Received Signal Strength Indicator Based Local Positioning System

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1. Introduction

1.1 Project Description

1.1.1 Background

In this era of automation, the capacity to precisely navigate through various environments predicts the success of the system. The positioning systems are designed to fit numerous purposes, use cases, and environments and facilitate determining the location and the direction of a system or individuals. Obtaining real-time positioning information is crucial for various instances, including navigation of ships and airplanes, situational management in emergency services, agricultural monitoring, military applications, industrial automation robotics, etc. Different positioning systems provide varying levels of accuracy and precision based on technology, algorithms, and the environment in which they operate. Most common systems used in smartphones for general purposes have an accuracy of approximately 5 meters [1]. While this accuracy is generally sufficient for everyday use and navigation, some cases, such as autonomous surveillance and navigation, require a more enhanced degree of accuracy. Furthermore, precision and accuracy rely heavily on the operating environment to the extent that some positioning systems might not function efficiently and properly in specific environments. For this reason, different types of positioning systems are used.

Those can be classified into two main categories: global and local positioning systems. Global positioning systems (GPS) utilize satellites to provide worldwide coverage and relatively accurate location information. On the contrary, local positioning systems (LPS) use short-range signaling nodes to obtain the exact location of systems.

GPS operation principle requires continuous signal reception from at least four GPS satellites. The end-receiver determines its distance from the satellites using the time it took for the signals to travel, hence triangulating and obtaining its position. While GPS provides worldwide coverage, its application can be limited to specific environments. Three significant problems can be identified: weak reception of GPS signals, compromised GPS signal integrity, and restricted positioning accuracy [2].

As mentioned above, undisturbed signal reception is necessary for the operation of GPS; however, the signals cannot fully penetrate water, walls, bridges, or similar obstacles. This makes GPS less, if not minimally efficient, for cases like underground positioning, navigating by huge obstacles, or in subsurface areas.

The location is obtained in relation to the satellites from which the system receives signals. This means incorrect satellite position, distance measurement, or malicious signal manipulation would result in inaccurate positioning. Sometimes, the incorrect signals might not be detected, hence, the system will be unaware of the faulty positioning calculation.

The signals might also be impacted by their path environment. As the signals pass through the atmosphere, their speed is affected; additionally, measurement noises or clock errors on the receiver end lead to possible calculation errors [2]. All problems mentioned are critical issues if high accuracy of the positioning is required. Continuous monitoring and signal correction are necessary to reduce the possible errors, but the accuracy would still be limited.

Compared to GPS, LPS can operate in limited geographical areas and have operation ranges depending on the system specifications. Technologies and algorithms utilized by LPS are more particular to the operational environment and can be altered accordingly to meet certain needs. These systems can function based on Wi-Fi triangulation, Bluetooth, radio signals' time-of-flight measurement algorithms, infrared sensors, or a combination of different technologies. The short-range signaling specification of LPS allows to obtain the more accurate and precise positioning information, enabling systems to alternate their precision based on specific needs (i.e., power consumption, system limitation, use cases, etc.). LPS outperforms global systems in environments where GPS is denied, or its accuracy and precision are highly limited.

Compared to various types of LPS, utilizing Software-Defined Radio (SDR) technology gives the advantage of having adaptable and flexible solutions. SDR technology provides software-based algorithms and configurations, allowing it to process diverse signals and operate in different environments and conditions. This advantage enables obtaining better and more accurate positioning information and tailoring algorithms, protocols, and solutions to suit particular applications and needs. Prototyping and testing are relatively more straightforward and less complicated due to their adaptiveness, providing a great environment to improve and upgrade the algorithms without changing the hardware specifications and avoiding additional costs.

In the scope of positioning systems satisfying various environmental specifications and applications, the principles of Time of Arrival (TOA) and Received Signal Strength Indicator (RSSI) form the basis of many techniques for determining accurate location information.

Obtaining positioning information using the technique TOA involves determining the position of a target in relation to known base stations. TOA measurements rely on the principle that the time taken by a signal to travel between two points is directly linked to the distance between those points [3]. TOA-based positioning methods also include techniques such as Time

Difference of Arrival (TDOA) and Time Sum of Arrival (TSOA), although the latter is less commonly used.

In Received Signal Strength Indicator (RSSI)-based localization, again, multiple base nodes are used to locate a target node through triangulation. However, unlike TOA, RSSI estimation relies on measuring the strength of the received signal to find the distance traveled by the signal [3]. For a coplanar scenario, assuming known transmission strength and channel characteristics, at least three base nodes are typically required for effective triangulation. With proper configurations and calibration, high precision (0-50 meters) of localization can be achieved [3].

Earlier positioning applications, particularly those emphasizing high accuracy over system simplicity, favored methods like TDOA/TOA or Angle of Arrival (AOA) measurements, especially in scenarios involving a limited number of receivers or sensor arrays. However, the tendency has shifted with the increased number of wireless devices and networks, leading to more observation points closer to the target. This process has raised the need to adopt RSS-based approaches, especially in indoor or non-line-of-sight (NLOS) environments.

Despite the generally lower accuracy with fewer nodes, RSSI-based localization stands out as a cost-effective and straightforward solution. RSS information, already integral to many wireless standards, serves various fundamental radio functions and can be used in location systems without additional hardware or modifications. This simplicity makes RSSI a feasible method, especially in scenarios where it may be the only available ranging information due to environmental challenges or specific applications, such as surveillance or security.

RSSI based local positioning systems rely heavily on accurate distance measurements for precise positioning. While considering the constraints of traditional RSSI based algorithms, which often rely on standard parameters that are sensitive to environmental influences, this project focuses on refining these distance estimation processes. Most implementations of this systems traditionally focus more on enhancing positioning accuracy after distance calculation are made. This approach often overlooks the critical role of initial distance estimation. However, this project prioritizes improvements in distance estimation to ensure more accurate positioning from the onset, by implementations of advanced filtering algorithms and appropriate signal propagation methods.

1.1.2 Assumptions and Constraints

As the project aims to achieve high precision, various factors impacting RSSI measurements should be considered. Those can be signal attenuation changes due to obstacles, signal reflections, or interferences from neighboring devices. To enhance accuracy, the number of base stations can be increased. The utilization of more stations will allow to refine location estimates, enhancing the system's precision within the 0-50 meter range. However, while additional stations contribute to improved accuracy, optimizing their utilization and placement requires careful consideration.

The environment the system operates in plays a crucial role, as the objects near the target might highly influence the measurement results. Specifically, the presence of metallic or reflective surfaces might have a notable effect, as these materials can significantly change the signal propagation through reflection or refraction, affecting the RSSI reading. However, the effects of this issue might be minimized by strategic sensor placement. Positioning sensor in elevated areas in indoor environments, such as ceiling, can decrease the chances of signal propagation and increase the measurement reliability.

Similarly, environmental variations pose significant challenges that can lead to potential inaccuracies. Factors such as signal interference from natural or artificial sources and signal degradation due to atmospheric conditions contribute to measurement inconsistencies. Incorporating corrective techniques, such as using a minimum of two stations for initial calibration and environmental adaptations, aid in correcting these inconsistencies. These corrections are essential, yet in some cases, might not be necessary. The relative nature of distance calculations allows to skip the corrections if all stations are positioned closer to each other and are affected by the same environmental conditions.

It is essential to acknowledge that achieving the best implementation and final concept will require prolonged development time because of the complexity of SDR implementations.

This development phase is the initial proof of concept, demonstrating the feasibility and foundational aspects of the project. However, it's important to note that this is the initial phase. Further work and in-depth development with a more extensive timeframe will be needed past this proof-of-concept stage to achieve the comprehensive final version of the project.

1.2 Overview of the Envisioned System

1.2.1 Overview

The proposed LPS is built based on the Adalm-Pluto module, implementing distance measurement between nodes. The Adalm-Pluto module, developed by Analog Devices, is a compact and cost-effective Software-Defined Radio solution. With its wide frequency coverage and customizable features, it's an accessible platform for experimenting with wireless communication protocols and signal processing techniques. The system mainly utilizes the capabilities of the Adalm-Pluto module's Software-Defined Radio to accurately measure the distance between two points and obtain location positioning information. The project's objectives are the advancement of accuracy and precision in distance measurement using the RSSI technique within the SDR framework.

Moreover, the system's positioning methodology is based on a network consisting of a minimum of three nodes. By employing multiple nodes strategically, the system aims to triangulate positions accurately, ensuring dependable positioning capabilities, especially in dynamic and complex environments. This methodology is essential for the system’s overall performance, especially in specialized applications such as drone surveillance in NLOS environments.

In order to improve the distance measurement results, this project focuses on several crucial aspects: the modulation type of the signal, the selection of antennas, the operating frequency, and the application of post-measurement filtering techniques. Each of these play an important role in enhancing the accuracy and reliability of distance estimations. It is important to note that the platform provided by Adalm-Pluto, specifically the use of SDR, allows seamless integration of different changes based on different needs. This project provides the basis for improved distance estimation; however, most parameters can be adjusted accordingly to meet the range, data rate, power consumption, security and much more specific requirements. In the scope of this project a simple GUI is provided, to implement changes, tackle parameters and test a system based on integration requirements.

1.2.2 System Scope

The primary objective of the LPS is to precisely determine the distance between two nodes within the system, which may serve as the basis for various platforms, including drones, automated vehicles, indoor positioning systems etc. The system should be incorporated into specific setups and configured appropriately. The project provides the key functions and operational modes for obtaining appropriate positioning information.

The current stage of the project primarily emphasizes distance measurement, with plans for future development to accommodate synchronization, refined communication protocols, and additional functionalities between the nodes. This focus on distance measurements aligns with the project's initial objective to set the foundation and groundwork for advancement in system capabilities and enhancement in the future.

This project intentionally excludes physical housing or mounting specifications, focusing solely on the operational and technical aspects. The mounting specifications should be tailored and adjusted based on the use cases and setups into which LPS will be integrated.

2. Documents

2.1 Applicable Documents

1. **Adalm-Pluto Schematic:** This schematic provides detailed insights into the hardware layout and components of the Adalm-Pluto module [4]. It serves as a fundamental reference for understanding the module's architecture, aiding in the development and integration of the system.

2. **AD9363 Datasheet:** This datasheet contains comprehensive technical information about the AD9363 chip, detailing its functionalities, specifications, and electrical characteristics [5]. It serves as a critical resource for understanding the capabilities and limitations of the chip integrated within the Adalm-Pluto module.
3. **“Handbook of Position Location: Theory, Practice, and Advances”:** This book serves as a reference for implementing RSSI techniques, algorithms, and descriptions relevant to the system's positioning methodology [3]. Specific sections or algorithms related to RSSI-based positioning will be utilized as guidance for the system's design and implementation.
4. **“A Novel Robust Trilateration Method Applied to Ultra-Wide Bandwidth Location Systems”:** This paper proposes a modified approach to trilateration, essentially covering wider case scenarios and allowing better error correction. The project utilizes the proposed approach in the positioning technique, to prove the feasibility of the improved distance measurements.

2.2 Reference Documents

In LPS the important part is converting RSSI measurements result to actual distances. RSSI measures the power level which the receiver detects when receiving the signal from the transmitter. The fundamental connection between the RSSI and distance is based on the idea that the measurement results decrease as the distance between the transmitter and the receiver increases, which is known as the path loss model [6].

The simplest model is typically expressed in a log-distance form:

$$RSSI = -10 \cdot n\, log_{10} \frac{d}{d_0} + RSSI_0 \qquad \text{Eq. 1}$$

Where:

- n – the path loss exponent, depends on a specific environment, based on calibrated data
- d – the distance between the transmitter and receiver
- d_0 – the reference distance between the transmitter and receiver
- $RSSI_0$ – the reference RSSI measurement at d_0

As already mentioned, environmental factors affect the measurement reading, hence the need for calibration. Environment specific calibration adjusts $RSSI_0$ and n parameters according to the noise level to that area, increasing the accuracy for the distance measurements.

The distance is respectively obtained following the logic of Eq. 1:

$$d = d_0 \cdot 10^{\left(\frac{RSSI_0 - RSSI}{10n}\right)} \qquad \text{Eq. 2}$$

When the distance between the node (transmitter) and the target (receiver) is obtained, trilateration methods support the computation of positioning information.

Trilateration is a mathematical technique used to determine the positions of target devices based on the distances from multiple known static nodes. Typically, trilateration discusses the cases involving three nodes, and multilateration is used in the context of a system with more than three nodes. This technique is fundamental to many positioning systems, including GPS, as it provides a reliable method for calculating the target's location based on measured distances.

In the context of this project and positioning system, trilateration plays an important role in accurate positioning within the operational area coverage created by the nodes. The reference documents discussed in this section provide comprehensive insights about the algorithms, improved methods of trilateration and mathematical methods to optimize the process for real-world applications.

When considering trilateration alongside the ideal and simple case is considered the real world, non-ideal implementation. In the ideal scenario, trilateration involves non-colinear nodes that transmit signals to a receiver, which has precise information about their positions. This distances, if treated as radiuses create circles, which, in ideal case, intersect at exactly one point, marking the target's exact location. However, in real-world scenarios, especially considering obstacles and signal interference, the distance measurement is not very precise, hence the circles don't intersect so perfectly.

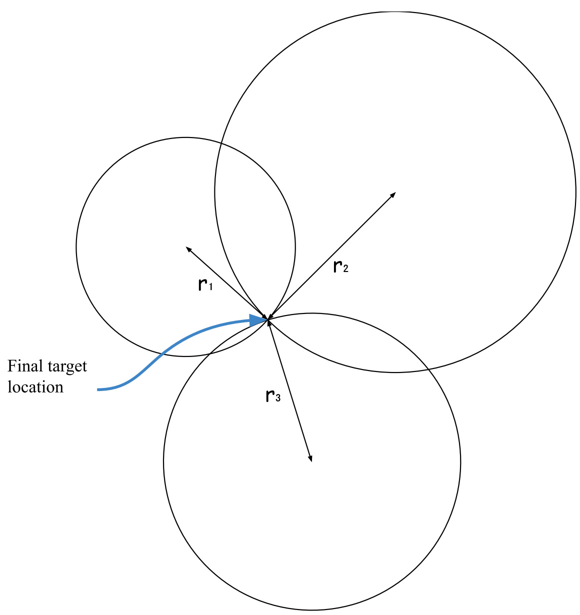


Figure 1: Ideal Case of Trilateration

In real-life applications of trilateration, specifically in complex indoor environments, with unknown obstacles, the non-ideal factors play a significant role in the location estimations' accuracy. The inherent assumption of trilateration is that the measured distances are very precise and that the circles formed by these distances intersect at a single point. However, different real-life cases and challenges such as non-line-of-sight conditions or multipath effects on the received signal, often lead to inaccuracies in measurements. This errors, even small, result in circles that do not intersect perfectly, or may not intersect at all.

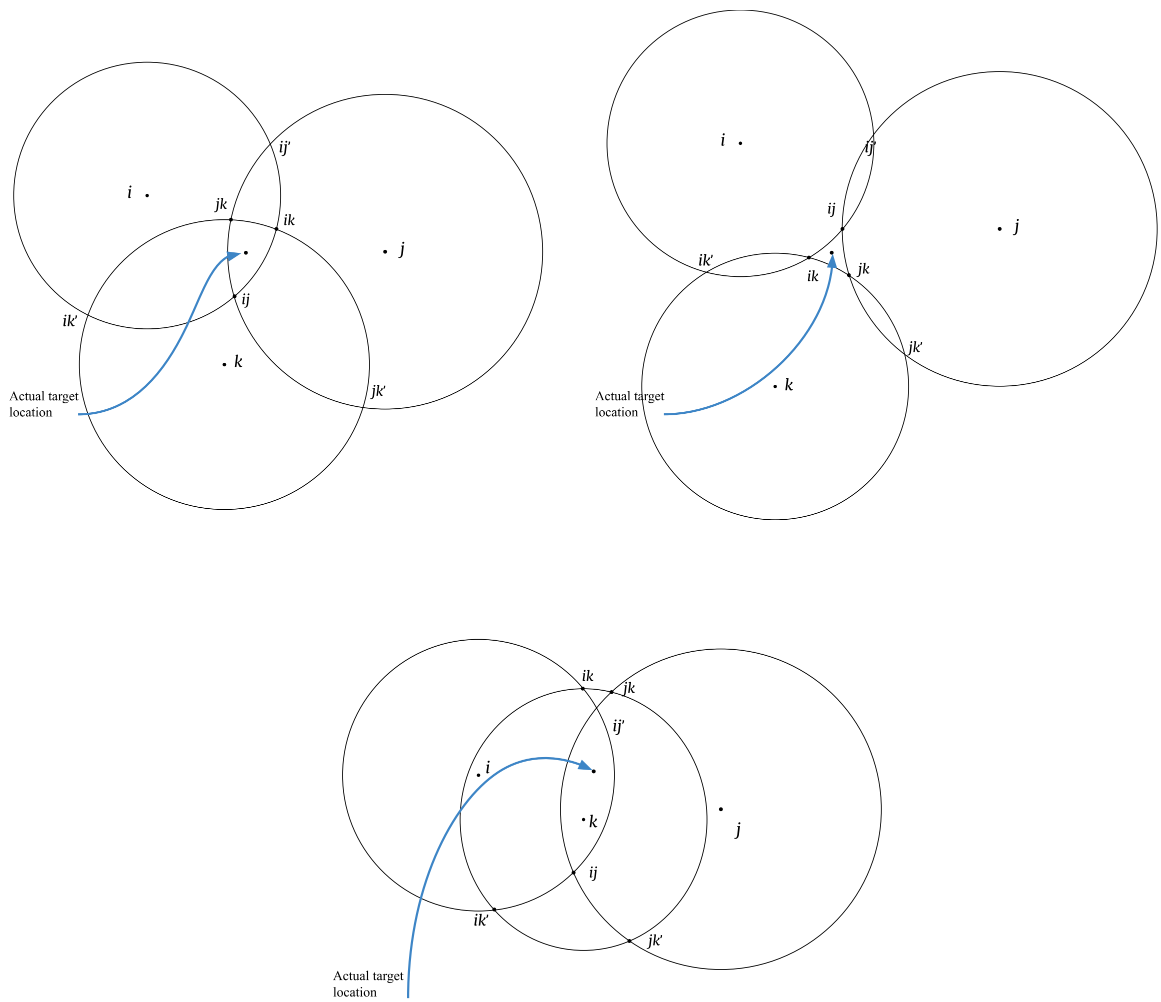


Figure 2: Possible Target Locations in Different Scenarios

The first issue to address is finding the intersection point for each pair of circles. To obtain the coordinates consider the following formulas, assuming the center of both circles are not coinciding. Refer to Figure 1 for geometrical representation.

Divided into groups, the equations achieve the following:

Equations for Distances

$$d = \sqrt{\left(x_j - x_i\right)^2 + \left(y_j - y_i\right)^2} \qquad \text{Eq. 3}$$

$$a^2 + h^2 = d_i^2 \qquad \text{Eq. 4}$$

$$(d - a)^2 + h^2 = d_j^2 \qquad \text{Eq. 5}$$

Establish the geometric relationships between the distances and radii of the circles. Eq. 3 calculates the distance d between the centers of the circles while Eq. 4 and Eq. 5 set up the relationships needed to find a and h.

Solving for Intersection Parameters

$$a = \frac{d_i^2 - d_j^2 + d}{2d} \qquad \text{Eq. 6}$$

$$h = \sqrt{d_i^2 - a^2} \qquad \text{Eq. 7}$$

$$C_0 = \left(x_i + a\cos\alpha\,, y_i + a \cdot \sin\alpha\right) = \left(x_i + a\frac{x_j - x_i}{d}, y_i + a\frac{y_j - y_i}{d}\right) \qquad \text{Eq. 8}$$

Eq. 6 and Eq. 7 solve for the specific distances a and h. The reference coordinate point C_0, to be later used in determining the exact intersection points, is obtained in Eq. 8.

Solving for Intersection Points

$$x_{ij}, x_{ij}^{'} = C_0 \pm h\left(\frac{y_j - y_i}{a}\right)$$

Eq. 9

$$y_{ij}, y_{ij}^{'} = C_0 \pm h\left(\frac{x_j - x_i}{d}\right)$$

The coordinates of the intersection points are obtained in relation to C_0 by adding and subtracting the perpendicular distance h, multiplied by cosine and sine for transitioning to coordinates.

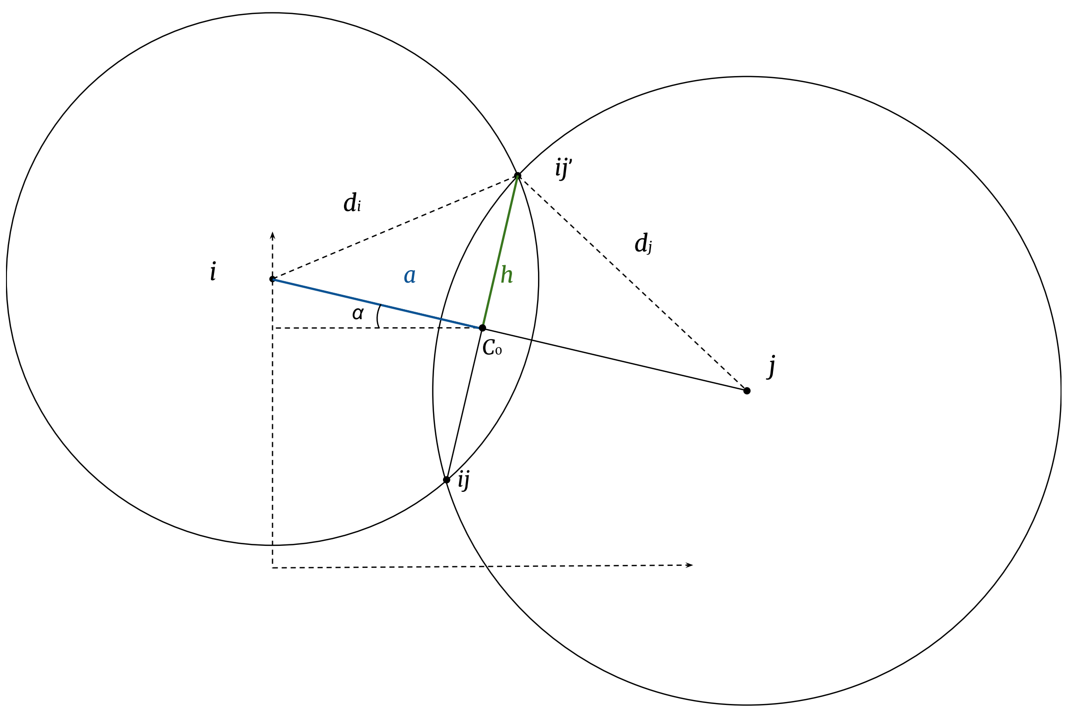


Figure 3: Intersection points of circles

In cases when all circles intersect with each other and 6 points are available, it is essential to determine the criteria for isolating the area which might include the target. Continuing with the previous formulas, when two intersection points are determined for the first circle, a criterion should be defined to choose the most appropriate intersection point. The traditional method, utilizes the following equation where x_k and y_k are the center coordinates of the third node:

$$(x_{ij} - x_k)^2 + \left(y_{ij} - y_k\right)^2 < (x'_{ij} - x_k)^2 + \left(y'_{ij} - y_k\right)^2 \qquad \textit{Eq. 10}$$

If the Eq. 10 holds true the best or most suitable intersection point is selected to be (x_{ij}, y_{ij}), otherwise calculations proceed with $\left(x'_{ij}, y'_{ij}\right)$. This method attempts to find the intersection point which is the closest to the third circle's center. However, this method is often prone to errors and inaccuracies while also being sensitive to noise. Considering these limitations, to address these challenges and minimize their effect, one of the sources suggest modification in the formula for detection of the intersection points [7]. Their suggested equation (Eq. 11) incorporates a confidence-based intersection approach.

$$\left(d_k - \sqrt{(x_{ij} - x_k)^2 + \left(y_{ij} - y_k\right)^2}\right)^2 < \left(d_k - \sqrt{(x'_{ij} - x_k)^2 + \left(y'_{ij} - y_k\right)^2}\right)^2 \qquad \textit{Eq. 11}$$

This new method is mainly reliant on the factor that TOA based positioning methods are assumed to follow a Gaussian distribution. This adaptation allows for more accurate intersection selection that is more likely to be closer to the true position of the target, allowing for more reliable localization despite the inherent challenges posed by real-world conditions.

Considering that RSSI measurements are also typically modeled using Gaussian Distribution to account for environmental influences, tin the current system the abovementioned method is used for trilateration [8].

After all suitable intersection points are obtained, in cases like this a simple approach is used to obtain the position of the target. As three nodes provide intersection points that form a triangle, the centroid is considered to be the position of the target. It is calculated as the average position of the vertices of the triangle, providing a balance point that can be considered the estimated location of the target.

In conclusion, the abovementioned sources provided a reliable ground for methods chosen for the system. By utilizing the statistical properties of the RSSI measurements and incorporating those in a simple yet effective positioning strategy, those methods improve the accuracy and reliability of trilateration in complex environments.

3. Description of the Envisioned System

3.1 Needs, Goals and Objectives of Envisioned System

The envisioned system strives for adaptability, designed as a versatile LPS that can seamlessly integrate into various systems and setups without being confined to any specific application or use case.

Initially, this project aimed to extend and optimize the implementation of LPS developed by Instigate Robotics while reusing the main algorithms. This approach was chosen because of identified needs that arose during the system's operation, such as the need for hardware implementation of Fast Fourier Transform (FFT) instead of software to achieve faster implementation. It was envisioned that these modifications would optimize and improve the implementation of their system. The model was intended to be used in drones surveying over a specified area in a sea. This allowed them to use positioning techniques without considering the factor of Line of Sight (LOS).

However, after intensive research and evaluation, a strategic shift in the project's direction occurred. Instead of pursuing optimization exclusively, a decision was made to implement a new positioning technique based on RSSI, leaving behind the original plan to enhance the initial system. The main optimization of it was based on the hardware implementation of FFT, however, this task faced constraints as the Adalm-Pluto architecture used extensive resources of Digital Signal Processing (DSP) blocks, obstructing the hardware implementation plan of FFT [9, 4]. Moreover, its operation was limited by its reliance on continuous unobstructed Line of Sight (LOS) due to its base positioning technique (TOA). The newly adopted methodology addresses these challenges by offering a less complex yet comparatively accurate system.

The project's revised goal centers on integrating an RSSI-based positioning technique. This strategic shift aims to utilize RSSI advantages over TOA, enhancing accuracy and precision without pursuing FFT optimization and avoiding the requirement for continuous LOS, thus overcoming the significant operational limitations of the initial system.

One of the objectives of the system is to use Adalm-Pluto module's SDR capabilities, to increase the accuracy and precision in distance measurements through the implementation of the RSSI technique within the SDR framework. Leveraging the flexibility of SDR allows to explore various characteristics such as modulation types, configurations, and signal processing techniques. This adaptability gives the freedom to experiment with different parameters, optimizing the system for improved in certain environments.

The system's primary objective remains to precisely determine distances between nodes, offering flexibility for integration into various platforms and setups.

3.2 Overview of System and Key Elements

The LPS is designed as a versatile framework including distinct functional elements collaborating to achieve precise node-to-node distance determination. These components include the Adalm-Pluto module with Software-Defined Radio capabilities, data processing units, signal transmission modules, and user interfaces. The system carries out seamless communication, data processing, and user interaction while remaining implementation-agnostic.

The platform is designed to serve to diverse user base, allowing users to experiment and customize the system according to their specific requirements. Users, whether looking for accurate distance measurement information or curious to explore different parameters and tackle with the range of operation of the system, can use the platform to tailor parameters. This approach allows users to explore and adapt the system to meet their diverse needs.

The primary objective of the system revolves around accurate distance measurement between nodes, using the RSSI technique within the SDR framework. RSSI provides the signal strength information, enabling precise distance estimation and minimizing dependencies on continuous LOS scenarios. In the designed RSSI based system, the process begins with the transmission of a signal from one node to the target device. Once the receiving node is identified with a custom message, RSSI measurements are taken to determine the signal strength. To enhance the accuracy of the measurement, after it is done, a Kalman filter is applied.

The Kalman filter is an algorithm that provides efficient means to estimate the linear dynamic system from a series of noisy measurements [10]. The filter operates in two main steps: prediction and updating. In the first stage the filter produces estimates of the current state variable from the measurements. Once the next measurement is obtained, the estimates are updated using a weighted average, with more weight given to the estimates. This filtering method effectively reduces the noise inherent in RSSI data, leading to better and more precise distance calculations. The application of the Kalman filter is essential in reducing the effects of variability introduced by various environmental factors and possible signal fluctuations, ensuring that the distance calculations made based on RSSI measurements are reliable.

To further refine the system and allow to perform real-time analysis and customization, a graphical user interface (GUI) is provided. The GUI serves as a simple platform for visualizing the received data, including the raw RSSI values and the outcomes post Kalman filter application. Users can alternate the modes, configurations, plot the data dynamically, observe the effects of the applied filter and adjust the parameters for required optimization. The default configuration set is the optimized parameters for enhanced distance measurement precision enquired during the development of this project.

When using multiple nodes, the target device can operate in a mode to function as an LPS. While this feature is for demonstration of its potential for expanded functionality, it’s important to note that LPS is in a prototype stage. The synchronization, communication establishment and other critical aspects are yet to be optimized for widespread use. However, this prototype shows the enhanced distance measurements are achievable within the system. This demonstration highlights the progress in refined distance measurements precision.

3.3 Interfaces

3.3.1 Radio communication

The communication between the nodes is supported by the SDR capabilities of Adalm-Pluto module. The modules enable to transmit and receive digital signals from one node to another using signal modulation. In the case of SDR, modulation is the process of converting the digital carrier signal into analog signals for optimized transmission. During this process the digital data is encoded in a signal with specific alternating characteristics such as amplitude, frequency, and phase. For example, if we utilized a simple case of frequency modulation, in the modulated data 0s would be distinguished with a frequency of f_1 and 1s with a frequency of f_2. Most common types of digital modulations are Amplitude shift keying (ASK), Frequency shift keying (FSK) and Phase shift keying (PSK).

Two things were considered when choosing the modulation type sensitivity to noise and strength variations due to changes in transmitted message. To ensure stable communication between the nodes ASK was not considered, as it can be susceptible to interference in noisy environments or over long distances. Additionally, as we rely on RSSI measurements for distance estimations, different messages would alternate the signal strength due to ASK's nature. Both PSK and FSK were suitable options, however with experiments it was decided to go ahead with FSK modulation. PSK modulated signal had limited range of operation and required consistent configuration adjustment to operate at different distances. When using PSK (in the experiments BPSK and QPSK were used) it is important to note that data integrity depends on the stability of the phase of the signal. In a scenario when the phase changes, even from environmental factors or hardware problems, the data being transmitted will be heavily influenced. As the distance was increased these changes became more apparent, and the receiver struggled to differentiate between the phases that represented different data bits, which led to inconsistent communication.

Unlike ASK and PSK, FSK is more resilient to amplitude related noises or phase disturbances in environments where signals can be affected because of obstacles, interferences, or varying distances. Moreover, FSK modulation is simpler to demodulate, compared to PSK when conditions are not so ideal. For these reasons, FSK modulation was preferred, and is the main cornerstone for node-to-node communication.

For this project, operational range is chosen within the 433 MHz frequency band, particularly connected to its legal allocation for unlicensed use in Armenia. This frequency is part of the Industrial, Scientific, and Medical (ISM) radio bands, which are widely recognized to be used for short-range communications, and do not require licensing, which simplifies the deployment and operational legalities for the project.

Along with this, the 433 MHz band penetrates obstacles better compared to higher frequencies. Lower frequency waves have longer wavelengths, allowing them to penetrate various materials more effectively and undergo less attenuation over longer distances. Higher frequencies, on the other hand, are more likely to be absorbed or reflected by obstacles and cover shorter distances. Lower frequency signals experience less attenuation.

Furthermore, GPS systems operate at much higher frequencies, at more than 1227.6 MHz. These frequencies are significantly higher than 433 MHz band, which leaves the system outside the more commonly jammed or interfered frequency ranges. In scenarios where GPS signals are denied or especially jammed, the use of 433 MHz band for local positioning system will support an additional layer of security. Operating on lower frequencies minimizes the system's vulnerability to the same jamming techniques that might be directed at GPS. This choice increases the reliability of the positioning system and enhances its resilience under diverse and adverse conditions.

In the project were used omnidirectional antennas, which are specific to project's application needs. Omnidirectional antennas radiate and receive signal in all horizontal directions almost equally. This makes them ideal for scenarios where the direction of the incoming signal direction is not constant or can't be predicted. This feature is beneficial for the system, as in dynamic environments the target is moving, and the system must interact seamlessly with all nodes without needing to reorient the antenna.

In the system, each node initiates a connection by sending a signal that includes a specific message to identify itself. This is important as the target needs to distinguish each node within the network to compute its position, based on the received signal.

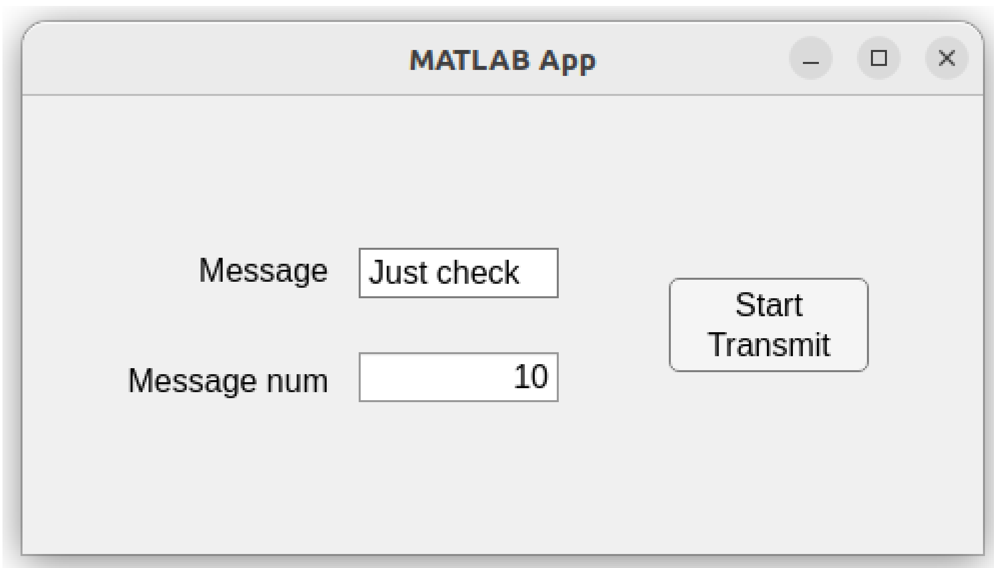
Overall, the radio communication interface is tailored to support continuous communication between the nodes, even in dynamic or obstructed environments.

3.3.2 User interface

The system includes two distinct graphical user interfaces (GUIs) developed in MATLAB, that are designed to manage the operations on both the transmitter and receiver sides. To establish a connection with Adalm-Pluto module a simple connection using its USB port is made. The first GUI is used for experimenting and obtaining estimated distance measurements, and the second is tailored for target positioning. Both interfaces allow the users to customize settings, initiate the process, and visualize results effectively, giving the platform for both experimentation and practical deployment of the positioning system.

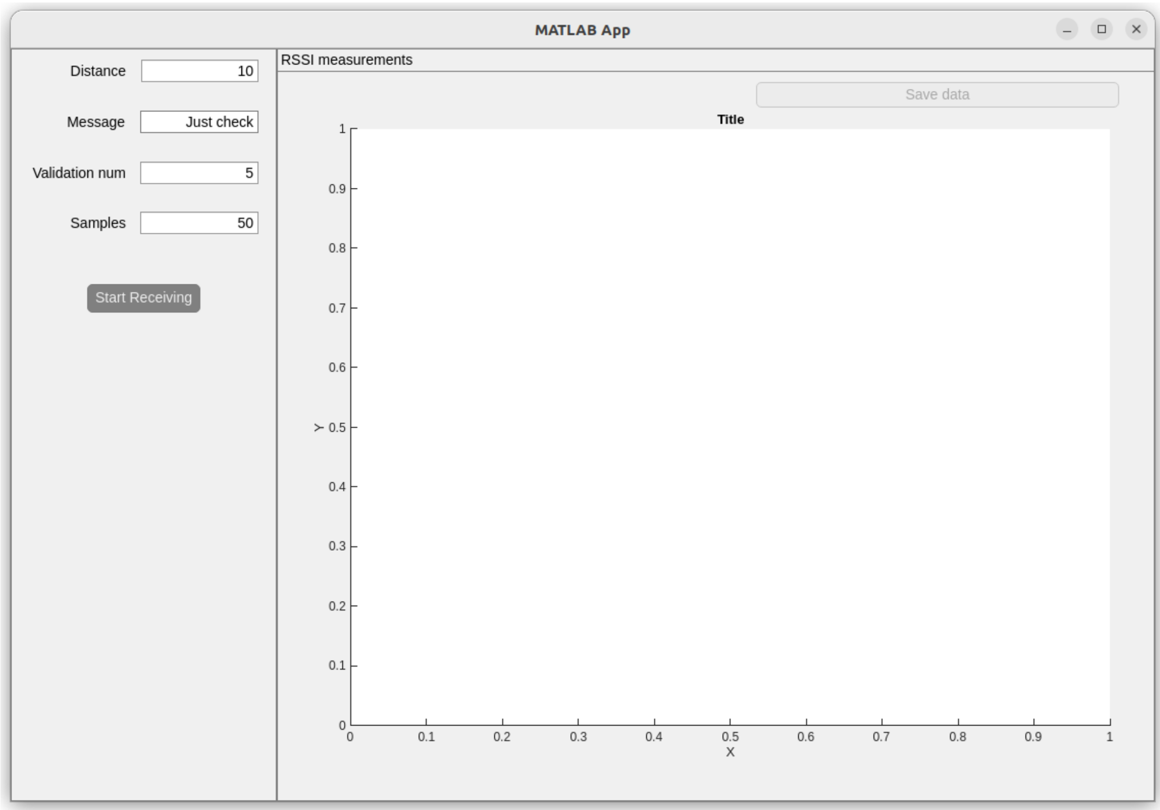
3.3.2.1 Experimental and Measurement Interface

Transmitter interface: The transmitter GUI supports the initiation of the transmission process from the node to the target. Users can set custom message for identification, select the number of messages to be sent, and choose the operating frequency. The initial values are preset for easy use and compatibility with the receiver.



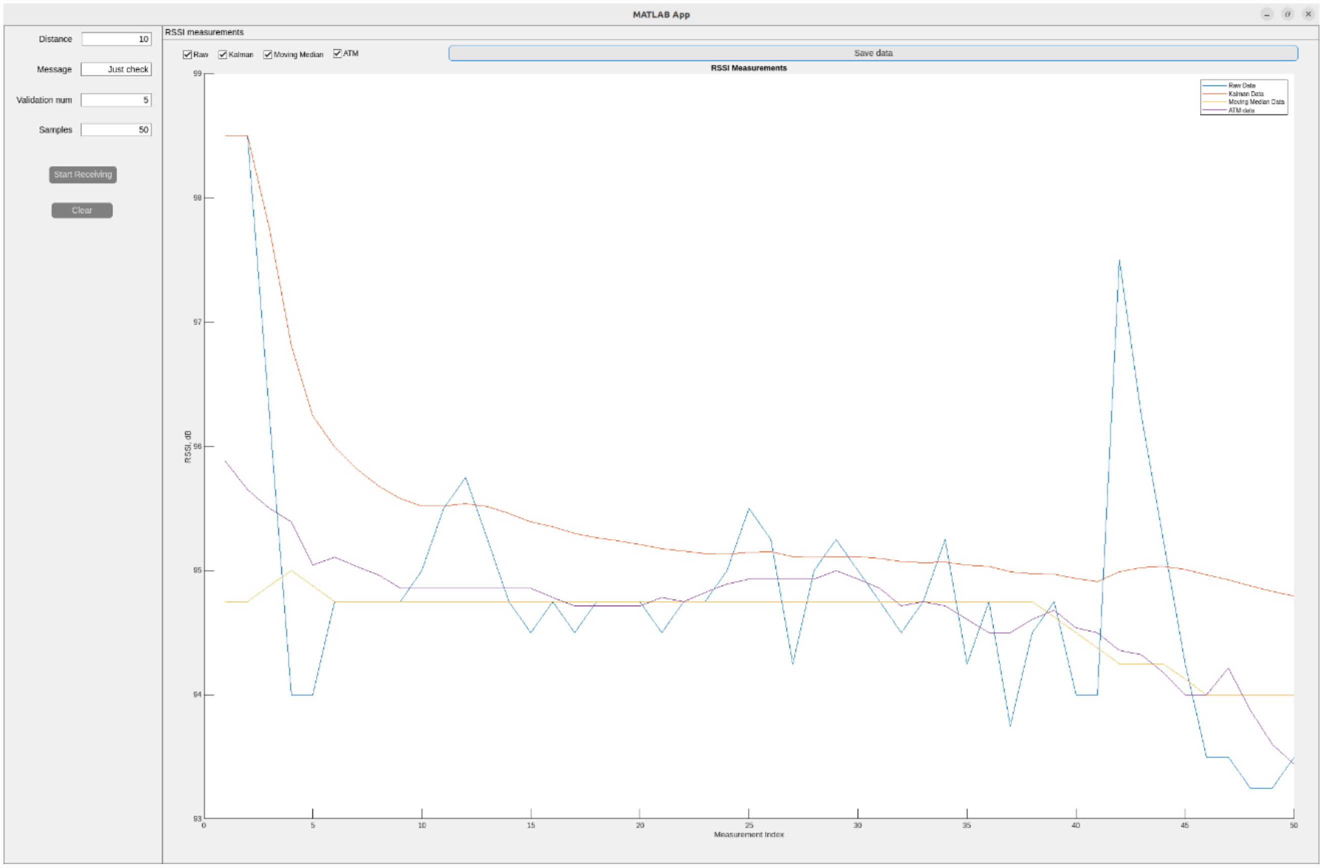
Picture 1: Transmitter GUI

Receiver interface: On the receiver side the GUI is designed to handle the reception process. Users can set the custom message to wait from the transmitter, number of messages to receive to confirm the identity of the node, the operating frequency and specify the number of measurements to make. The default values are compatible with the transmitter. As the reception of the signal is done, visualization of the signal is provided. The raw RSSI values are plotted, along with integrated filters: moving median, alpha-trimmed mean and Kalman[1]. Users can toggle these filters on or off for better analysis and save both the values and the plot. As the user conducts two tests at two different distances, the system also calculates the estimated distance based on these measurements and displays the estimation result.



Picture 2: Receiver GUI

[1] *Note:* RSSI values are negative, while in plots the values are positive for simpler visualization.



Picture 3: Receiver GUI after measurements

3.3.2.2 Positioning Interface

Transmitter interface: The transmitter’s side is made just for initiating or halting the process with a simple button and setting the identification number of the node (1, 2 … n). In case of positioning, custom transmission settings are not accepted.

Receiver interface: The receiver’s positioning GUI allows to configure the respective positions of nodes involved in the positioning process. Users can initiate the measurement process with options to adjust settings as necessary. When the measurements and calculations are complete, the system displays the estimated position of the nodes. This interface aims to provide a clear and intuitive visualization of the nodes' locations based on the optimized algorithm.

3.4 Modes of Operation

The system operates in two modes, each for different phases: Distance Measurement Mode for testing, experimentation, and calibration purposes, and the Positioning Mode for operational deployment.

3.4.1 Distance Measurement Mode

This mode is essential for development and testing, which allows to do adjustments of settings such as frequency selection, custom message configuration and the application of various filters to analyze their effect in different environments.

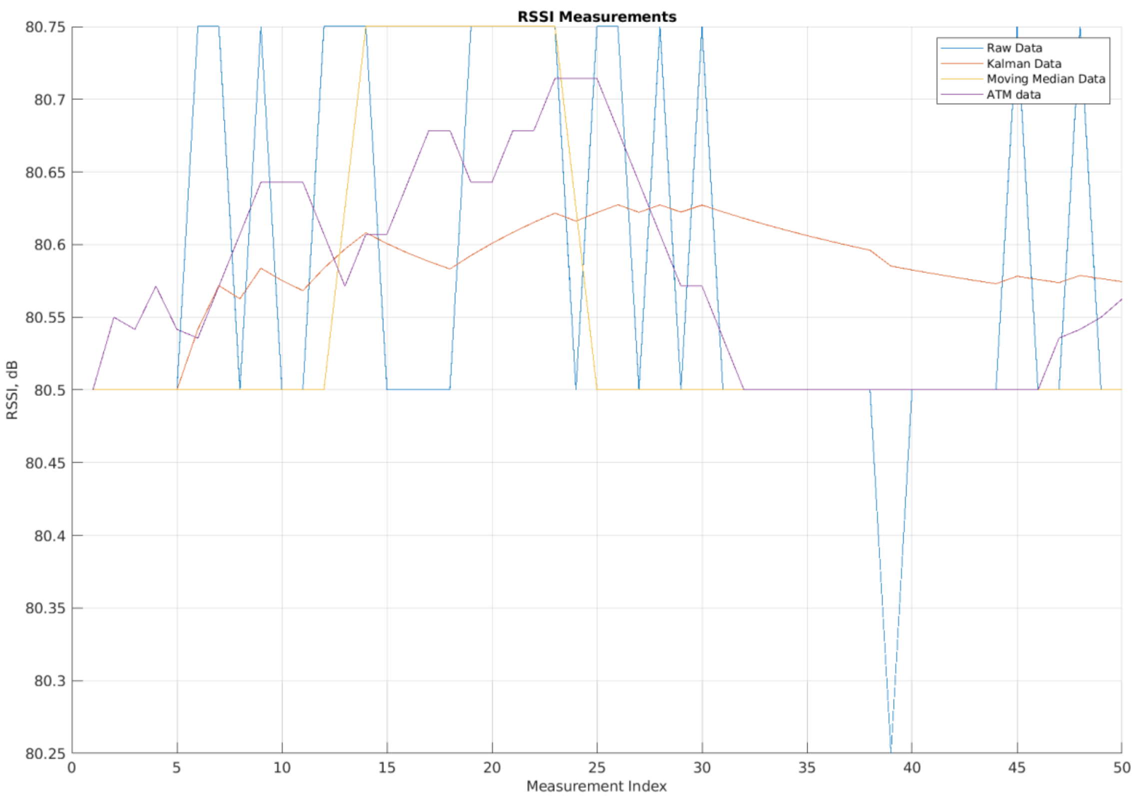
3.4.2 Positioning Mode

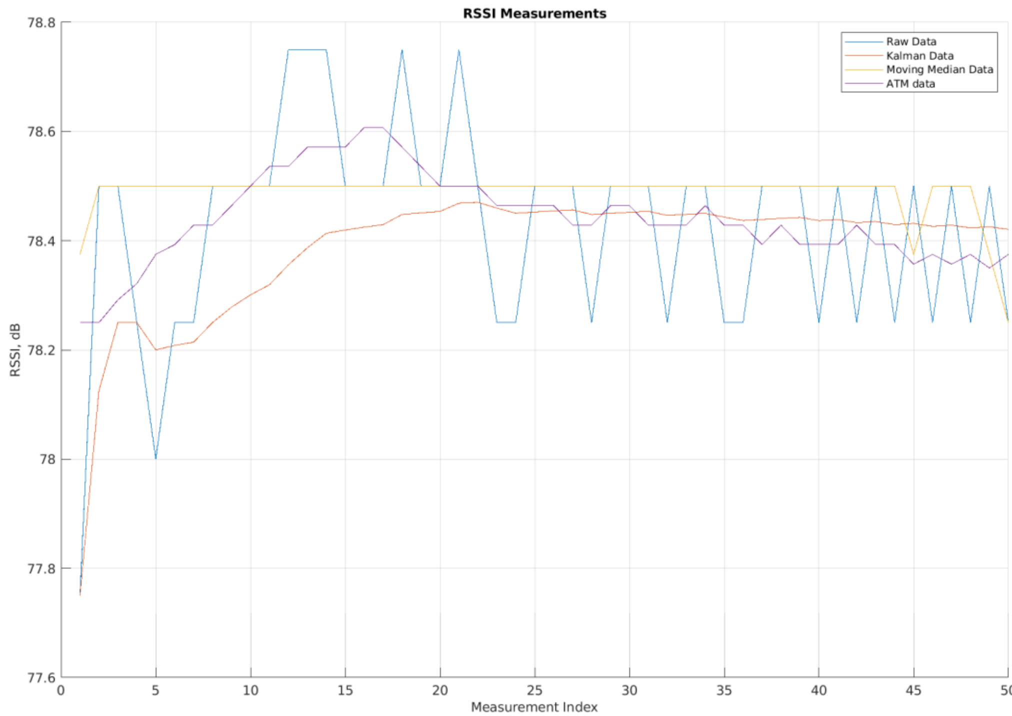
In the operational mode the system has simpler settings to ensure optimal performance in different environments. It includes fixed operational frequency range, predefined message setting compatible with all nodes to ensure easy integration.

The system operates at 433 MHz, specifically chosen for its effectiveness in better obstacle penetration and less susceptibility to interference. Both are important factors to ensure reliable communication in varied environments. Messages for identification are preset to ensure compatibility and easy identification among all nodes. This setup minimizes configuration mismatches and eases the use. In the system the focus is on utilizing time-division multiple access (TDMA) for node distinction. Each node transmits data in its designated time slot, reducing the likelihood of signal collision and improving the system organization.

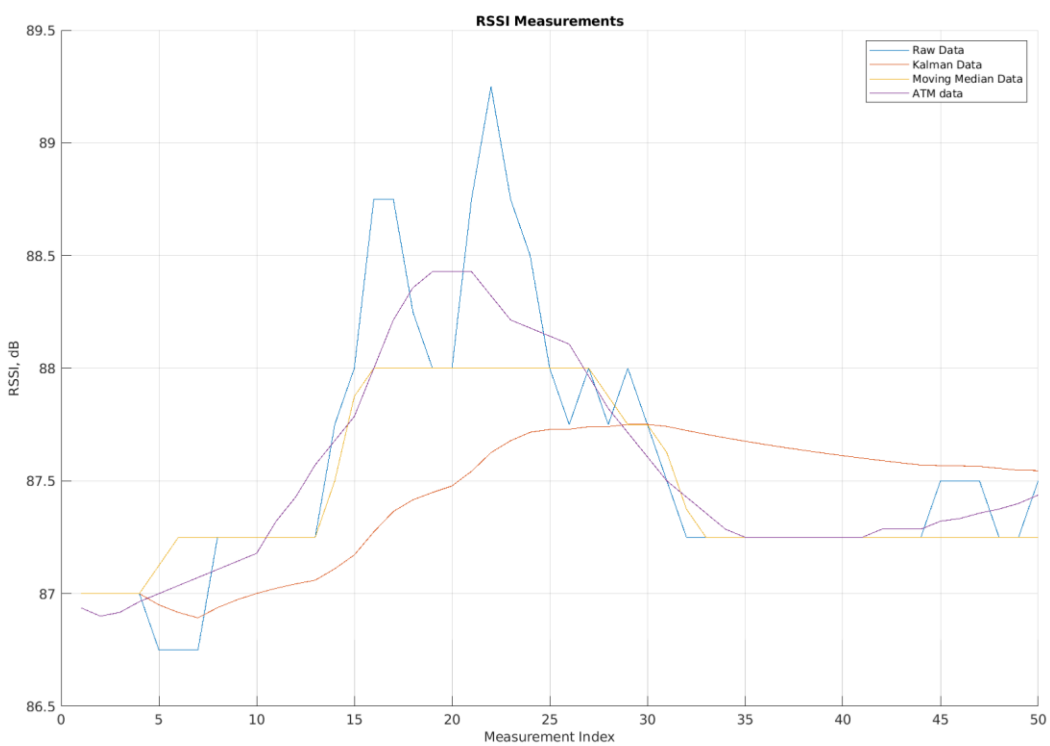
This method contrasts with frequency-division multiple access (FDMA) method, which allocates distinct frequency bands to different nodes. While FDMA can be effective, most often it introduces complexity in tuning and managing frequency allocations, especially in environments where spectrum restrictions might apply, or interference is a problem.

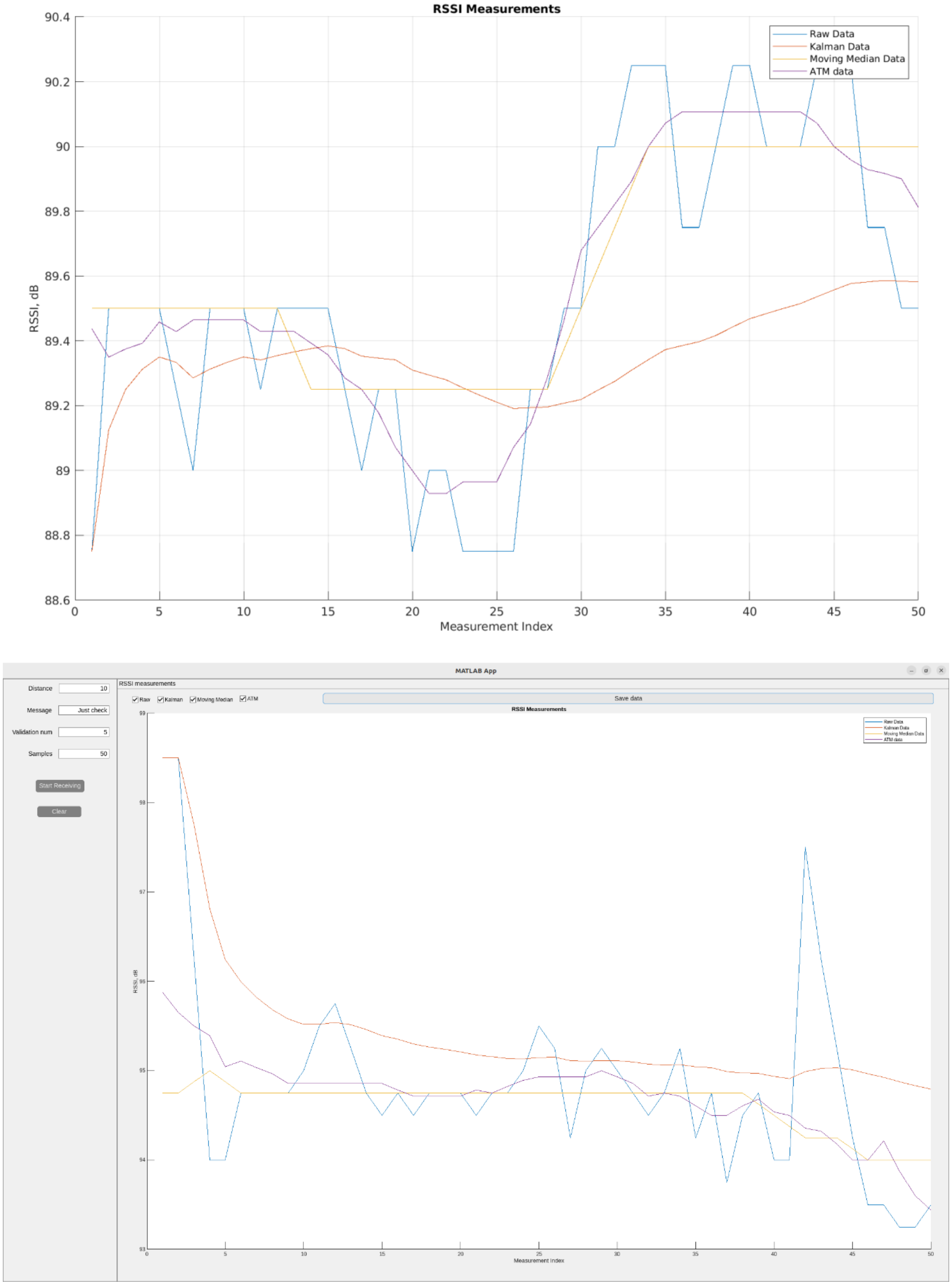
The specific use of the Kalman filter in the Positioning Mode is based on the experimental data obtained during the project implementation. It showed better and more consistent results in different conditions and proved to handle variable RSSI values effectively. This filter stands out in estimating states from unpredictable data, particularly useful in dynamic environments where signal integrity may be compromised. The Kalman filter continuously updates and corrects the system's estimates, which provides a higher level of accuracy, consistency, and real-time responsiveness, important for the precision required in positioning systems.





Picture 4: Measurement results in steady environment





Picture 5: Measurement results in noisy environment

The blue line representing raw RSSI data shows significant fluctuations indicating noises and caused by various factors. The orange line showing results of the Kalman filter demonstrates smoother and more refined data compared to raw data. The Kalman filter's mathematical approach considers the uncertainty and variance in the measurement process. It effectively predicts the future states of the RSSI measurements and updates this prediction as new data comes in. This approach minimizes the error between the estimated and actual measurements.

The next two lines visualize the results of the Moving Median and Alpha-Trimmed Mean filter. Those filters attempt to smooth out the results of raw data, however Kalman proves to be less prone to random noises or changes. The Moving Median filter reduces noise by replacing each data point with the median of neighboring points. However, it may not adapt as smoothly to the changes in signal dynamics as the Kalman Filter. The Alpha-Mean Trimmed filter is designed to smooth out the noisy data while removing the most extreme values in each section of the data. This method trims the outliers before computing the mean of the remaining values. While it is effective in handling random noises, its variability changes with the data, and may not provide a stable data set.

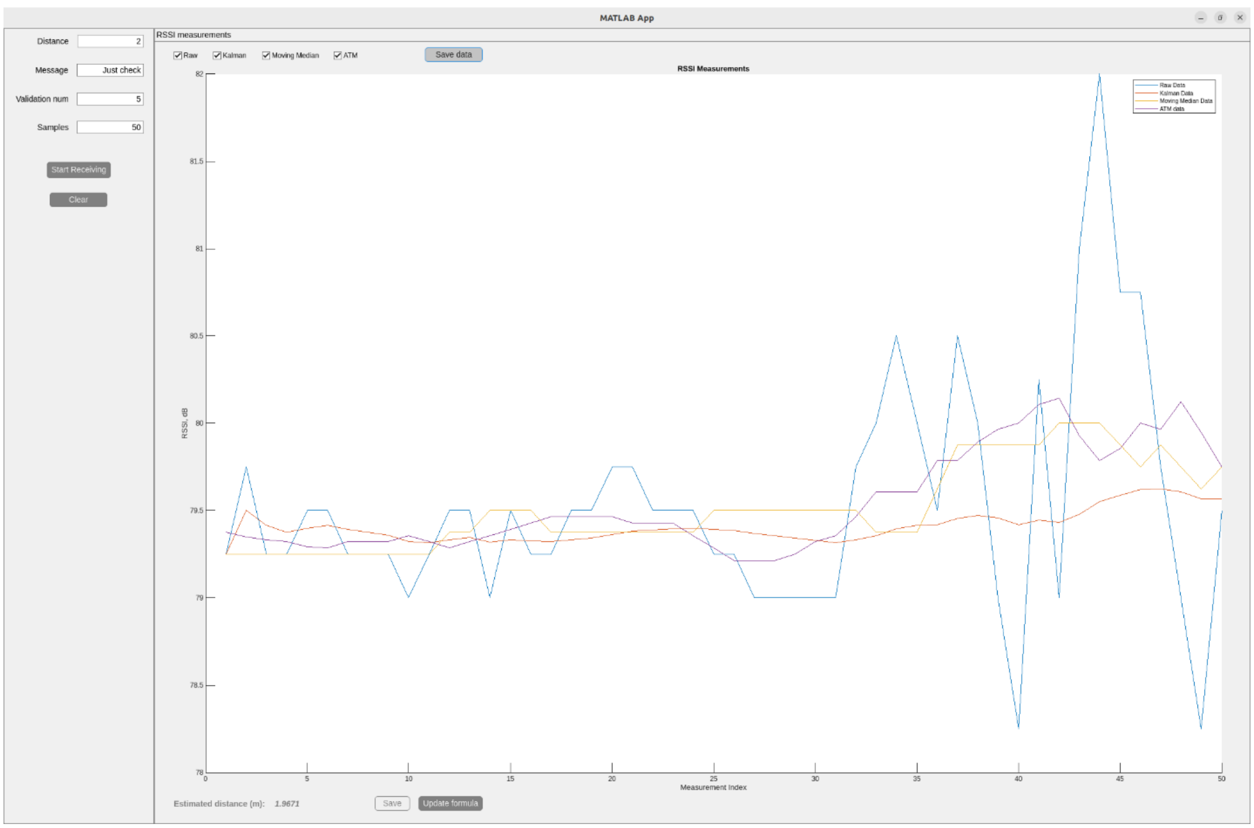
Overall, the performance of the Kalman Filter proves to be a better choice for this specific application, where data variability is a crucial issue. The smoother trend of the Kalman filtered data shows its ability to handle RSSI measurements variability introduces by various environmental factors and signal fluctuations, providing more reliable and consistent results.

With the focus on these specific methods, the system ensures optimized performance during both the testing phase and operational deployment. The integration of TDMA and the Kalman filter ensures the system is reliable and efficient.

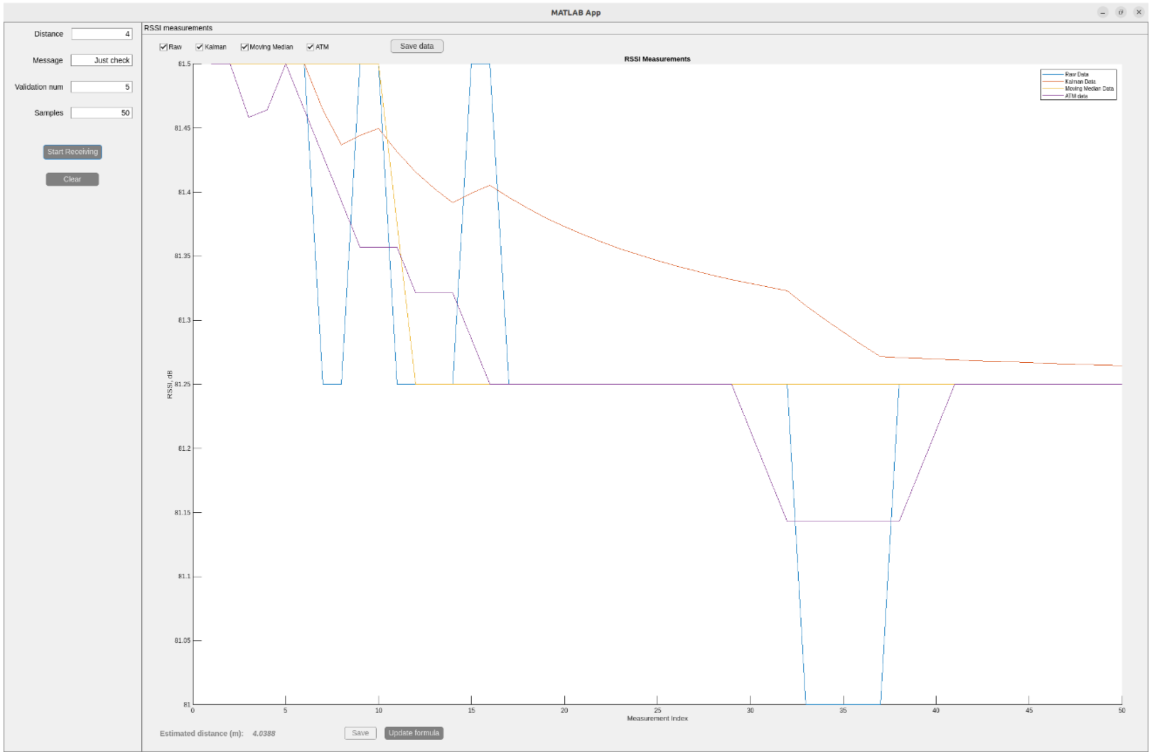
3.5 Proposed Capabilities

3.5.1 Precise distance measurements

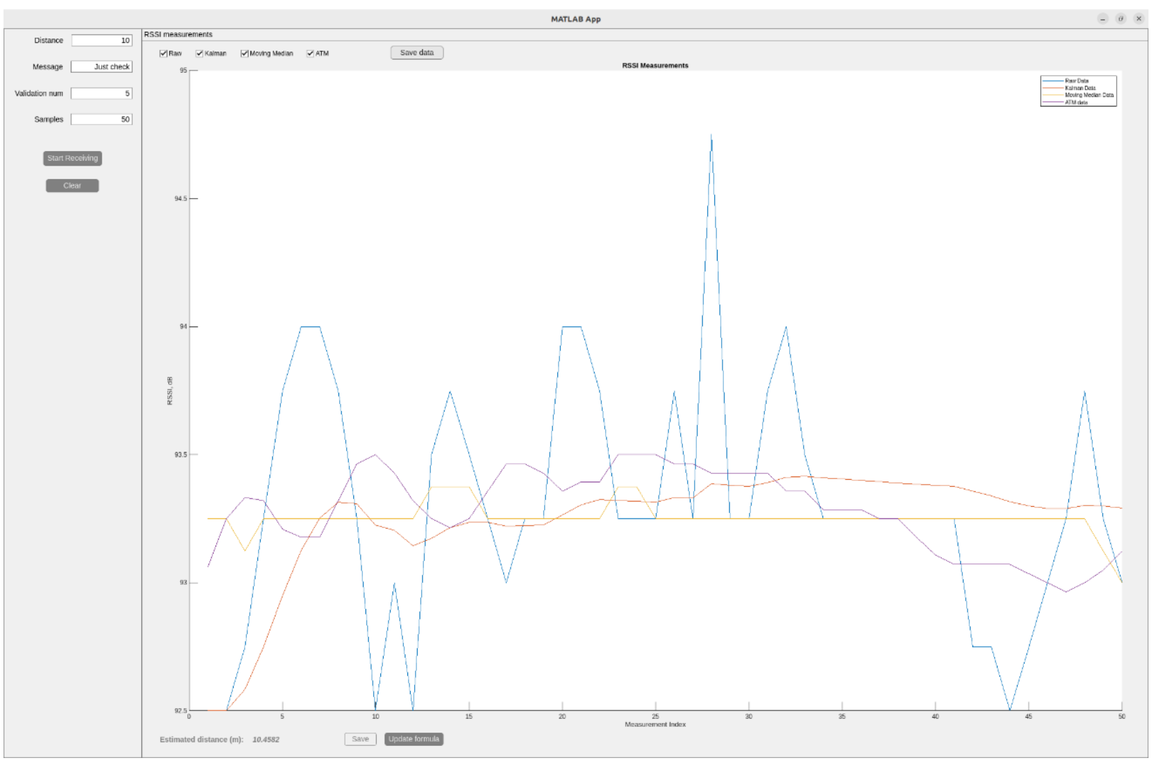
The main objective of this RSSI based Local Positioning System was to utilize the Adalm-Pluto module's Software-Defined Radio framework to achieve high accuracy in distance measurements. These measurements are critical to have better, more effective localization and navigation across different operational conditions. To validate the accuracy of the system, extensive testing was conducted in various environments and different distances (Picture 6, Picture 7, Picture 8).



Picture 6: Distance 2 m, Estimated Distance 1.96 m



Picture 7: Distance 4 m, Estimated Distance 4.039 m



Picture 8: Distance 10 m, Estimated Distance 10.458 m

Table 1 shows a comparative data between the actual distances and estimations by the system. Data does not represent all measurements, rather the ones conducted in different environment ranging from noisy to stable and optimal conditions. For each measurement the absolute and relative errors were also calculated to quantify the results' accuracy.

$$abs\ error\ =\ |meas\ dist\ -\ actual\ dist|$$

$$rel\ error\ =\ \left(\frac{abs\ error}{actual\ dist}\right) \times 100\%$$

Eq. 12

Actual Distance (m)	Measured Distance (m)	Absolute Error (m)	Relative Error (%)
2.0	1.895	0.105	5.25
2.0	1.9671	0.0329	1.645
2.5	2.26	0.24	9.6
3.0	3.093	0.093	3.1
3.0	2.82	0.18	6.0
4.0	4.039	0.039	0.975
5.0	4.89	0.11	2.2
7.0	7.099	0.099	1.414
8.0	8.89	0.89	11.125
10.0	10.45	0.45	4.5

Table 1: Distance measurement results

The analysis of these measurements shows a varying level of precision. The smallest relative error observed was at 4 meters, with an absolute error of 0.039 m and a relative error of 0.975%, showing the feasibility of this high precision LPS system. Conversely, the highest relative error was observed at 8 meters with an absolute error of 0.89 m and a relative error of 11.125%. Note that these measurements were done after proper calibration and environmental changes without recalibration yield higher error rates.

Studies have shown varying degrees of accuracy of RSSI based distance measurements, which are mostly influenced by environmental factors. However, those studies also show a difference which is influenced by the methodology and platform of choice. For example, distance measurement experiments using the ZigBee platform indicated an error margin of about 2 meters within a 20-meter range under ideal conditions, without considering environmental effects [11]. Other experiments with IRIS wireless sensor nodes, accuracies were as high as 91% outdoors and 57% indoors, which shows significant discrepancies due to environmental differences [12]. Bluetooth technology showed the most promising results with classic Bluetooth devices achieving impressive precision, averaging errors between 0.1 to 0.4 meters by utilizing filtering techniques such as median and Kalman filters and Bluetooth LE devices being able to reduce errors by around 13.4% through specific algorithmic strategies [13] [14].

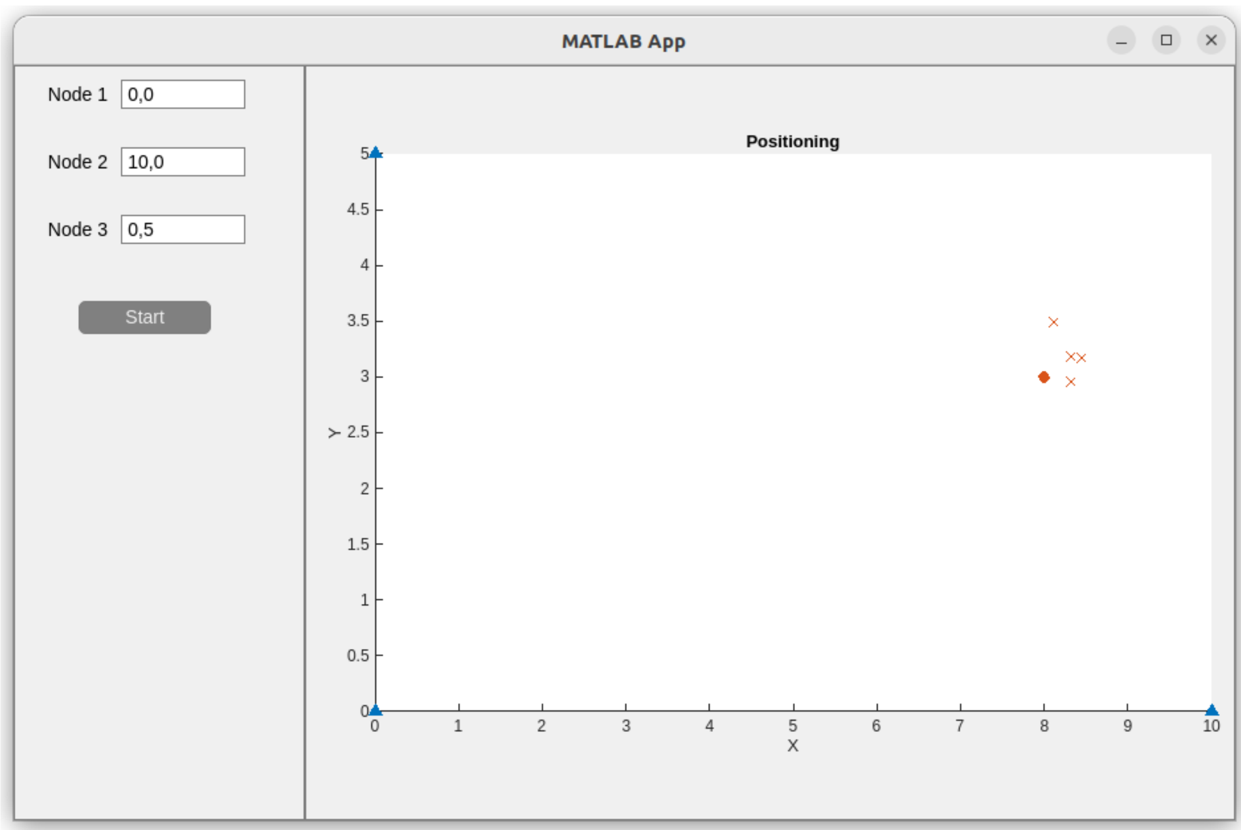
Considering these results, the accuracy obtained in this project, with error rates as low as 0.975% for distances around 4 meters, is competitive and promising. The Adalm-Pluto SDR module, despite its inconsistency due to environmental factors and its limited noise filtering capability, still seems to be capable of high accuracy when calibrated correctly and adapted to specific environments.

3.5.2 Location Positioning Estimations

To show the feasibility of the system and improved distance measurements a series of experiments were conducted to evaluate the system’s effectiveness and performance. The trials were executed in different environments, including NLOS scenarios. Multiple experiments were done to understand the effects of the optimized methods, and were set up to simulate real-world scenarios. Three of those experimental results are presented below.

The first set of experiments, the system was set up the following way: three nodes were positioned in a way that one was set as the origin of our coordinates (0, 0) node, the other ones (10, 0) and (0, 5) (Picture 9). The following results were obtained:

- Trial 1 Error: 0.4671 meters
- Trial 2 Error: 0.3174 meters
- Trial 3 Error: 0.3543 meters
- Trial 4 Error: 0.4969 meters

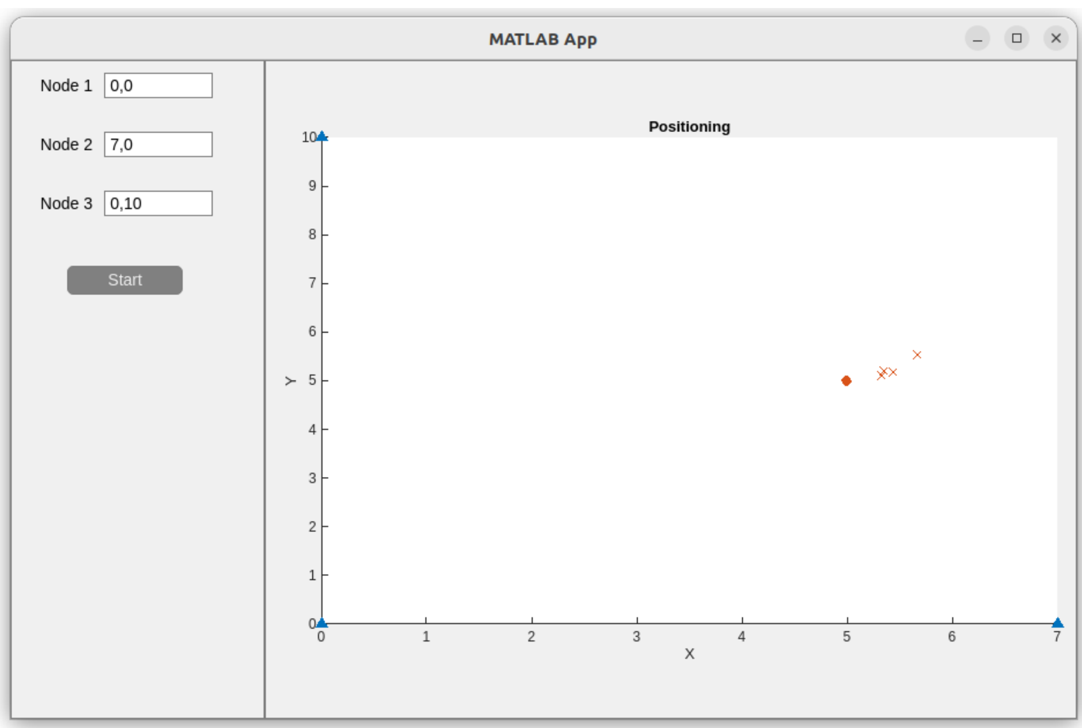


Picture 9: Experiment 1

The mean error for these measurements was 0.41 meters. These initial results show promising results, demonstrating that the system has the potential to achieve higher accuracy with optimized positioning techniques.

For the second set of experiments the system was in a noisier environment compared to the first test, however these set showed more precise and matching results (Picture 10). The errors were as follows:

- Trial 1 Error: 0.3981 meters
- Trial 2 Error: 0.4670 meters
- Trial 3 Error: 0.3439 meters
- Trial 4 Error: 0.8418 meters

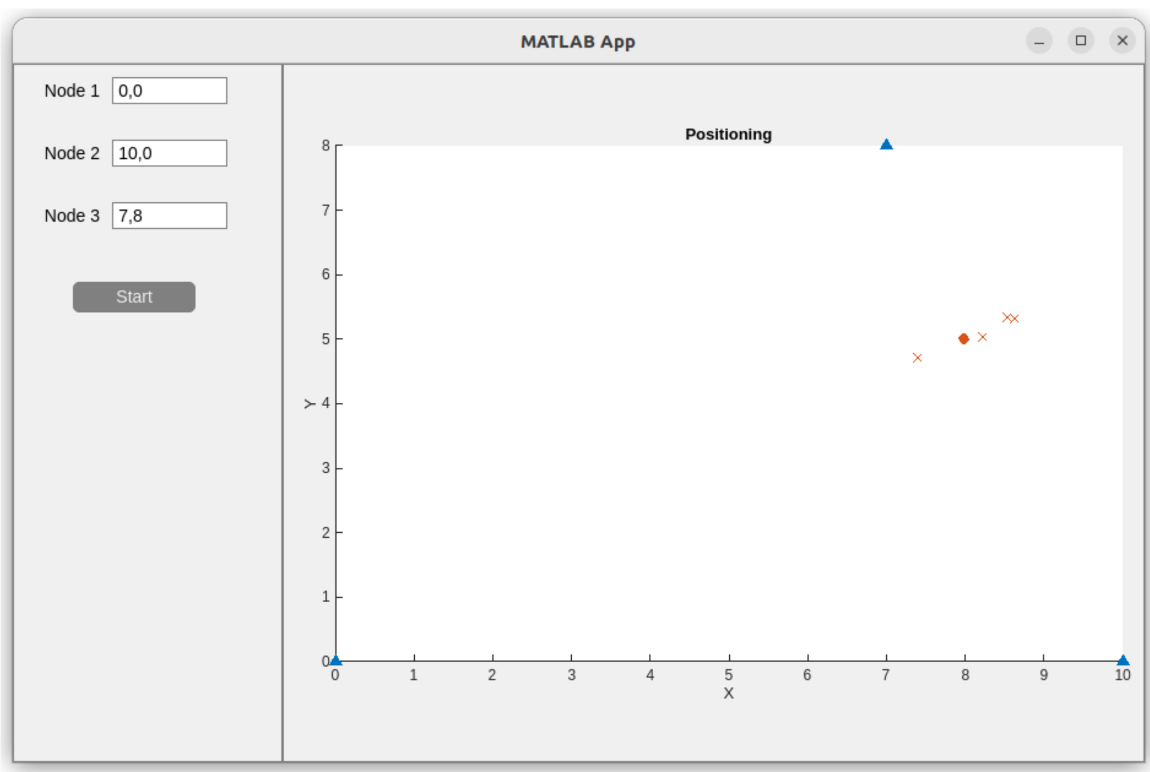


Picture 10: Experiment 2

The mean error increased to 0.5127 meters. The notable increase in the error during the fourth trial showed the system's sensitivity to environmental changes and raised the need for adaptive calibration strategies.

The third series was conducted shortly after the second test and aimed to repeat the same testing conditions, with the addition of NLOS testing (Picture 11). During the experiments One of the nodes was positioned behind the wall. It is important to note that the system was calibrated again for this environment. The errors recorded were:

- Trial 1 Error: 0.6397 meters
- Trial 2 Error: 0.2346 meters
- Trial 3 Error: 0.7119 meters
- Trial 4 Error: 0.6562 meters



Picture 11: Experiment 3

The mean error calculated from this set was 0.56061 meters, a slight increase in average error compared to the previous tests. This series showed the impact of NLOS conditions on the system's accuracy, even though the calibration was specifically conducted in the same configuration to mitigate these effects.

These experiments in different settings showed the influence of environmental factors, including NLOS conditions, on the accuracy of RSSI-based local positioning systems. While the system recorded a reasonable accurate results under NLOS conditions when calibrated appropriately, the variability in errors, specifically with higher deviations for some trials, suggests that continuous environmental assessment and tailored system calibration are important for showing optimal performance.

These experiments showed the feasibility of the system and gave valuable insights into the potential and limitations of the RSSI-based LPS, especially in complex environments with physical obstructions. These will be essential in future development efforts, focusing on enhancing algorithmic adaptability and refining calibration processes. Those will help to achieve more consistent and reliable positioning results, important for applications such as indoor navigation and automated vehicle tracking in dynamic settings.

4. Physical Environment

The operational conditions envisioned for the proposed LPS proof of concept primarily align with normal atmospheric parameters, including temperature variations and ambient humidity levels. Notably, owing to the current absence of protective housing —a characteristic inherent to the proof of concept nature—the system's resilience to extreme weather conditions such as rain or snow remains a consideration for future iterations. This aspect highlights the ongoing developmental phase of the project, where the priority lies in demonstrating core technical functionalities rather than physical protection.

5. Support Environment

At this phase, the system needs physical updates. These updates involve establishing connections and installing new firmware to ensure operational efficiency and updated functionalities.

6. Future Work

This project represents just the initial prototype of the RSSI based Local Positioning System. It demonstrated the system's potential in achieving precise distance measurements and effective positioning. However, the outlined future work is essential for advancing this prototype into a fully functional system suitable for more demanding applications. Improvements and refinements will be necessary to transition from this prototype stage to a robust, market-ready solution.

Antenna Upgrades for Extended Range

Upgrading antennas will extend the system's range and improve signal quality, specifically for large areas or outdoor environments. The choice of antenna has a significant impact on the system’s performance. This change would be particularly beneficial in environments where long-range communication is needed, such as in large industrial complexes or for outdoor navigation applications.

Dynamic Kalman Filter Adjustments

The Kalman filter, used in the system to reduce measurement noise, will be optimized for dynamic environment with changing environmental conditions such as movement, temperature fluctuations, or weather changes. This enhancement will improve the filter's effectiveness in real-time, leading to more reliable distance estimations.

Advanced Trilateration Techniques

Future work will include implementing more sophisticated trilateration techniques to improve the system and operate precisely in non-line-of-sight conditions. This will improve the accuracy of determining positions from the distances measured to multiple nodes in situation where the errors are high, or the circles formed by the nodes don’t intersect at all.

Continuous Calibration and Environmental Monitoring

As the experiments showed, the system need continues calibration in response to environmental changes to ensure stability and accuracy. Automatic adjustments and calibration will reduce the need for human intervention and will increase the reliability of the system. This feature will be useful for applications where precision is critical, such as in autonomous vehicle navigation and emergency response scenarios.

Time Syncronization

Another critical change to be included in the future development is the improvement of timing and synchronization for Time-Division Multiple Access (TDMA). In this phase the synchronization was done manually, however other and automatic approaches will be necessary for the future versions. Enhanced timing precision and synchronization will give faster and more reliable communication between nodes, which is important in real-time positioning and for rapid response applications. Optimizing TDMA will also allow the system to handle high-density node deployments without signal collision, making it more scalable and adaptable to various operational environments.

Conclusion

As this phase of the project is concluded, it is important to note that while the prototype has shown promising results, there is substantial work to be done to refine system's capabilities. The integration of advanced trilateration techniques, dynamic adjustments to the Kalman filter, are just a few of the strategies that will drive the system towards higher precision and reliability. Moving forward, these enhancements will be important cornerstone in transforming the prototype into a robust, adaptable, and efficient positioning system.

Appendix A: Acronyms

GPS – *Global Positioning System*

LPS – *Local Positioning System*

SDR – *Software Defined Radio*

TOA – *Time of Arrival*

RSSI – *Received Signal Strength Indicator*

TDOA – *Time Difference of Arrival*

TSOA – *Time Sum of Arrival*

AOA – *Angle of Arrival*

NLOS – *Non-Line of Sight*

LOS – *Line of Sight*

FFT – *Fast Fourie Transform*

ATM – *Alpha-Trimmed Mean*

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