, the above equation can be rewritten as $AX = b$, where

$$X = \begin{bmatrix} x \\ y \end{bmatrix}^T, A = 2 \begin{bmatrix} (x_1 - x_n) & (y_1 - y_n) \\ \vdots & \vdots \\ (x_{n-1} - x_n) & (y_{n-1} - y_n) \end{bmatrix}, b = \begin{bmatrix} d_n^2 - d_1^2 + x_1^2 - x_n^2 + y_1^2 - y_n^2 \\ \vdots \\ d_n^2 - d_{n-1}^2 + x_{n-1}^2 - x_n^2 + y_{n-1}^2 - y_n^2 \end{bmatrix} \quad (3.5.8)$$

Then, we can obtain

$$X = (A^T A)^{-1} A^T b \quad (3.5.9)$$

Actually, the multilateration is the extension of the trilateration method.

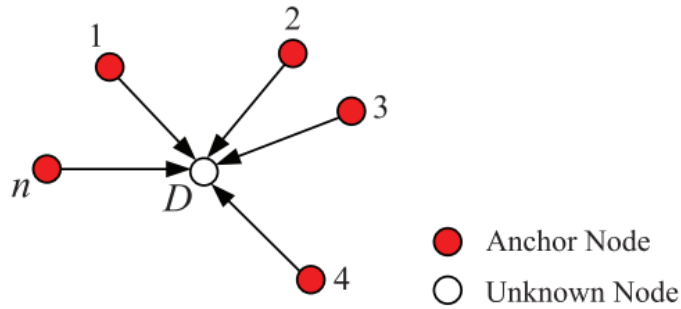


Figure 3.3: An example of the multilateration[4].

3.6 Range-free localization

Range-free localization is a technique employed in WSNs to determine the location of a node without relying on distance or angle measurements [61–63]. Instead, range-free localization algorithms utilize radio connectivity information to infer the node’s location [13, 64]. While range-free localization algorithms may exhibit lower accuracy compared to range-based methods, they provide a cost-effective and straightforward implementation [61, 63]. These algorithms can be categorized into two groups: fully range-free and hybrid range-free schemes [65].

3.6.1 Fully range-free:

These algorithms employ a single approach based on connectivity and/or topology information. Some notable approaches in the literature include centroid, DV-hop,

and APIT.

Centroid localization Algorithm (CA): The Centroid Localization Algorithm calculates the position of an unknown node by determining the geometric center of its neighboring anchor nodes, assuming that the unknown node is located at the centroid of its neighbors.

In [14], the authors introduced the Centroid Localization Algorithm to estimate the coordinates (x, y) of an unknown node based on the coordinates (x_i, y_i) of a set of anchor nodes A_1, A_2, \dots, A_n . The estimation is performed using the equation [14]:

$$(x, y) = \left(\frac{\sum_{i=1}^n x_i}{n}, \frac{\sum_{i=1}^n y_i}{n} \right) \quad (3.6.1)$$

where n is the number of anchor nodes. After localization, the unknown node itself becomes an anchor node and broadcasts packets to the surrounding area. This method of localization is simple, cost-effective, and easy to implement. However, its accuracy can be affected by the density and deployment of anchor nodes. Additionally, this algorithm is designed for 2D networks.

WCL (Weighted Centroid Localization): WCL method was introduced in [66]. The primary objective of WCL is to design an algorithm that minimizes computation, communication, and cost. In WCL, the positions of nodes are estimated by calculating the weights of anchor nodes based on their estimated distances. The weight function, denoted as w_{ij} , is defined as the reciprocal of the distance d_{ij} raised to the power of g , where g is a predefined degree based on different scenarios.

$$w_{ij} = \frac{1}{(d_{ij})^g} \quad (3.6.2)$$

The node position can then be estimated by taking the weighted sum of anchor positions:

$$p_i = \frac{\sum_{j=1}^n w_{ij} \cdot a_j}{\sum_{j=1}^n w_{ij}} \quad (3.6.3)$$

where p_i is the (x_i, y_i) coordinates of the unknown node i , and $a_j = (x_j, y_j)$ is the position of anchor node j .

After replacing the weights w_{ij} with the Received Signal Strength Indicator (RSSI) values, the final node position can be estimated by:

$$p_i = \frac{\sum_{j=1}^n \text{RSSI}_{ij} \cdot a_j}{\sum_{j=1}^n \text{RSSI}_{ij}} \quad (3.6.4)$$

Weight-Compensated Weighted Centroid Localization Based on RSSI

(WCWCL-RSSI): The WCWCL-RSSI algorithm, proposed in [67], builds upon the idea of WCL [66]. Let $a_i = (x_i, y_i)$ denote the coordinates of an anchor node i , and g represents the degree determining the contribution of each anchor node. The weight of anchor node a_i , denoted as w_i , depends on the distance between anchor node i and the unknown node. The WCWCL-RSSI algorithm involves three essential phases:

1) When the unknown node receives signals from different anchor nodes (with the size ranging from 1 to n anchor nodes, i.e., $i = 1 \cdots n$, where $n > 1$), it records the RSSI values and the coordinates of each anchor a_i .

2) Let w_i be the weight of anchor node i , and the improved weight Wn_i is calculated as [67]:

$$Wn_i = \frac{W_i \cdot n^{2 \cdot W_i}}{\sum_{j=1}^n (W_j \cdot n^{2 \cdot W_j})} \quad (3.6.5)$$

where

$$W_i = \frac{w_i}{\sum_{j=1}^n w_j} = \frac{\sqrt{\left(10^{\frac{RSSI_i}{10}}\right)^g}}{\sum_{j=1}^n \sqrt{\left(10^{\frac{RSSI_j}{10}}\right)^g}} \quad (3.6.6)$$

3) Finally, the position of the unknown node is expressed as:

$$P = \sum_{i=1}^n Wn_i \cdot a_i \quad (3.6.7)$$

Where, $P = (x_p, y_p)$ represents the unknown node coordinates, and $a_i = (x_i, y_i)$ represents the location of anchor i .

WCWCL-RSSI, is derived from WCL theory. Compared to WCL, WCWCL-RSSI streamlines parameter requirements, notably reducing the need for parameters like the path loss exponent. This reduction in parameters leads to a decrease in algorithmic complexity. Moreover, WCWCL-RSSI enhances energy efficiency by minimizing node energy consumption, thereby extending network lifespan due to its range-free nature. In [67–69], WCWCL-RSSI stands out as the most accurate centroid localization algorithm when compared to WCL.

Approximate Point in Triangle (APIT): The APIT, proposed in [13], is a localization algorithm used to estimate the position of an unknown node within a triangular region formed by three anchor nodes. It is based on the concept of

dividing the triangle into smaller sub-triangles and determining the closest sub-triangle that contains the unknown node.

The APIT algorithm involves calculating the barycentric coordinates of the unknown node with respect to each sub-triangle. These barycentric coordinates represent the weights or proportions of the three anchor nodes that contribute to the position estimation. By computing the barycentric coordinates, the algorithm determines the approximate location of the unknown node within the selected sub-triangle. The accuracy of the estimation depends on the number and distribution of anchor nodes.

DV-hop (Distance-Vector Hop) localization Algorithm:[\[15, 70\]](#) The DV-hop localization algorithm is a range-free method used to estimate the position of unknown nodes in WSNs. It is based on the concept of hop count, where nodes estimate their distances based on the number of hops required to reach the anchor nodes. The algorithm works as follows:

- **Network Initialization:** Each anchor node is assigned a known position, and each unknown node is assigned an initial position, typically random.
- Each anchor node broadcasts its position along with a hop count of zero.
- The neighboring nodes receive the broadcast messages and update their hop count by incrementing it.
- The intermediate nodes forward the broadcast messages to their neighbors, increasing the hop count by one.
- When a non-anchor node receives multiple broadcast messages from different anchor nodes, it selects the anchor node with the minimum hop count as its

reference anchor.

- The unknown node calculates its distance from the reference anchor based on the hop count and a predetermined hop distance value. The hop size is determined by averaging the hop distances of neighboring nodes. Each unknown node calculates its hop size based on the average hop distances of its neighbors using the following formula:

$$\text{HopSize}_i = \frac{\sum \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}}{\sum \text{hop}_{ij}}$$

Where $i \neq j$, HopSize_i represents the hop size of node i , x_i and y_i are the coordinates of node i , x_j and y_j are the coordinates of neighboring nodes j , and hop_{ij} is the hop count between nodes i and j . Lastly, each anchor will flood its hop-size to all network nodes. The unknown node calculates the distance to the anchor nodes as follows:

$$d_i = \text{HopSize}_i \times L_i$$

Where L_i is the hop value between the i^{th} anchor node and unknown node.

By using triangulation or other localization techniques, the unknown node estimates its position based on the known anchor positions and the distances to the reference anchor.

3.6.2 The hybrid range-free localization algorithm:

The hybrid range-free localization algorithm is a method that combines different approaches to estimate the position of a node without relying on precise distance

measurements. It leverages both topology and connectivity information to improve the accuracy of localization.

The authors in [71] proposed an Iterated Hybrid Localization Algorithm (IHLA), which combines the centroid scheme and DV-Hop scheme. In this algorithm, each unknown node first computes its initial coordinates using the centroid scheme. Then, it re-estimates the distances between each unknown node and the beacon nodes using the DV-Hop scheme. After that, the Taylor Series Expansion (TSE) algorithm is employed to further refine the coordinates of each unknown node. The IHLA algorithm achieves better localization accuracy compared to the centroid scheme and DV-Hop scheme. However, due to its hybrid nature, it is more complex and requires more computing time to execute.

In general, range-based localization algorithms have higher positioning accuracy and complexity than range-free localization algorithms [72].

3.7 Mobile anchors based localization

The initial WSNs localization algorithms rely on a common approach of using statically deployed nodes known as landmarks, anchors, or beacons. These nodes have known coordinates and can transmit their coordinates to the unknown sensors. This information assists the unknown sensors in localizing themselves within the network. The landmarks or anchors are typically equipped with GPS technology, which enables them to accurately share their coordinates with other nodes [11–17].

Mobile anchors based localization refers to a localization technique in WSNs where the localization process is assisted by mobile anchor nodes. In this approach, in-

stead of using static anchor nodes with known coordinates, mobile anchor nodes are deployed in the network. These mobile anchors are equipped with positioning capabilities such as GPS and move throughout the ROI. The role of mobile anchors is to periodically broadcast their current locations to the other nodes in the network. By receiving these location updates from the mobile anchors, the unknown sensor nodes can estimate their own positions relative to the mobile anchors. This information helps in determining the locations of the unknown nodes within the WSNs [73, 74]. There has been a comprehensive exploration of mobile anchor node-based localization algorithms, as discussed in [4].

3.7.1 Architecture and Operation

The network design is illustrated in Figure 3.4. There are two types of sensor nodes in the network: the unknown node and the mobile anchor (beacon). All sensor nodes have the same radio communication range. The unknown nodes are randomly deployed within the coverage area. The mobile anchor moves along a predefined trajectory and periodically broadcasts its current location to assist the unknown nodes in self-localization.

This type of architecture offers significant practical advantages:

- The mobile anchor is not limited in energy like a simple sensor node.
- The size of an anchor is much larger than the size of a sensor, making it much easier to install a GPS unit.
- Facilitates the deployment phase.
- Reduces cost.

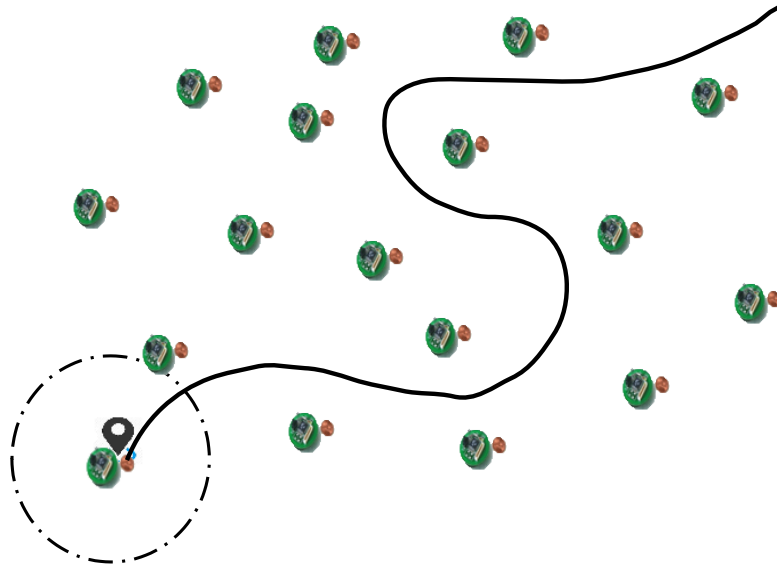


Figure 3.4: The network design.

- Localization accuracy can also be improved (by specifying the correct trajectory).
- It allows for more flexibility and adaptability as the anchors can dynamically adjust their positions based on the network requirements.
- Mobile anchors can cover a larger area and reach nodes that are far away from static anchors, thereby improving the localization coverage.
- Mobile anchors can help mitigate the effects of obstacles and signal variations by actively moving to different locations.

The process of localization with a mobile node consists of two essential parts. The first part is dedicated to the trajectory (path planning), and the second part involves estimating the distances between the anchor and the nodes, and the localization algorithm (position derivation). The second part of the localization process with a mobile anchor is very similar to those of other processes with fixed anchors.

3.8 Path planning for a mobile anchor

The "trajectory" part is the core of the localization process with a mobile anchor and the most challenging one. This part is divided into two sub-parts: (a) defining the trajectory (which path the mobile anchor will follow to ensure the localization of all nodes), and (b) the packets (what do they contain? At what moments or positions should the anchor send them?).

3.8.1 Definition of trajectory

Mobile anchors based localization also presents challenges. The movement of the mobile anchors needs to be well-planned to ensure effective coverage and minimize localization errors. Path planning algorithms are employed to determine optimal trajectories for the mobile anchors, considering factors such as the number of unknown nodes to be localized, energy consumption, and localization precision. The key challenge is to design a trajectory that satisfies three main properties [22, 75]: (i) closely passing by potential node positions to localize as many unknown nodes as possible, (ii) ensuring that all possible unknown nodes are covered by at least three non-collinear anchor points for unique estimations, and (iii) minimizing energy consumption and localization time by keeping the trajectory as short as possible. Additionally, careful planning of the mobile anchor's movement is crucial to maximize the positions of beacons that offer high localization precision [25]. The choice of an optimal path of the mobile anchor is a complex problem. The authors of paper [22] are the first authors who raised the problem of finding a good path planning and discussed it, but without offering any specific solution. In [4], There are two main ways to implement this localization scheme: using a

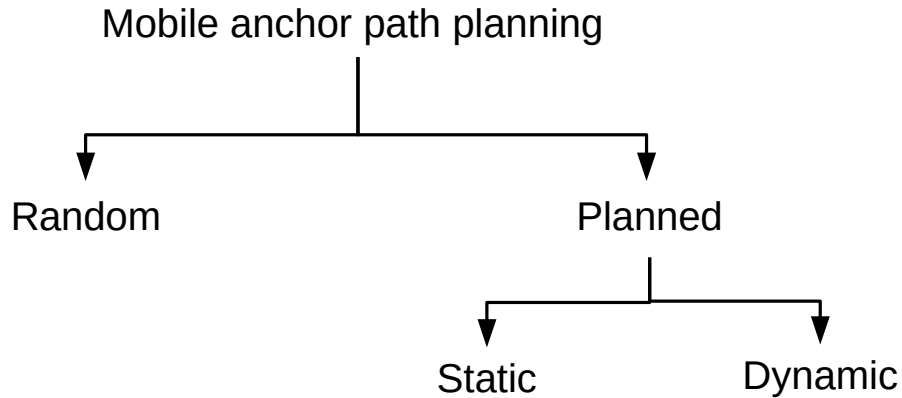


Figure 3.5: Path planning models for mobile anchor-based localization.

random movement strategy for the mobile anchors, or employing a planned path for them to follow as shown in Figure 3.5.

- **Random mobility in mobile anchor-based localization:** refers to a strategy where the mobile anchor moves throughout the WSN with no predetermined path, random mobility introduces randomness into the movement patterns of the anchor nodes as shown in Figure 3.6. Random mobility involves the random selection of movement direction and step sizes, along with other parameters like velocity and movement length. This type of mobility is typically employed when precise localization or high localization ratios are not required. Consequently, there's no assurance that all unknown nodes will receive sufficient localization information, leading to many unknown nodes unable to estimate their positions.

However, random mobility offers advantages in its flexibility and adaptability to dynamic network conditions. It enables anchor nodes to effectively explore the environment, even in scenarios with obstacles or uneven sensor node distribution. Additionally, random mobility enhances localization system

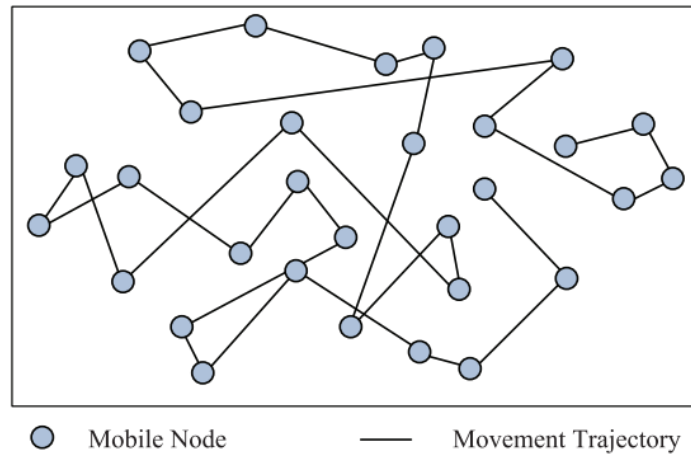


Figure 3.6: RW mobility model.

robustness by diversifying anchor node positions, thus mitigating the impact of node failures or environmental changes.

Random mobility can be implemented using various strategies, such as random waypoint, random walk, or random direction mobility models [4]. These models govern the movement of anchor nodes by defining parameters like speed, direction changes, pause times, and maximum displacement.

- **Planned models:** Planned path planning strategies may adopt a static or dynamic approach. In static planning, the movement trajectory is predetermined prior to execution, with the mobile anchor node adhering to a predefined path during localization. Conversely, dynamic planning adjusts the movement trajectory either in real-time or partially based on the surrounding environment or deployment conditions.
 - **Static path planning:** focuses on pre-defining the movement path of the mobile anchor. This path is carefully designed to optimize local-

ization accuracy and ensure complete coverage of the sensor network area. The mobile anchor follows a predetermined path, often based on geometric shapes or patterns that guarantee good sensor node coverage. This predetermined path, often structured around geometric shapes or patterns, guarantees efficient sensor node coverage. Compared to other mobility models, static approaches offer minimal localization error, facilitating more precise location estimation by the unknown nodes. Nevertheless, proposing a static path demands thorough consideration of beacon points and trajectory details to mitigate potential issues like collinearity and path length discrepancies. Various examples of 2D static path planning in WSNs are examined, such as SCAN, DOUBLE-SCAN, and Hilbert [9], Gosper-curve [76], Circles and S-Curves [77], K-coverage [78], PI [79], LMAT [80], 'S' Type [25], H-curve [69], etc.

- **Dynamic path planning:** refers to the process of determining a movement trajectory in real-time or adjusting it partially based on changing environmental conditions or situational requirements. Unlike static path planning, where the trajectory is predefined before execution, dynamic path planning allows for adaptability and responsiveness to dynamic changes in the environment. In dynamic path planning, algorithms continuously analyze data from sensors or other sources to make decisions about the optimal path. This could involve avoiding obstacles, optimizing for efficiency, or responding to real-time changes in the environment.

Dynamic path planning finds applications in various fields, includ-

ing robotics, autonomous vehicles, and mobile robotics, where quick decision-making and adaptability to changing conditions are essential. Examples include path planning for drones navigating through dynamic environments, autonomous vehicles adjusting their routes based on traffic conditions, and mobile robots navigating cluttered or unpredictable environments.

Dynamic path planning schemes can be categorized into two groups: those with obstacle consideration and those without. Various examples of dynamic path planning in WSNs are proposed, such as Breadth-First (BRF) and Backtracking Greedy (BTG) algorithms [81], Snake-like [82], deterministic beacon mobility scheduling (DREAMS) [83],

3.8.2 Beacon points

After choosing the trajectory, it is necessary to define the positions (or time) from which the packets will be sent, as well as their content. The mobile node traverses the deployment zone following a chosen static curve, and each time it reaches a well-defined position according to the chosen trajectory, it broadcasts information containing the value of its current position. In turn, the nodes receiving this information execute the localization algorithm.

In the context of mobile anchor-based localization, recent models have primarily utilized three regular geometric shapes - triangles, squares, and hexagons - to partition a two-dimensional plane. These shapes serve as the foundation for constructing routing paths and optimizing the localization process [76]. Various research studies have explored different approaches based on these geometric shapes. For instance, square grid decomposition has been investigated in works

such as [9, 23–25]. Similarly, triangle grid decomposition has been utilized in research studies like [78–80, 84, 85]. Additionally, hexagonal grid decomposition has also been explored in studies such as [75, 76, 86, 87]. These models leverage the properties and characteristics of these geometric shapes to devise efficient routing paths that facilitate accurate localization within the WSNS.

3.9 Triangle grid decomposition

In a triangular grid, the entire network is divided into numerous non-overlapping triangular cells, serving as the basis for various path planning approaches in mobile anchor-based localization as shown in Figure 3.7.

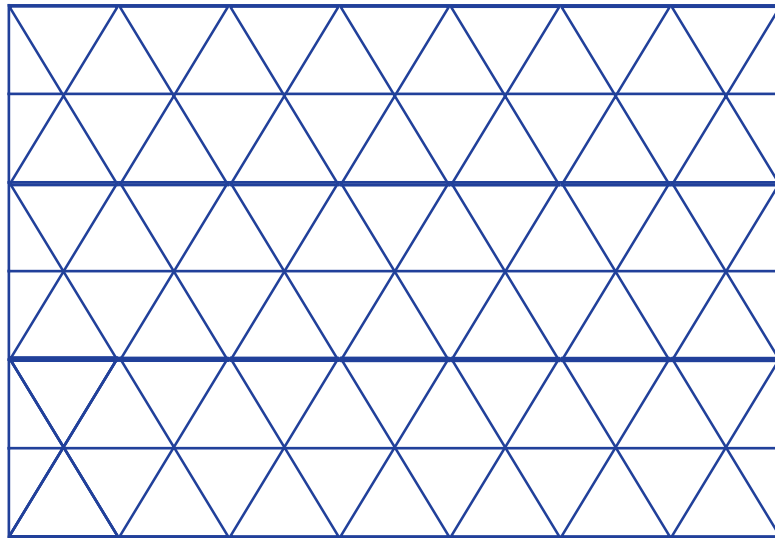


Figure 3.7: Triangle grid decomposition.

An instance of path planning in the research conducted by Han et al. [80]. provide a Localization method based on Trilateration (LMAT) with a Mobile Anchor node as shown in Figure 3.8. The mobile anchor node in this method broadcasts its current position regularly while moving through the deployment region

on a trilateration trajectory. In a different study, Han et al. [84] present SLMAT, which considers post-disaster scenarios and handles the mobile anchor node's finite energy consumption, notably during starting, turning, and uniform motion. An LMAT + SCAN algorithm integrated path-planning method (SLMAT) is presented to maximize location accuracy and energy usage. In order to preserve the mobile anchor node's energy, SLMAT minimizes the number of corners along the intended path while ensuring that each unknown node is covered by a regular triangle made up of beacons.

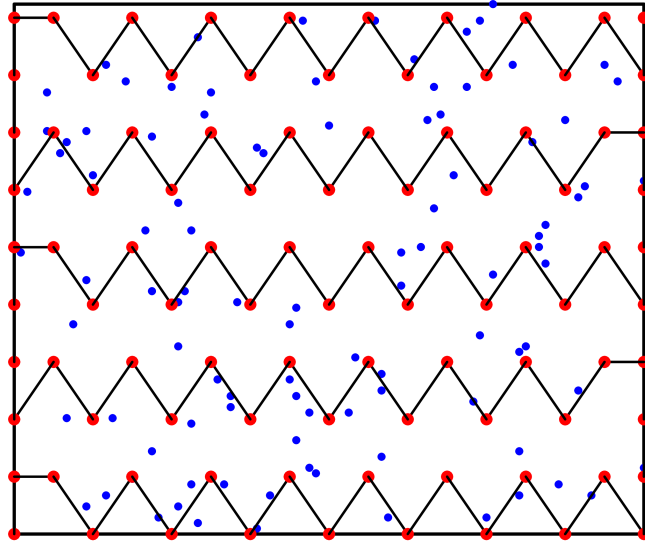


Figure 3.8: LMAT path planning.

3.10 Hexagon grid decomposition

A hexagon grid refers to a tessellation pattern where the entire area is divided into interconnected hexagonal shapes, forming a grid-like structure as shown in Figure 3.9. Similar to triangular grids, they serve as a foundation for path planning in

mobile anchor-based localization. The grid helps define the movement path of the mobile anchor to ensure efficient coverage and data collection from sensor nodes.

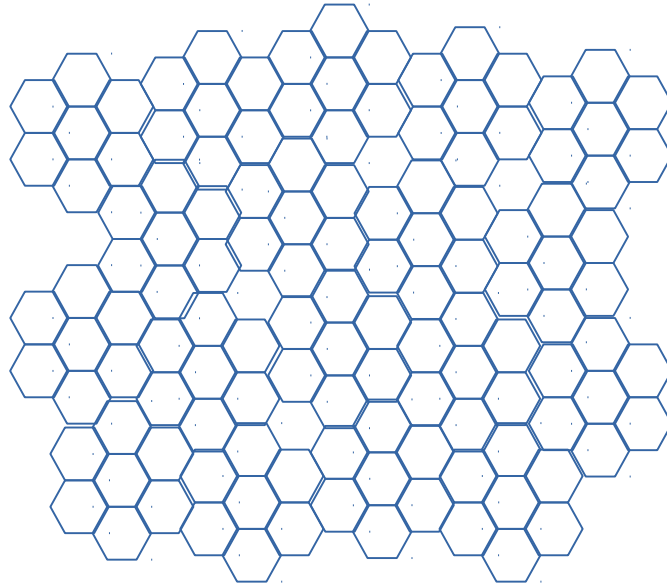


Figure 3.9: Hexagon grid decomposition.

In existing literature, various hexagonal addressing methods have been discussed for identifying hexagons within a hexagonal tessellated plane. For example [Chen and Wang \[76\]](#) investigate the routing path for mobile anchor localization using a node-Gosper curve, which is based on hexagonal tessellation. The node-Gosper curve is generated by iteratively replacing each node with a seven-segment generator curve, resulting in a fractal space-filling curve. Applying the Gosper curve to data collection or distribution by a mobile anchor and clustering sensors in a WSNs inside areas bounded by regular hexagons show that routing through the centers of these hexagons is more efficient than routing through their chords, which is what the Gosper curve does as shown in [Figure 3.10](#). A node-Gosper curve is a particular kind of Gosper curve that tracks the centers of hexagons.

In [\[87\]](#), a novel traversing path scheme called Linear-Hexagonal (LH) traversal

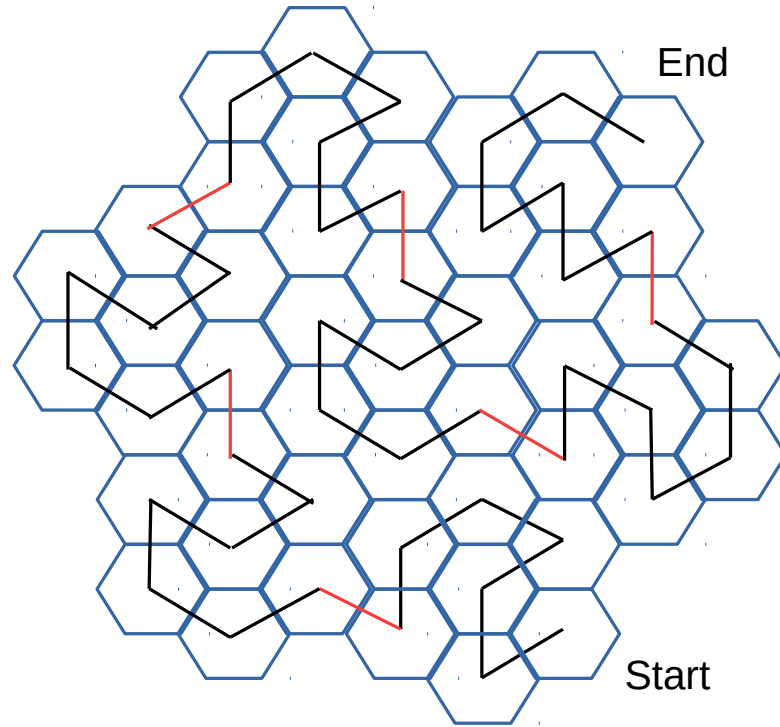


Figure 3.10: Gosper island Level-2 with its corresponding type-R node-Gosper curve.

scheme is introduced. This proposed scheme combines the hexagonal approach with linear traversal. While previous studies have shown lower localization error with polygonal traversal, it often results in increased traversal length. To address this, a polygonal sequence is integrated into the traversal scheme SCAN to reduce the path length as shown in Figure 3.11.

3.11 Square grid decomposition

Square grid decomposition is a method used to divide a two-dimensional plane into a grid consisting of square cells, as shown in Figure 3.12. This approach offers a structured and organized framework for managing sensor nodes in a WSNs. By assigning nodes to specific cells based on their coordinates, the management and

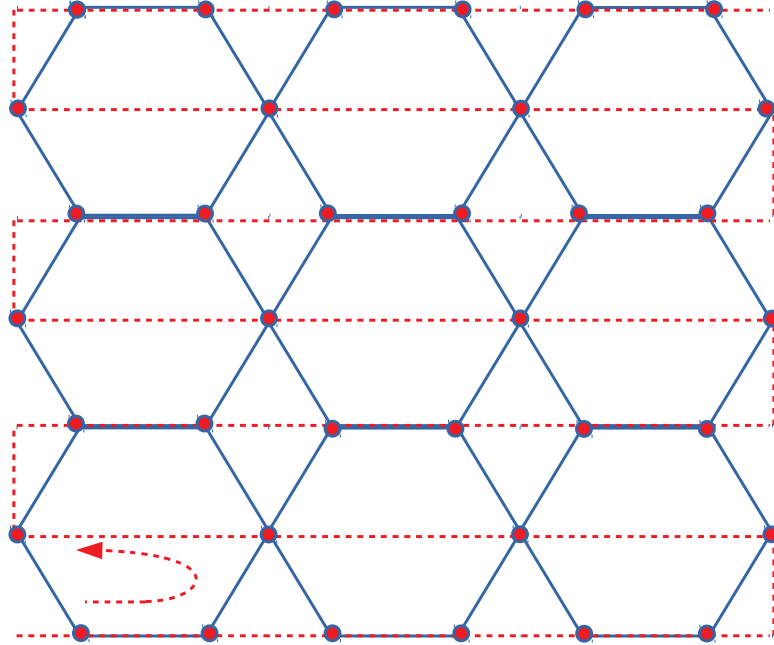


Figure 3.11: Linear-Hexagonal path planning.

organization of nodes become simplified. Additionally, the structured nature of the grid enables the implementation of efficient routing algorithms, as it provides a clear pathway for data transmission between nodes residing in the same or neighboring cells. This decomposition technique promotes effective coordination and communication among sensor nodes, enhancing the overall performance of the network.

Examples of localization models based on square grid decomposition are as follows:

D.Koutsonikolas and al in [9] explore three distinct trajectories for the mobile anchor: Scan, Double Scan, and Hilbert. They emphasize the significance of deterministic trajectories covering the entire area, demonstrating substantial advantages over random trajectories.

SCAN path: This trajectory, depicted in Figure 3.13, is a straightforward and easily implementable approach where the mobile anchor moves along one dimen-

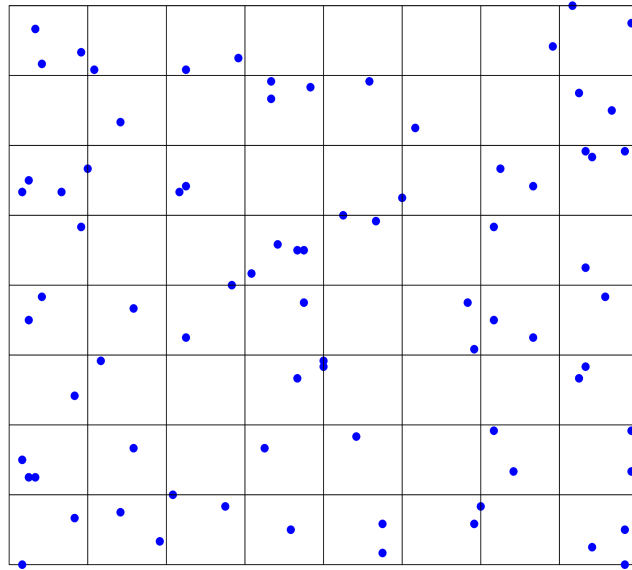


Figure 3.12: Square grid decomposition.

sion, specifically the y-axis. The distance between successive segments of the trajectory defines its resolution. SCAN ensures uniform coverage of the entire network, allowing all nodes to receive beacons from the mobile anchor when a suitable resolution is chosen. While maintaining low maximum error due to its uniformity, SCAN faces a notable drawback - the collinearity of beacons. At higher resolutions, nodes may only receive beacons from one line segment and one direction, introducing uncertainty and hindering accurate estimates along the x-axis. To address this issue, the trajectory must be sufficiently dense to allow sensors to hear the mobile anchor when moving on two successive segments along the y-axis, eliminating uncertainty and ensuring high accuracy.

HILBERT path: A HILBERT space-filling curve is a geometric construct that organizes points in a higher-dimensional space in a linear order while preserving the spatial relationships between these points. Specifically, a level- n HILBERT

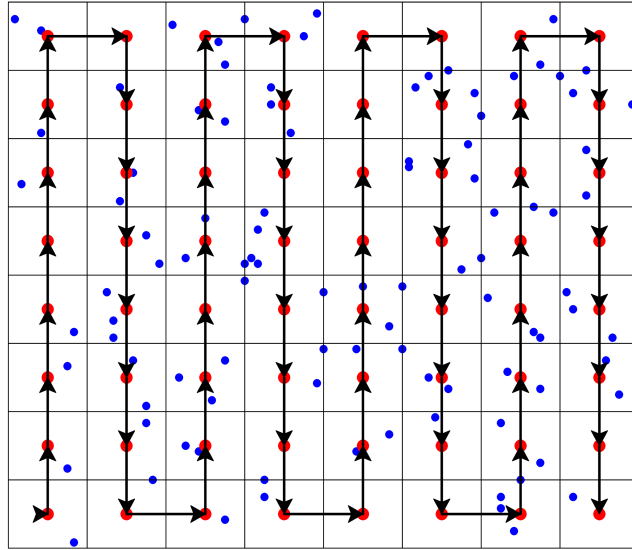


Figure 3.13: SCAN path.

curve partitions a 2-dimensional space into 4^n square cells. The centers of these cells are then interconnected by 4^n line segments, and the length of each segment corresponds to the side length of the square cells, as shown in Figure 3.14.

The Hilbert approach operates by partitioning the given area into four uniform squares and establishing connections between the points situated at the boundaries of these squares. Utilizing localization information obtained from various non-collinear positions, the unknown nodes can achieve more precise estimations of their locations compared to the SCAN method. However, a notable challenge in the Hilbert method lies in the coverage problem. This arises when unknown nodes positioned at the periphery of the area struggle to receive sufficient information, hindering their ability to accurately estimate their locations. Consequently, this issue adversely impacts the overall localization ratio and contributes to an increase in localization errors.

SCAN offers the best performance with a fine path degree, but with a coarse path degree, while HILBERT is the best choice since it solves the problem of collinearity posed by SCAN, but with an increase in the number of corners.

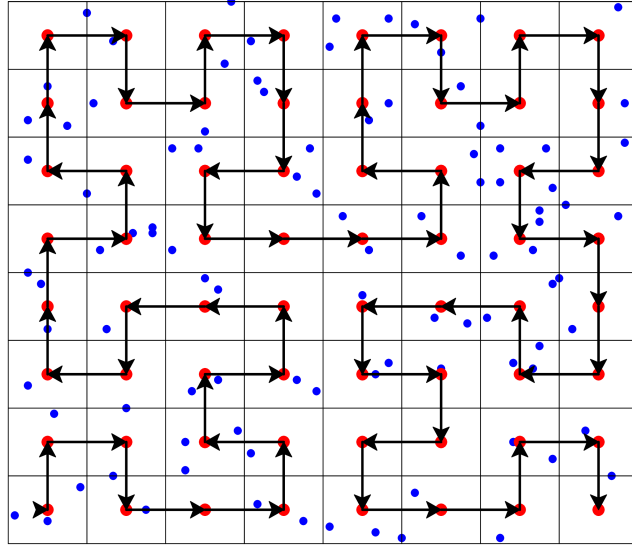


Figure 3.14: HILBERT path.

Another example of a space-filling curve is the **Z-curve** [23], where a level- n Z-curve divides the ROI into 4^n squares and connects the centers of squares and the center of each basic curve via a Z-shape, as shown in Figure 3.15. The square side length is the Z-curve path degree. This algorithm solves the collinearity problems but increases the number of corners. In parallel, the Z-curve decreases the path length and reduces the localization time. In [88], an algorithm with two mobile anchors instead of a single mobile anchor was proposed using the Z-curve trajectory.

S-Type path: The strategy we suggest in [25] involves utilizing an 'S' type trajectory as a macro moving pattern for a mobile anchor, illustrated in Figure 3.16.

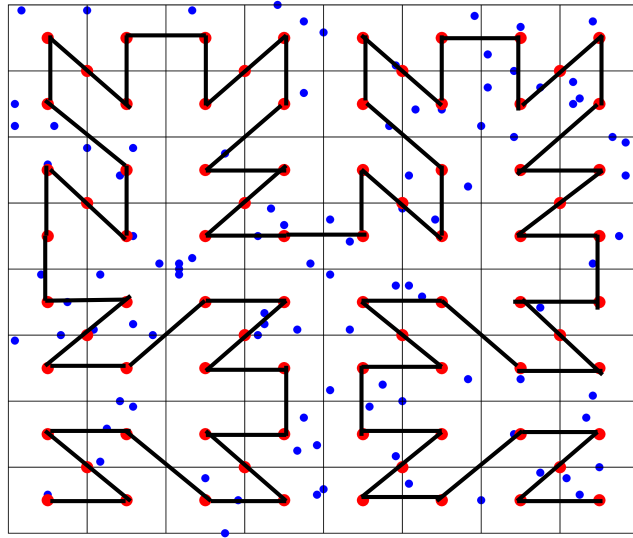


Figure 3.15: ZCURVE path.

This not only contributes to extending the lifespan of the mobile anchor but also enhances the overall reliability of the system. Another noteworthy benefit of this movement strategy is that unknown nodes within a small square area can receive four evenly distributed beacon messages, thereby enhancing the accuracy of location information. This approach compared the trilateration with two generalized geometrical localization algorithms.

The Σ -Scan curve proposed in [24], illustrated in Figure 3.17, is a cross between SCAN and Z-curve that benefits from both of their advantages. It has three kinds of units, namely Double-Unit, Square-Unit, and Triple-Unit. The latter can constitute an arbitrary rectangle to give the best exploitation of ROI compared to Hilbert and Z-curve, but it is relatively complex in their implementation. The unit side length represents the Σ -Scan path degree.

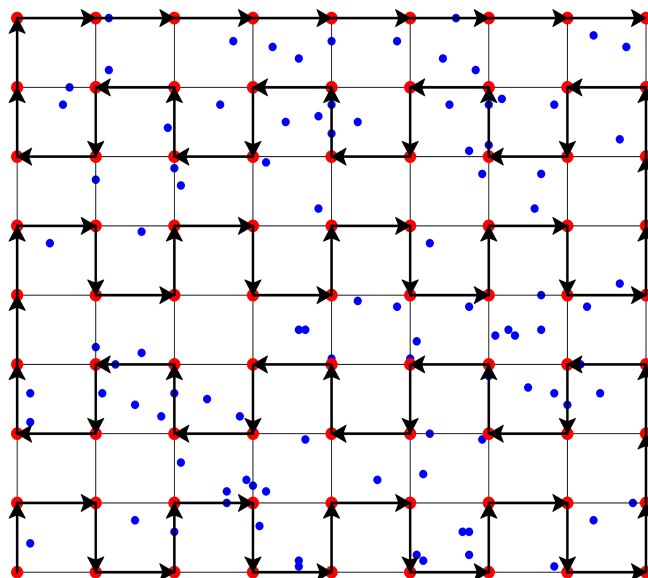


Figure 3.16: S-TYPE path.

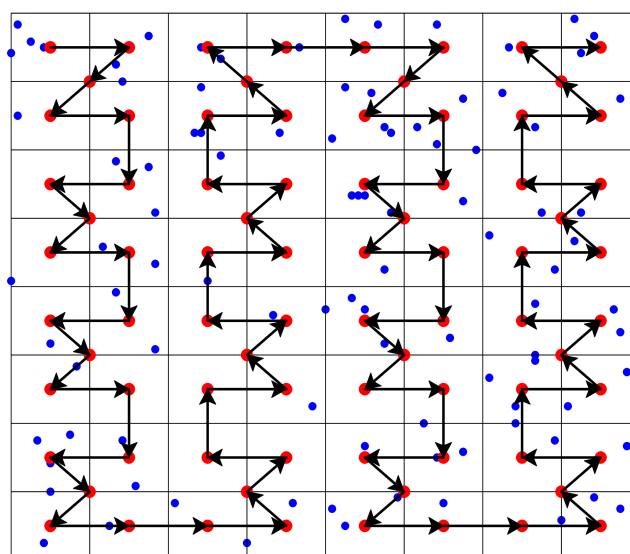


Figure 3.17: SCAN path.

3.12 Conclusion

Localization is a crucial element in sensor networks, particularly in communication protocols for applications that rely on geographic routing. This chapter gives an overview of localization, covering its key components and classification. It also emphasizes a specific approach to localization using a mobile anchor. In this method, planning the right trajectory and determining optimal positions for beacon points are critical. Finally, we introduce a model based on dividing the area into squares for improved localization.

CHAPTER 4

Proposed approach: Union-curve algorithm for mobile anchor-based localization

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4.1 Introduction

We present a novel path planning model for mobile anchor-based localization in WSNs in this chapter, called Union-curve. The main contribution of this chapter is the competitive path planning model that is proposed and shown to perform better than previous methods. The objective of the improved path model is to increase the percentage of successfully located nodes and enhance localization accuracy. Our approach ensures that when the resolution is equal to or greater than one, location information will be received by all nodes in the network, enabling unknown nodes to estimate their current locations based on the received information.

The proposed approaches are introduced in Section 4.2, followed by a detailed description of mobile anchor path planning in Section 4.3. Section 4.4 details the localization algorithm applied in our model. A summary of the chapter can be found in Section 4.5.

4.2 Proposed approach

In this section, we outline the key elements of our proposed mobile anchor-based localization model, known as the Union-curve algorithm. The model consists of two main steps illustrated in Figure 4.1. The initial step involves defining the path planning for the mobile anchor, while the second step focuses on the implementation of the localization algorithm. Subsequent subsections will provide

further insights into these two steps.

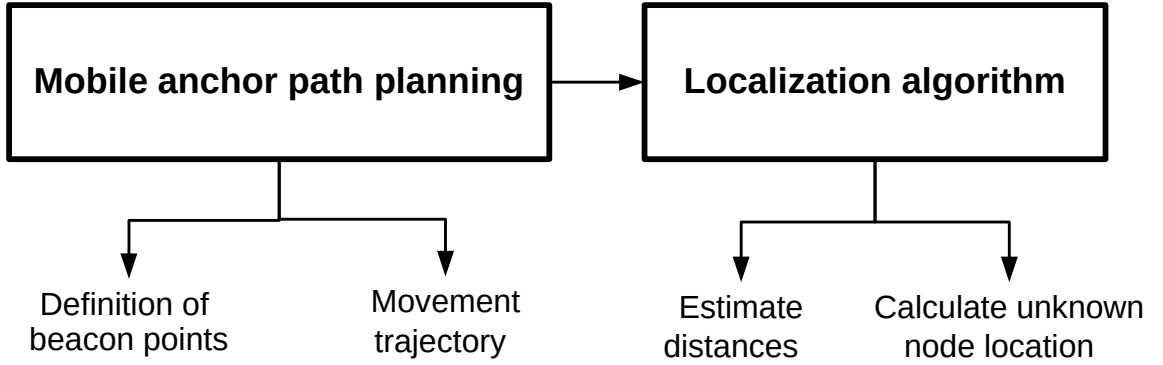


Figure 4.1: Union-curve algorithm.

4.3 Mobile anchor path planning

During this stage, it is crucial to establish the trajectory for the mobile anchor and determine the timing for broadcasting beacon packets.

4.3.1 Position of beacon points based on square grid decomposition

We assume the deployment of a WSNs in a two-dimensional area of size $S \times S$. The Region of Interest (ROI) is divided into squares using square grid decomposition, as illustrated in Figure 4.2(a). The side length of each square, denoted as L , is adjusted based on the communication range r of the mobile anchor node and the length of the ROI, S . The value of L represents the path degree. To enhance the accuracy of location determination for unknown sensor nodes, finding the optimal deployment of beacon points is essential. In this regard, three possibilities are explored based on square grid decomposition to determine the positions of beacon

points:

- **The beacon points are strategically placed at the centers of squares,** as depicted in Figure 4.2(b). SCAN and HILBERT divide the two-dimensional deployment area into square cells and connect their centers using straight lines. By analyzing these two trajectories and examining their choice of beacon points, it becomes evident that both SCAN and HILBERT opt for the centers of squares as the designated beacon points. However, it is worth noting that in these two path plannings, the mobile anchor passes through the same broadcast points, although not in the same order, as shown in Figure 4.2.
- **The beacon points are defined at the vertices of squares,** as depicted in Figure 4.2(c). In the S-Type trajectory, after the division of the area into squares, the mobile beacon passes through the vertices of the squares in an S-shape, determining the beacon positions at the vertices of square cells, as indicated in Figure 4.2.
- **The beacon points are defined at both the centers of squares and the centroid points of each four sub-squares,** as illustrated in Figure 4.2(d). Two path planning methods, namely Z-curve and Σ -Scan, adopt this proposition. It is important to note that Z-curve and Σ -Scan pass through the same beacon points, but not in the same order.

4.3.2 Defining of Union-curve's beacon points

In our proposed path planning model, Union-curve, beacon points are strategically placed at both the centers and the vertices of squares, as illustrated in Figure 4.3.

Union-curve encompasses all the beacon points of the other five paths (HILBERT, SCAN, Z-curve, S-type, and Σ -Scan), as shown in Figure 4.3. This extensive deployment allows Union-curve to pass very close to unknown node positions, providing high-quality packets with a strong signal that enhances precision [22]. Within each sub-square, unknown nodes can receive five beacon messages, as depicted in Figure 4.4, ensuring full coverage of all unknown nodes.

4.3.3 Movement trajectory

The Union-curve is a simple and easily implementable path planning model characterized by diagonal scanning coverage. Initially, a mobile anchor node is placed at the corner of the area. It subsequently traverses the entire Region of Interest (ROI) along the Union-curve trajectory, broadcasting its location at intervals of L for vertical or horizontal movement and $\frac{\sqrt{2}}{2} \times L$ for diagonal movement, as depicted in Figure 4.3. This trajectory design aims to minimize the number of corners, optimizing path planning efficiency [84]. The path length of the Union-curve is determined by Equation 4.3.1.

$$length_{Union} = (2 \times S) + \left(\frac{\sqrt{2}}{L} \times S^2\right) \quad (4.3.1)$$

4.4 Localization algorithm

A localization algorithm based on a mobile anchor operates as a decentralized approach, distributing the task of calculating the positions of unknown nodes among sensor nodes. These algorithms prioritize energy efficiency by restricting

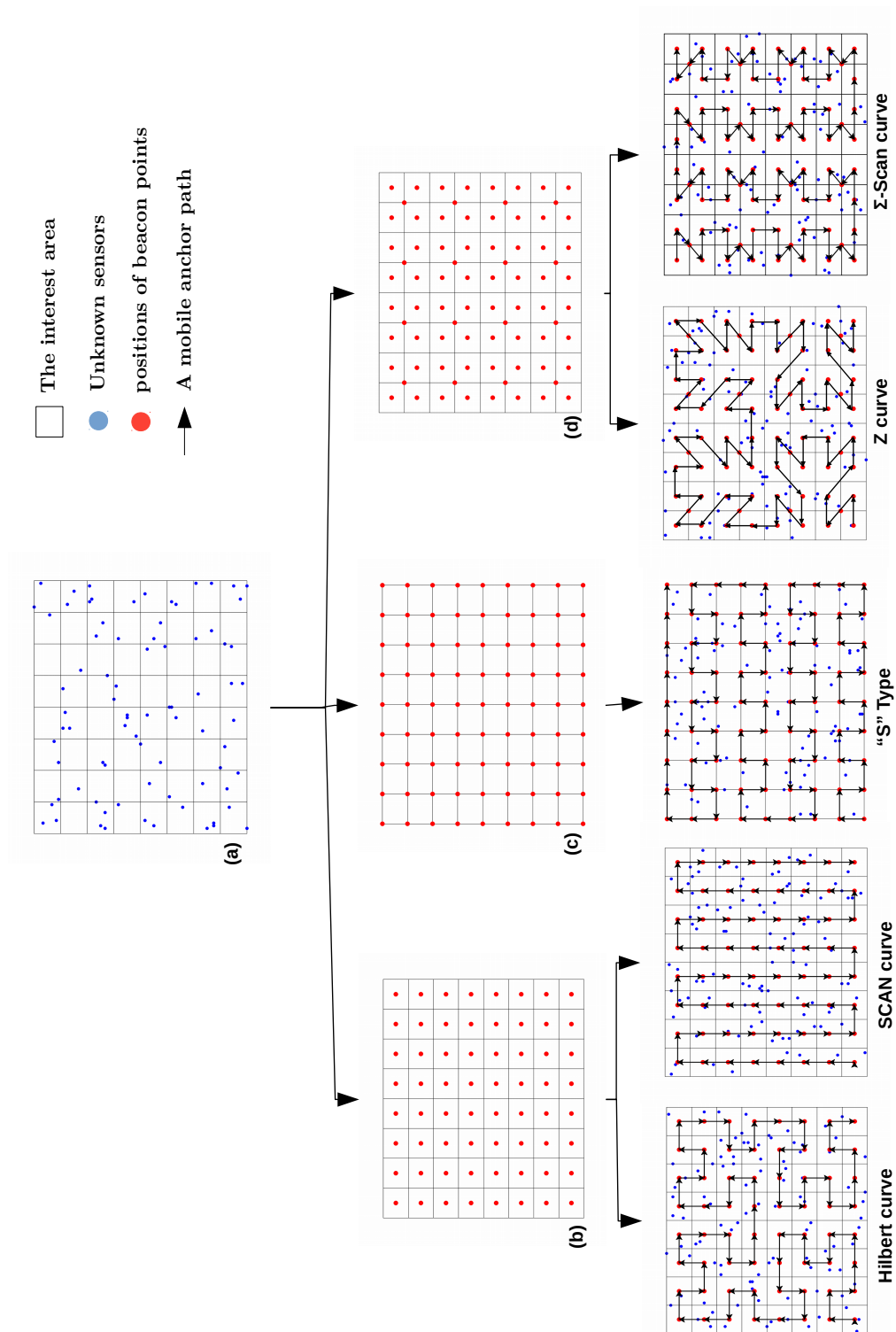


Figure 4.2: Decomposition of area and determination of positions of beacon points.

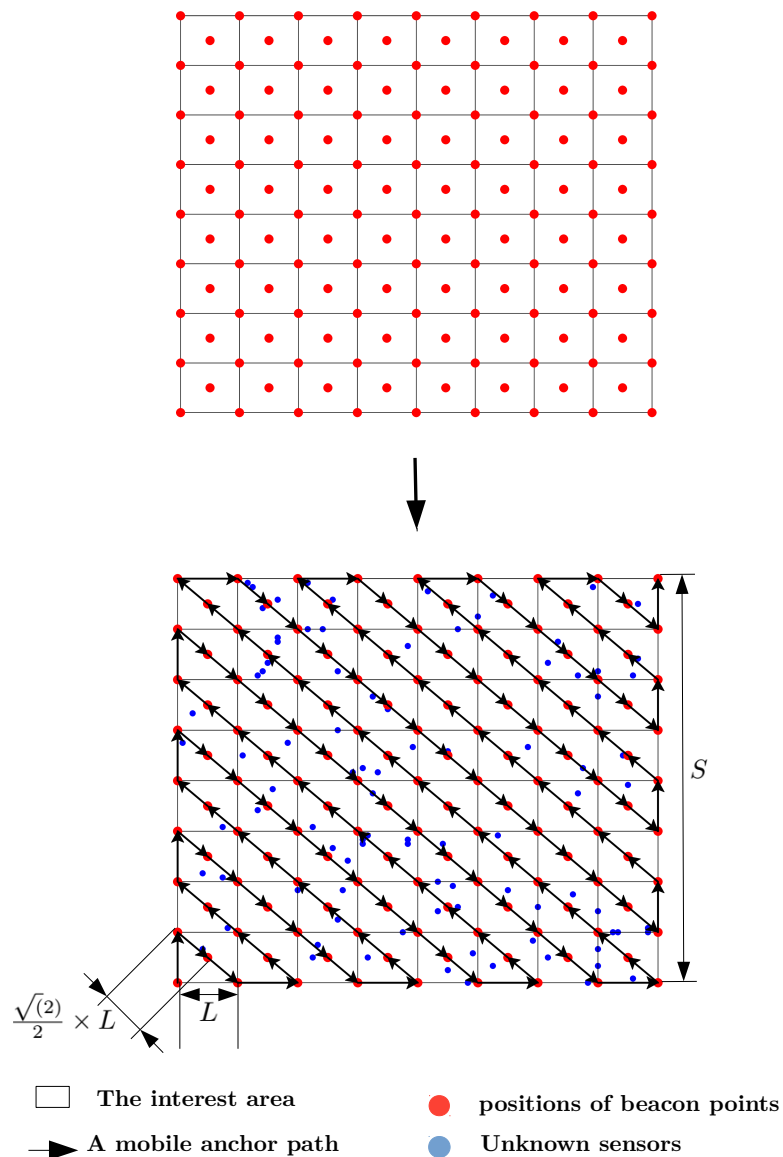


Figure 4.3: Union-curve.

communication solely to interactions between the mobile anchor and unknown nodes.

The localization algorithm begins with the following steps:

1. The network is composed of N unknown nodes, strategically dispersed randomly and uniformly throughout an obstacle-free detection field, along with

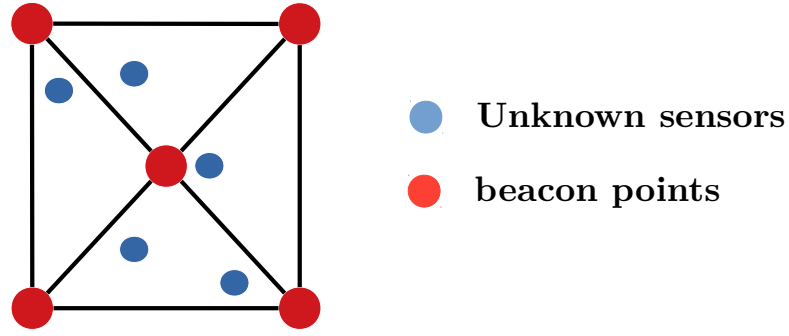


Figure 4.4: The sub-square in Union-curve.

a single mobile anchor.

2. The path for the mobile anchor is determined, outlining its trajectory across the region of interest.
3. System parameters are configured, including the distance between beacon points (path degree), the communication range of the mobile anchor, and other relevant factors. The specific values are adjusted based on the size of the area and the characteristics of the materials involved in the network.

Following the configuration of the localization system, the algorithm initiates two simultaneous processes. The first process is executed by the unknown nodes, while the second is managed by the mobile anchor node. This dual-process framework promotes collaborative and efficient localization, with a primary emphasis on minimizing energy consumption. In the subsequent sections, we will delve into the details of each process, elucidating the roles and contributions of both the unknown nodes and the mobile anchor node.

4.4.1 The mobile anchor process

After defining the path and determining the positions of the beacon points, the mobile anchor traverses the region of interest along a predefined trajectory. At each beacon point along its path, the mobile anchor broadcasts a packet containing its current position. The process concludes upon the mobile anchor reaching the end of its designated path. The algorithm flowchart of the mobile anchor process is depicted in Figure 4.5.

4.4.2 The unknown node process

In parallel with the mobile anchor process, at each beacon point, if the unknown sensor nodes are within the coverage area of the mobile anchor, they receive a beacon packet. Subsequently, the unknown nodes calculate their positions using one of the localization techniques, such as range-based localization (APT) or range-free localization (WCWCL-RSSI).

A. The unknown node process using the APT technique, as illustrated in Figure 4.6, can be summarized in two steps.

- a) **Distance Estimation:** Upon receiving a packet, the unknown sensor node estimates its distance to the sender using Received Signal Strength Indicator (RSSI).

However, it misses the second crucial step:

- b) **Trilateration and Collinearity Check:**
 - The unknown node discards all packets except the three with the smallest estimated distances. This reduces the impact of outliers and poten-

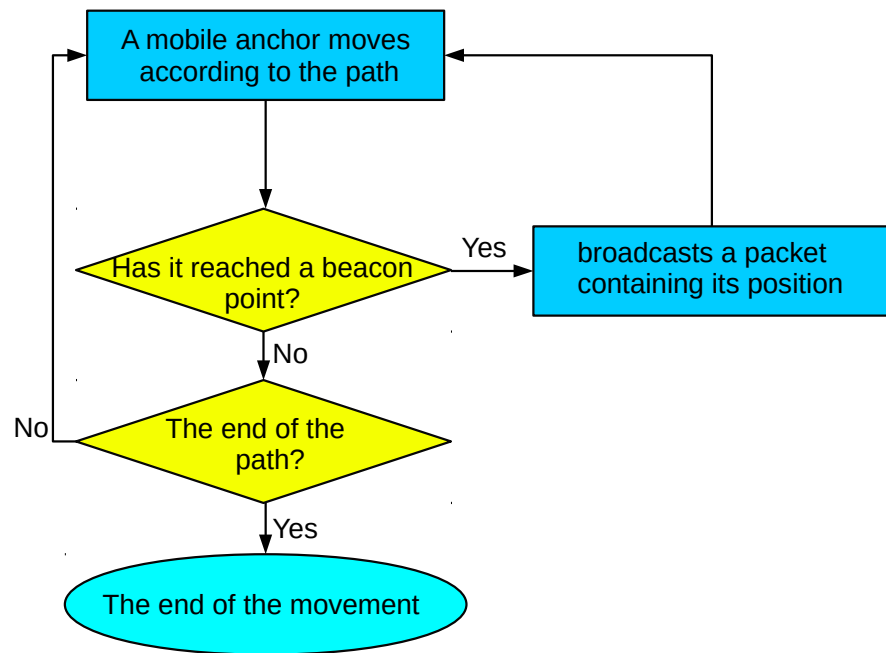


Figure 4.5: The mobile anchor process.

tial errors.

- It then performs a collinearity test on the remaining three packets. If they are found to be collinear (i.e., lie on a straight line), they are discarded, and the process restarts with the next highest distance packets.
- If the three packets pass the collinearity test, they are assumed to be non-collinear and used for trilateration. This calculation leverages the distances from the three reference nodes to estimate the unknown node's position.

By incorporating the collinearity check and utilizing only the shortest valid distances, the APT technique effectively minimizes the impact of the collinearity problem, leading to more accurate localization.

B. The process of the unknown node using the WCWCL-RSSI technique is illustrated in the algorithm flowchart presented in Figure 4.7. Each un-

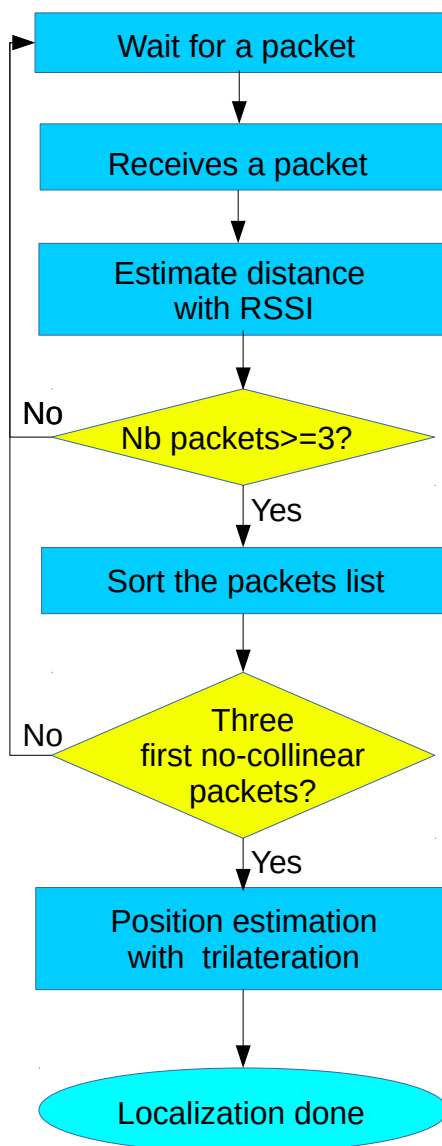


Figure 4.6: The unknown node process with APT method.

known node receives multiple (more than three) localization packets and employs WCWCL-RSSI to calculate its position based on them.

Performance Evaluation: To assess the WCWCL-RSSI technique's performance, two experiments were conducted:

- a) Experiment 1: The unknown node uses only the first 10 received messages for position calculation, ignoring others.
- b) Experiment 2: The unknown node sorts received packets based on signal strength (strongest first). It then calculates its position using WCWCL-RSSI with varying numbers of top-ranked messages: 3, 4, and 5.

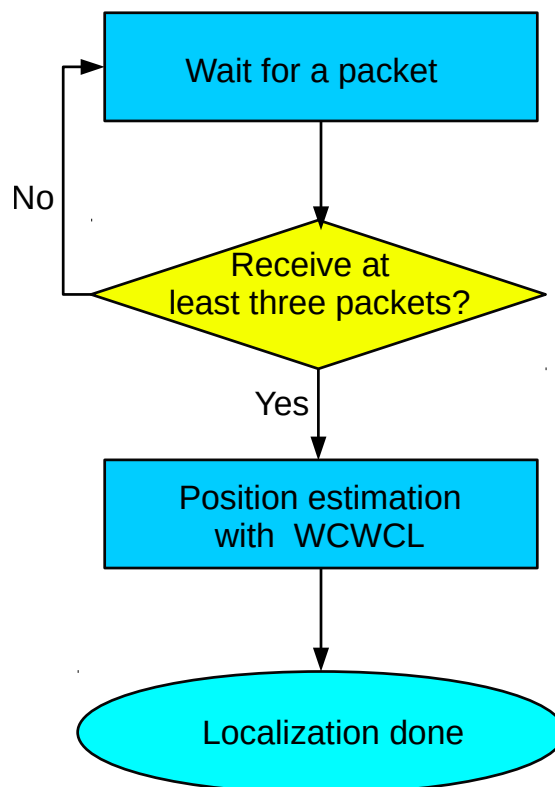


Figure 4.7: The unknown node process with WCWCL-RSSI method.

4.5 Conclusion

We present a novel static path planning model for localization in this chapter, in which the mobile anchor moves along a constant trajectory. Our model is developed using the square decomposition of the region of interest, which is comprised of the union of beacon points from five static trajectories: S-type, Z-curve, Scan, Hilbert, and Σ -Scan. The Union-curve ensures high-quality packet delivery with a robust signal, thereby enhancing precision by guiding the mobile anchor to travel as closely as possible to unknown node positions. It involves sending five beacon messages to unknown nodes within each sub-square, ensuring that all unknown nodes are covered.

CHAPTER 5

Performance Evaluation and Simulation Results

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5.1 Introduction

The evaluation includes determining unknown node positions through two localization techniques: range-based localization (APT) and range-free localization (WCWCL-RSSI). To assess and validate our model's effectiveness, we employ five key analysis metrics.

The simulation environment and parameters are discussed in Section 5.2. Section 5.3 presents the simulation results and performance evaluation, demonstrating how path parameters affect localization. Using four analysis metrics, we assess the efficacy of the Union-curve model. The conclusion is provided in Section 5.4.

5.2 Simulation environment and parameters

Our proposed model, implemented in Python 3, underwent a series of simulations to analyze and assess its performance. The results were averaged over 50 run times.

For the wireless channel model, we used realistic measured data reported in [50]. In this research, the researchers conducted an outdoor experiment to measure the distance between a mobile node and a coordinator node in a simple point-to-point ZigBee WSNs. The distance was determined using the RSSI measured by the coordinator node from the mobile node. They developed a Log-Normal Shadowing Model (LNSM) specifically tailored for outdoor conditions. Additionally, key parameters of the propagation channel, such as standard deviation and path loss

exponent, were estimated. RSSI values were meticulously measured and analyzed in outdoor settings, covering a distance range of 1-100 meters. The experiments utilized the 2.4 GHz ZigBee wireless protocol with XBee Series 2 modules. This choice was motivated by the ZigBee's capability to conduct RSSI measurements without requiring extra hardware, along with its advantages of being cost-effective, simple, and energy-efficient. The simulation parameters are detailed in Table 5.1.

Table 5.1: Simulation parameters.

Parameters	Symbol	Value
Network size	S	96 m \times 96 m
Number of unknown nodes	N	100
Number of mobile anchors	M	1
Mobile anchor communication range	r	12, 24
Resolution	$R = r/L$	3/4, 1, 5/4, 3/2, 7/4, 2, 9/4, 10/4
Path loss exponent	γ	2
Standard deviation (dB)	σ	1.326
Reference distance (m)	d_0	1
Path loss at a distance d_0 (dBm)	PL_0	32
Transmitter power (dBm)	P_T	2
Distance under test (m)	d	1-100
Number of simulation runs	SR	50

5.3 Performance evaluation and simulation results

In this section, firstly, we examine the impact of metrics and path parameters on the degree of satisfaction of localization criteria. Secondly, to analyze and evaluate the effectiveness of the proposed Union-curve model, four key analysis metrics are utilized: average localization error, standard deviation of the localization error, localization ratio, energy consumption, and the number of beacon points.

5.3.1 Effect of Path Parameters on Localization

In the study conducted by [2], it was observed that the challenge lies not only in selecting the appropriate path but also in determining the parameters that yield optimal results. To explore the impact and significance of path parameterization on the quality of localization systems with a mobile anchor node, a series of simulations were conducted. Four path planning models were chosen for analysis, and each model was evaluated using four key quality metrics.

Choosing the right path alone is insufficient; accurate path parameters such as the mobile anchor communication range (r) and path degree (L) must also be set to achieve precise results. It is noteworthy that certain parameters may conflict with each other, and enhancing one parameter may potentially compromise another. The analysis metrics are dependent on two parameters, r and L . Thus, the path resolution (R) is defined as the ratio of r to L , i.e., $R = r/L$.

Figure 5.1 provides a graphical representation to illustrate the concept of path resolution R . Assuming L is the distance between two diffusion points p_1 and

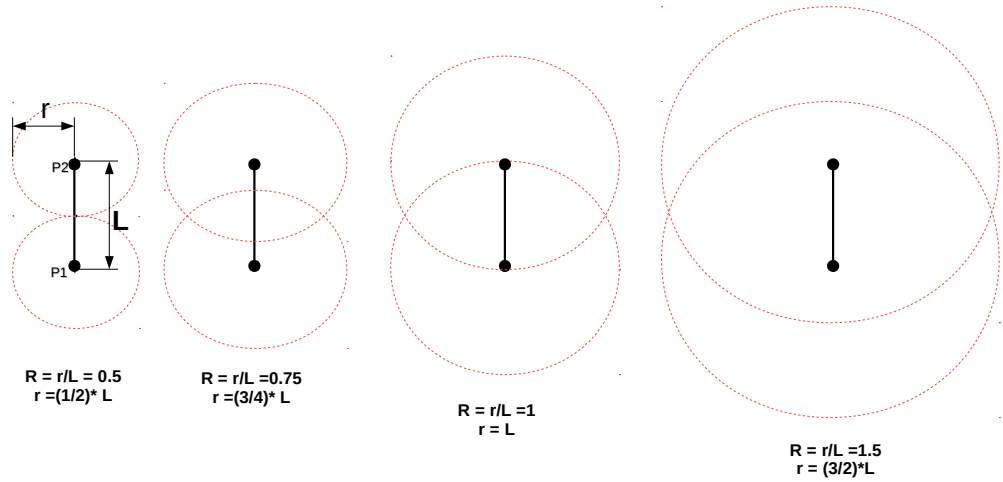


Figure 5.1: Graphical representation of path resolution R .

p_2 , and r is the communication range of the mobile anchor, the radius coverage is represented by a circle. When $R = 0.5$, the intersection between two circles is a single point, and as R increases, the coverage becomes larger, as depicted in Figure 5.1.

Two main parameters influence the performance of the localization algorithm:

- a) Mobile anchor communication range: A larger communication radius of the mobile anchor covers more unknown nodes. Consequently, unknown nodes receive more packets, but the distance estimation error increases, leading to a higher average localization error.
- b) Broadcast interval (path degree): A smaller broadcast interval implies more frequent broadcasting of the mobile anchor's location, improving localization performance. However, this results in a longer path length and higher energy consumption.

5.3.2 Average localization error

The average localization error is a crucial metric for evaluating the performance of localization algorithms in WSNs. It is calculated using Equation 5.3.1.

$$L_e = \frac{\sum_{i=1}^n Error(i)}{n} \quad (5.3.1)$$

where

$$Error(i) = \sqrt{(x_{ei} - x_i)^2 + (y_{ei} - y_i)^2} \quad (5.3.2)$$

In equation 5.3.2, (x_{ei}, y_{ei}) and (x_i, y_i) represent the estimated and real coordinates of node i , respectively. L_e and n indicate the average localization error and the number of successfully localized nodes, respectively. It's important to note that $n \leq N$, where N is the total number of unknown nodes.

Figure 5.2 visually compares the average localization error at different resolution values between our model and five static path planning algorithms (Σ -Scan, Z-curve, SCAN, HILBERT, and S-type), utilizing APT as the localization method. The analysis indicates that the proposed Union-curve model achieves the highest accuracy and the lowest average error rate, followed by S-type, Σ -Scan, Z-curve, SCAN, and HILBERT. Notably, when the resolution value exceeds 1.25, a substantial difference in error rate of approximately 0.26 emerges between the Union-curve and the second most efficient, S-type.

The results further demonstrate that pairs of curves (Σ -Scan, Z-curve) and (SCAN, HILBERT) exhibit comparable performance, as the associated mobile anchor traverses the same beacon points albeit in a different order. Additionally, the APT method prioritizes minimizing distances without considering the order in which messages are received.

In Figure 5.2, all curves stabilize independently after reaching a specific resolution value. At this point, all unknown nodes receive three messages corresponding to the three smallest distances. Consequently, any further increase in resolution does not impact the error rate, as the results remain unchanged. This is due to the fact that all messages received by these unknown nodes originate from remote beacon points and are, therefore, not considered in the analysis. Furthermore, the Union-curve exhibits rapid convergence, maintaining a stable error rate of 0.3 after reaching a resolution value equal to or greater than 1.0.

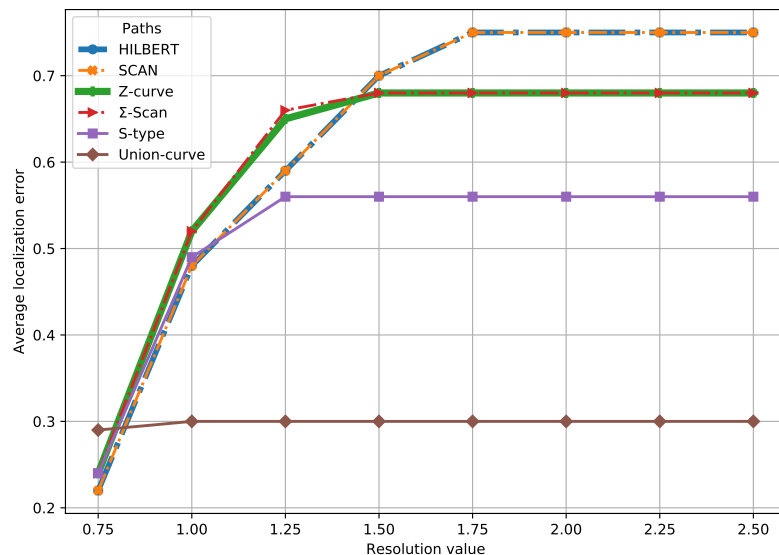


Figure 5.2: Comparison of average localization error rate based on APT method.

In Figure 5.3(a), we present the average error ratio results obtained by comparing algorithms for different resolution values when applying the WCWCL-RSSI method with ten messages. Notably, Union-curves and S-type emerge as the two best-performing path models, each exhibiting the lowest error rate in 4 out of 8 cases, demonstrating their capability to achieve comparable performance in terms of average error rate.

Referring to the results in Figure 5.3(b), the resolution value is fixed at 1.5, and the

number of messages varies from 3 to 5, increasing by one each time. It is essential to remember that the WCWCL-RSSI algorithm bases its decisions on a specific number of received messages with the most significant RSSI values. Our model consistently demonstrates a lower average error rate, providing a more accurate estimated location, particularly when the number of messages equals 4. Similar to the APT method, the curves of Σ -Scan and Z-curve yield the same results because they share the same beacon points. Similarly, the curves of SCAN and HILBERT also coincide due to their common set of beacon points.

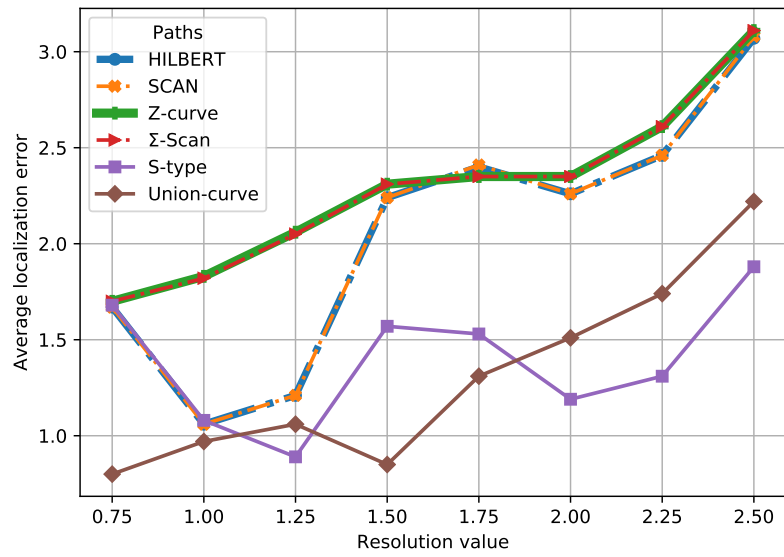
5.3.3 Standard deviation of the localization error

The second analysis metric involves assessing the standard deviation of the average localization error. A lower standard deviation suggests that the localization error values of unknown nodes are closely clustered around the average localization error. The standard deviation of the localization error rate, denoted as std_{error} , is computed using Equation 5.3.3:

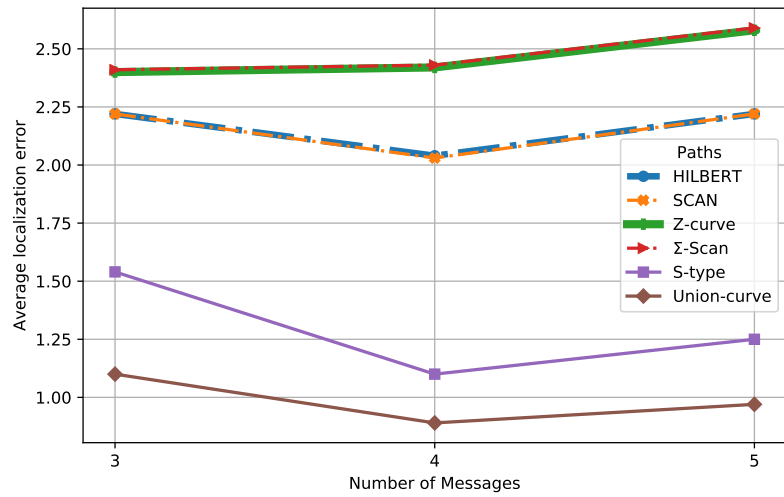
$$std_{error} = \sqrt{\frac{1}{n} \sum_{i=1}^n (Error(i) - L_e)^2} \quad (5.3.3)$$

Where, n , $error(i)$, and L_e represent the number of localized nodes, the localization error for unknown node i , and the average localization error, respectively.

The outcomes derived from employing the APT method are illustrated in Figure 5.4. Among all path models, the Union-curve exhibits the lowest standard deviation values for this metric, followed by S-type. This observation indicates that the dispersion around the average localization is minimal in comparison to the other models. Additionally, it is noteworthy that as the path resolution in-



(a)



(b)

Figure 5.3: Average localization error with WCWCL-RSSI method.

creases, the standard deviation values also increase until the localization ratio reaches 100%, signifying the stabilization point.

The standard deviations of the localization error values for each approach, determined by the WCWCL-RSSI method with the resolution value as a parameter, are depicted in Figure 5.5(a). The results illustrate a direct proportionality be-

tween the standard deviation of the localization error and the path resolution. This implies that an increase in the precision value leads to a rise in the standard deviation of the localization error rate for all six paths, although to a lesser extent for Union-curve and S-type.

Similarly, the standard deviations of the localization error values for each approach based on the WCWCL-RSSI method, with the number of messages as a parameter, are presented in Figure 5.5(b). The results reveal that Union-curve and S-type exhibit the best performance compared to the other paths. Additionally, our proposed path competes closely with the S-type curve path, showing a relatively modest enhancement when the number of messages is 3 or 4.

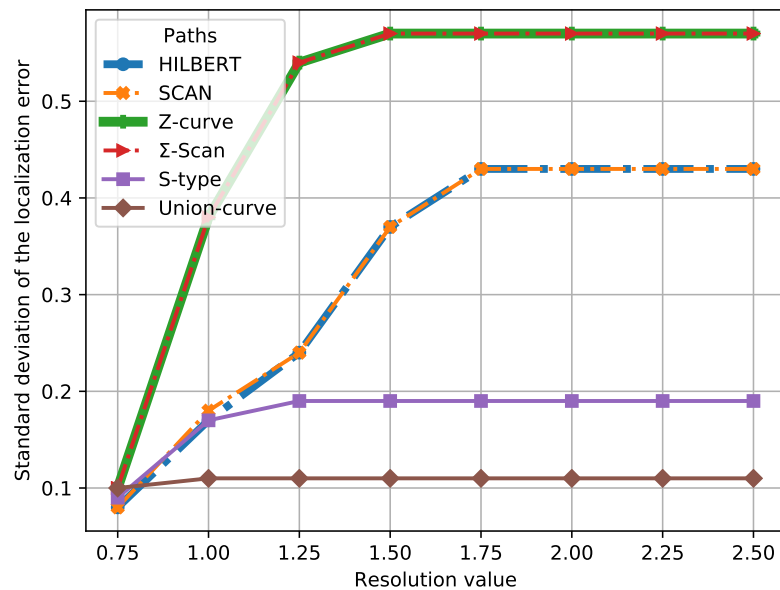
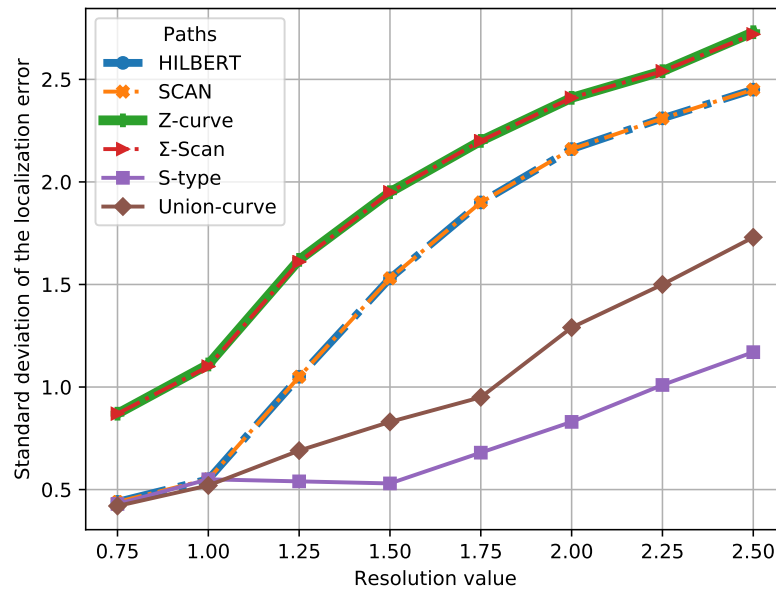


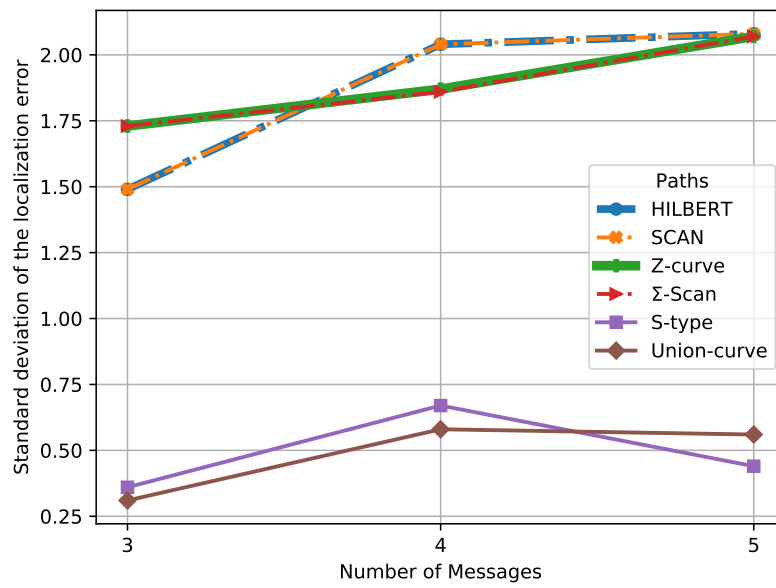
Figure 5.4: Standard deviation of the localization error with APT method.

5.3.4 Localization ratio

Another vital performance metric is the localization ratio (coverage), providing the proportion of sensor nodes that can be localized to the total number of nodes.



(a)



(b)

Figure 5.5: Standard deviation of the localization error with WCWCL-RSSI method.

The objective for each path is to achieve a high number of localized nodes with a small value for the path resolution. The localization ratio (C_R) can be calculated using the following formula:

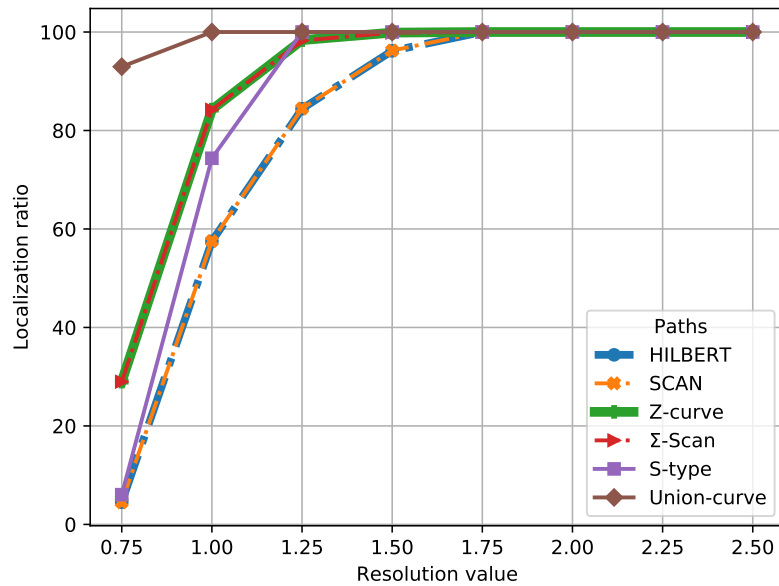


Figure 5.6: Localization ratio with APT method.

$$C_R = \frac{n}{N} \quad (5.3.4)$$

As mentioned earlier, the terms n and N represent the number of localized nodes and the total number of unknown nodes, respectively.

The analysis results for all paths regarding the localization ratio are depicted in Figures 5.6 and 5.7, utilizing the APT and WCWCL-RSSI methods, respectively. Notably, the two figures are almost identical, indicating that the localization ratio for each path remains consistent concerning the resolution value when applying either APT or WCWCL-RSSI, with a very slight exception in the case of SCAN and HILBERT paths. Furthermore, the resolution value has a significant impact on the localization ratio, and this influence is consistent across all paths, producing similar results for both methods. Let R denote the resolution value. The Union-curve achieves a localization ratio of 100% (fully localized nodes) at $R = 1$, while S-type, Σ -Scan, Z-curve, SCAN, and HILBERT reach this value at $R = 1.25$,

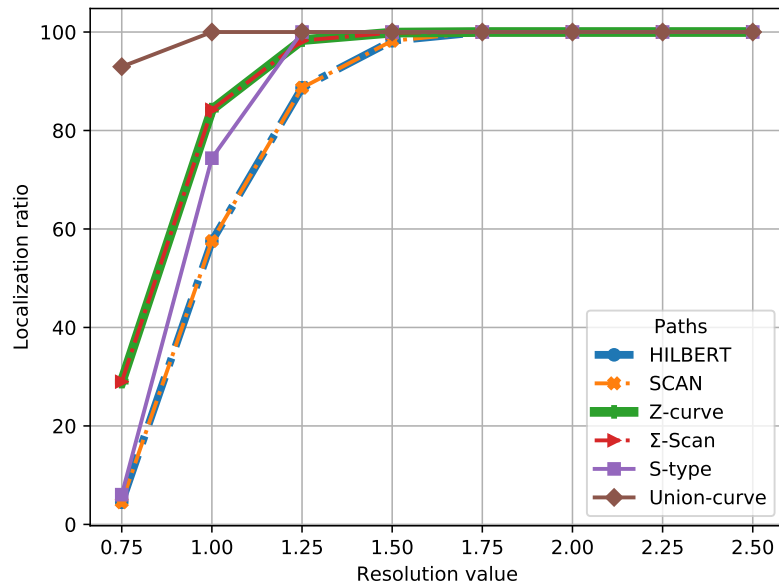


Figure 5.7: Localization ratio with WCWCL-RSSI method.

$R = 1.5$, $R = 1.5$, $R = 1.75$. Furthermore, the Union-curve can attain a localization ratio exceeding 90% at $R = 0.75$, whereas the others fail to surpass a 40% localization ratio at this particular resolution value.

5.3.5 Energy consumption and number of beacon points

The computation of energy consumption is grounded on the average number of processed or received messages by unknown nodes. As illustrated in Figure 5.8, an increase in the resolution value R results in unknown nodes receiving more messages for processing.

Specifically, the Union-curve exhibits the highest average number of received messages. To mitigate energy consumption, each unknown node considers only the first ten received messages during its calculations and disregards any subsequent ones.

Table 5.2 provides a comparison of the number of beacon points for the Union-

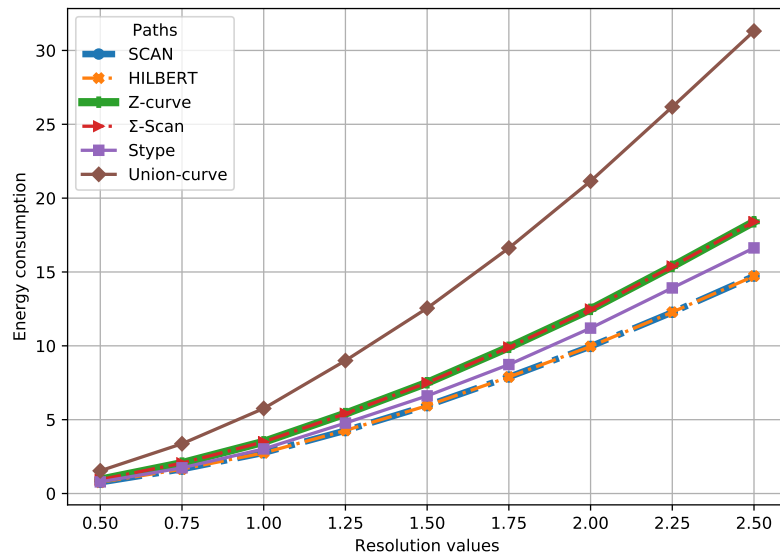

Figure 5.8: Energy consumption.

Table 5.2: Number of beacon points.

Paths.	Number of beacon points
SCAN(8*8 unit squares).	64
HILBERT(order 3).	64
Z-curve(order 3).	80
Σ -Scan(4*4 Square-Unit).	80
S-type (8*8 unit squares).	81
Union-curve (8*8 unit squares).	145
Union-curve with double L (4*4 unit squares).	41

curve, SCAN, HILBERT, Z-curve, Σ -Scan, and S-type curve. The quantity of beacon points is contingent on the network size S and the path degree L (distance between each pair of beacon points). It is noteworthy that the number of beacon points decreases as the value of L increases. For instance, in the case of the Union-curve, when the value of L is doubled, as depicted in Figure 5.9, the

number of beacon points decreases to 41. The order o_b of HILBERT and Z-curve

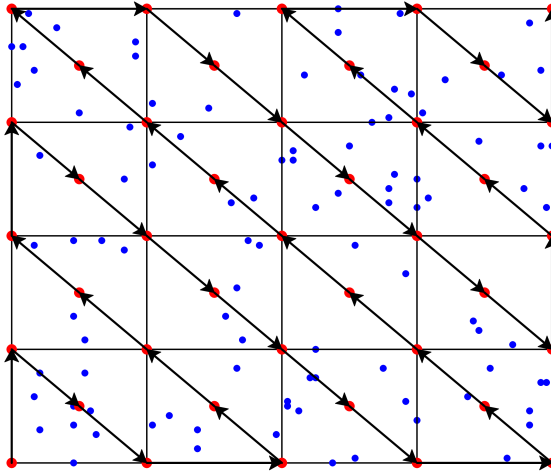


Figure 5.9: Union-curve with a double path degree L .

is computed using Equation 5.3.5 with 4^{o_b} units squares. For SCAN, S-type curve, and Union-curve, there are $Nb_s \times Nb_s$ units squares, where Nb_s is determined by Equation 5.3.6. Table 5.2 indicates that the Union-curve has a greater number of beacon points.

$$o_b = \log_2(S/L) \quad (5.3.5)$$

$$Nb_s = S/L \quad (5.3.6)$$

A reduced broadcast interval (path degree) implies that the mobile anchor broadcasts its location more frequently [2], enhancing localization performance. However, this improvement comes at the cost of increased average and standard deviation of the localization error, as evident in the results depicted in Figure 5.10 and Figure 5.11. While the obtained results are deemed acceptable, the trade-off is noticeable, showcasing higher average and standard deviation in the localization

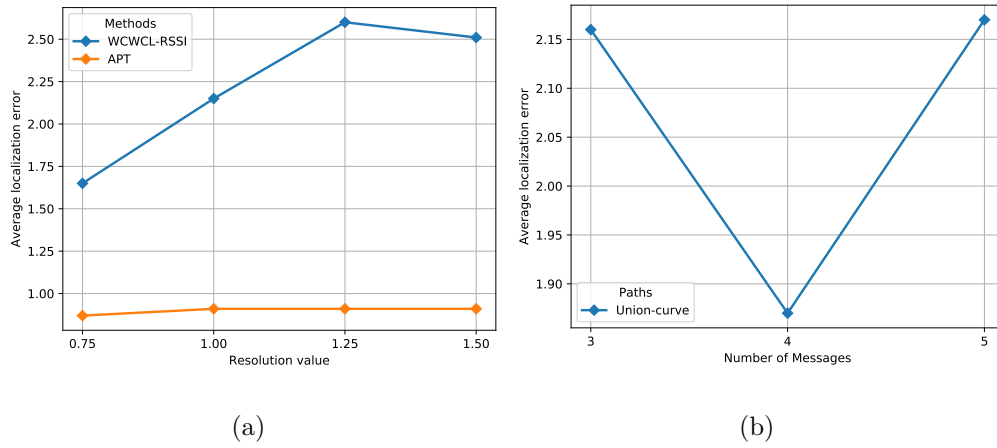


Figure 5.10: Average localization error of Union-curve with a double path degree L.

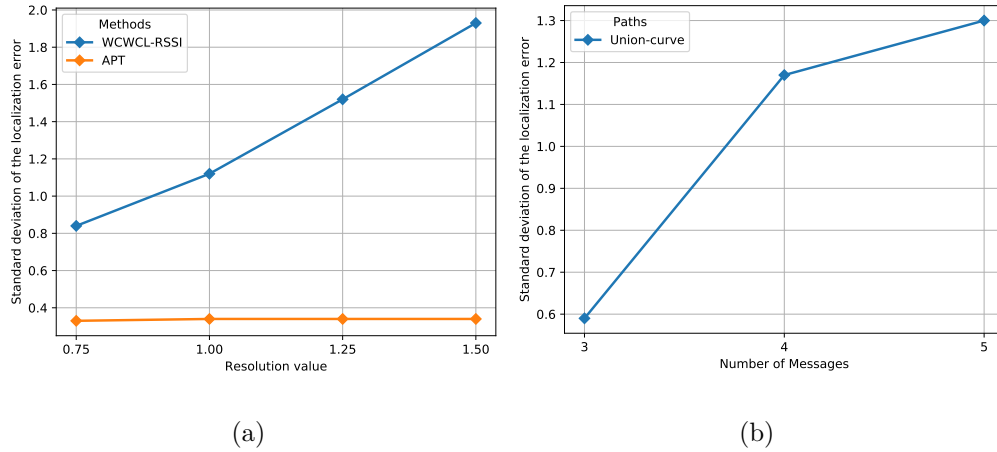


Figure 5.11: Standard deviation of the localization error of Union-curve with a double path degree L.

error compared to those in Figure 5.2, Figure 5.3, Figure 5.4, and Figure 5.5 for all the methods utilized. Moreover, it is observed that optimal results are achieved using either the APT or WCWCL-RSSI methods with the number of messages set to four.

5.4 Conclusion

In this chapter, we enhance the effectiveness of our model using four metrics. Compared to other static models, our approach shows superior results, especially in metrics such as accuracy. The Union-curve demonstrates high accuracy in both APT and WCWCL localization techniques. Consequently, regardless of resolution values, the Union-curve consistently achieves competitive coverage rate results. Finally, this work includes a study on energy consumption, revealing improvements achieved by doubling the path degree value.

CHAPTER 6

Conclusions and Future Works

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Low-power wireless sensor networks represent one of the significant opportunities in information technology and are leading the way in shaping the future of computing. However, this field presents significant research challenges in terms of organization, communication, management, and data exploitation. The issue of node localization in sensor networks is the main topic of this thesis. This chapter reviews the contributions of the thesis and suggests directions for further research. The primary contributions discussed in this thesis are described in Section 6.1, and Section 6.2 presents some recommendations for possible future research that should be taken into consideration.

6.1 Conclusions

We consider the two-dimensional, obstacle-free deployment of a WSNs in outdoor environments. The network consists of one mobile anchor and N unknown nodes that are uniformly and randomly distributed throughout the network. The main goal of this thesis was to create and introduce path-planning models for mobility-based localization in WSNs. Consequently, the primary contributions in WSNs include:

1. Study the existing trajectories in the literature by determining their beacon points or broadcasting points, paying particular attention to trajectories that rely on the division of areas into squares.
2. In the context of the square grid decomposition of the area, we center our attention on the beacon broadcasting positions. We introduce a refined path planning model named Union-curve, designed to minimize the number of corners, incorporating the collective beacon points from five trajectories based on the square grid-specifically, S-type, SCAN, HILBERT, Z-curve, and Σ -Scan. This model operates on a decentralized approach, employing a localization algorithm based on a mobile anchor, which delegates the task of calculating unknown node positions among sensor nodes. The evaluation involves determining unknown node positions using two localization techniques: range-based localization (APT) and range-free localization (WCWCL-RSSI). To evaluate and confirm the effectiveness of our model, we utilize four essential analysis metrics. Simulation results demonstrate that the Union-curve model excels in delivering robust, high-quality packets, enhancing accuracy by optimizing the proximity of the mobile anchor

to unknown node locations. Additionally, it ensures complete coverage by broadcasting five beacon messages to unknown nodes in each sub-square. Our approach guarantees that when the resolution is equal to or greater than one, all unknown nodes in the network will receive location information to estimate their current positions. We assess the WCWCL-RSSI algorithm within our approach, exploring three scenarios with varying numbers of received packets featuring the strongest signal: the top three, top four, and top five packets. Remarkably, our results demonstrate that the Union-curve, when combined with the WCWCL-RSSI algorithm, achieves superior performance when the number of received messages is set at four. In computing energy consumption, the Union-curve exhibits the highest average number of received messages. To mitigate energy consumption, each unknown node considers only the first ten received messages for its calculations, disregarding any subsequent ones.

3. We analyze how the performance metrics of path planning models for localization based on mobile anchors are affected by precisely specifying localization parameters, to improve the localization system's performance.

6.2 Future Works

The following is a list of potential extensions of the models that have been suggested for our future research:

1. **Grid Decomposition Analysis:** We intend to analyze alternative paths based on triangular or hexagonal grid decomposition.

2. **Obstacle-Resistant Mobile Anchors:** Investigating the integration of obstacle-resistant mobile anchors within a specified ROI.
3. **Additional Parameters:** We intend to explore additional parameters, including equipment type, and environmental conditions.

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ملخص: تستكشف هذه الرسالة مسألة تحديد الموقع في شبكات الاستشعار اللاسلكية باستخدام الخوارزميات الموزعة. بعد النشر العشوائي للمستشعرات هناك حاجة ماسة لمعرفة موقعها وخاصة من أجل معرفة مكان الأحداث. نقترح استخدام مستشعر خاص يكون متحركاً و مزوداً بوحدة GPS، يسمى مرساة، تتحرك المرساة داخل منطقة الاهتمام وفق مسار معد مسبقاً وتبث موقعها بانتظام لمساعدة المستشعرات غير معرفة الموقع في التحديد الذاتي لإحداثياتها. تقوم المستشعرات الغير معرفة الموقع بتقدير إحداثياتها باستخدام تقنيات APT و WCWCL-RSSI. السؤال الذي حاولنا الإجابة عليه في هذه الرسالة هو ما هو أحسن مسار يمكن أن تسلكه المرساة. قمنا في البداية باقتراح مجموعة من المعايير التي تسمح لنا بقياس جودة المسار. قمنا كذلك بدراسة و تحليل خمسة مسارات معتمدة على تقسيم منطقة الاهتمام الى مربعات : SCAN HILBERT, S-type, Z-curve, Σ -Scan. اقترحنا في النهاية مساراً جديداً سميناه Union-curve الذي يجمع جميع نقاط البث للمسارات الخمسة السابقة. تظهر نتائج محاكاة النموذج المقترح أنه يحقق دقة استثنائية، مما يؤدي إلى تقليل كبير في معدلات الخطأ مقارنة بالنماذج البديلة، علاوة على ذلك، يضمن تغطية كاملة مع دقة مسار أقل.

كلمات مفتاحية: تحديد الموقع؛ مرساة متحركة؛ نموذج تخطيط مسار؛ شبكة الاستشعار اللاسلكية؛ تقسيم الشبكة المربعة؛ نقاط البث.

Abstract: This thesis explores sensor networks, focusing on distributed algorithms for localization challenges. It addresses the need to determine node positions after random deployment, crucial for event localization. The proposed solution involves employing a mobile anchor with GPS units, moving within the area of interest, periodically broadcasting its location to assist unknown nodes in self-localization. A novel path planning model for mobile-based localization in WSNs is introduced, incorporating beacon points from five established paths (SCAN, HILBERT, S-type, Z-curve, and Σ -Scan) on the widely used square grid decomposition. Unknown sensor nodes estimate positions using APT and WCWCL-RSSI techniques. The simulation results demonstrate that the proposed model achieves exceptional accuracy, leading to a significant reduction in error rates when compared to alternative models. Moreover, it ensures maximum coverage with a lower path resolution value, indicating its effectiveness in optimizing localization outcomes. The thesis underscores the impact and importance of path parameterization in enhancing the quality of a localization system with a mobile anchor node.

Keywords: Localization ;Mobile anchor; Path planning model; Wireless sensor network; Square grid decomposition; Beacon points