WiFi-based Positioning System

Based on RSSI and Trilateration

Akshat Shah

Ganadhish Acharekar

Parth Nakar

Saharsh Jain

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Abstract

The most crucial problem in any navigation system is positioning. Object positioning is a key primitive in pervasive computing environments, where numerous applications depend on the rapid and accurate position estimation of objects. The Global Navigation Satellite System (GNSS) has been used in mobile unit positioning since long time. However, it is incapable of positioning in an indoor environment. Several solutions have been proposed to adopt a single location sensing technology that fits in both, indoor and outdoor situations. There are different methods available for positioning like Time of Arrival (TOA), Time Difference of Arrival (TDOA), Angle of Arrival and Signal Strength of Arrival (SSOA). Practical limitations of these approaches are briefly reviewed here. Among these methods, the RSS-based SSOA location estimation has received the most attention because of its minimum hardware requirements and the simplicity of its implementations. This paper aims to track user position in both indoor and outdoor environments by using RSSI (Received Signal Strength Indicator) technique together with enhancement algorithms. This paper also talks about various filtering methods available for smoothing RSSI and trilateration technique to locate the user.

1. Introduction

With the rapid development of mobile internet technology, the demand for location-based services (LBS) has also increased. Mobile unit positioning is the most fundamental and important problem in many applications such as unmanned autonomous vehicles, mobile robots in explore, search and rescue operation, asset tracking in warehouses, et cetera. The location estimation usually involves two groups of nodes. The first group consists of fixed nodes with known locations. These fixed nodes, sometimes referred to as *anchor nodes*, are used as references for the location estimation. The second group is the nodes with unknown locations, referred to as *tracked nodes or tags.* The main purpose of the location estimation is to determine the location of the tracked nodes with the help of the anchor nodes. There are three techniques which are popular for localisation.

1. Triangulation: This technique uses the angle of arrival of at least two reference points and their corresponding lines to find the intersection point which defines the estimated position of the object/person.
2. Trilateration: In trilateration, the position of an object is estimated by evaluating its distance from at least three reference points.
3. Scene Analysis: Scene Analysis uses fingerprinting to collect definitive description of a certain scene and matches it with the current information of a point to estimate the location.

GPS is a location positioning system for an outdoor environment. A GPS-enabled device determines its location by calculating its distance from three or more GPS satellites orbiting the Earth. Each GPS satellite continuously transmits messages containing the satellite location and the exact time. This message travels approximately with the speed of the light to reach the GPS receiver. The GPS receiver compares the exact time the message was received with the time the message was transmitted by the satellite to calculate the distance travelled. Knowing the distance to at least three satellites and the satellites' positions, the receiver calculates its own position. However, GPS is not suitable for indoors as it requires Line of Sight (LOS) between device and satellites. Therefore, efficient indoor positioning technology has become a very active research topic.

A variety of indoor positioning technologies have been proposed, such as Bluetooth, Ultra-Wideband (UWB), Radio Frequency Identification (RFID), Wireless Local Area Networks (WLAN), Computer Vision, Ultrasonic waves, Infrared signals and others. The metrics used in most of the approaches are: Received Signal Strength Indicator (RSSI), Time of Arrival (TOA) / Time Difference of Arrival (TDOA), and Angle of Arrival (AOA) or Direction of Arrival (DOA).

The rest of this paper is organized as follows: Section 2 discusses various processes for positioning, their pros and cons. Section 3 introduces and describes the proposed method.

Section 4 analyses the results of the experimental implementation of the proposed method. Finally, the conclusions of the study are presented in Section 5.

2. Methods of Positioning

2.1 Location Positioning Techniques

The choice of location-estimation algorithm depends on the application scenario. The location-estimation methods are compared based on their performance and complexity. There are several methods to determine the location as coordinates of the nodes such as Angle of Arrival (AOA), Time of Arrival (TOA), Time Difference of Arrival (TDOA), and Signal Strength of Arrival (SSOA). These methods are built on geometric principles to calculate the position of a node using straight lines and angles. Triangulation, multilateration and hyperbolic lateration are examples of these principles.

2.1.1 TOA/ TDOA

Time of Arrival (TOA), also named Time of Flight (TOF), refers to the travel time of a radio signal from a target node to transceiver stations and back. Distance between them is given by equation,

$$d = c.t$$

where 'd' is the distance between node and station, 'c' is the speed of light and 't' is the time travel of round trip. Then the location can be calculated by trilateration.

Time Difference of Arrival (TDOA) techniques are based on estimating the difference in the arrival times of the signal from the source at multiple receivers. Using above equation and hyperbolic mathematical principle the location of node is estimated.

By using these two techniques high accuracy can be achieved in position location of a target node. However, the need of synchronization between target node and transceiver stations introduces complexity as well as major source of error in measurement. Another source of error is multipath propagation which limits the accuracy of system. Signal spreading is a method used to mitigate the effect of multipath. Avery high-bandwidth signal such as a UWB signal improves the location estimation accuracy significantly beyond the accuracy achievable using an IEEE 802.15.4 signal. The systems using UWB for time-based location estimation can achieve resolution as low as a few inches. Generally speaking, when signals are using spreading techniques, the higher the bandwidth, the better is the location estimation accuracy.

2.1.2 AOA/ DOA

Angle of Arrival (AOA) is a network-based positioning method that measures the time taken by radio signals to arrive at several points. Triangulation principle is used for determination of position. Less number of transceiver stations and no need of synchronization are advantages of this approach, while need of directional antennas increases the cost.

2.1.3 SSOA

RSSI (Received Signal Strength Indicator) method can be used to locate a device. The RSSI values are first measured from an AP (Access Point), with multiple APs sometimes used to increase the accuracy of the distance estimation. RSSI is converted into distance by using path loss models and then by trilateration location of the tracked node can be known. However, due to factors like environment dependency of RSSI and logarithmic nature of path loss model, measured location remains inaccurate.

The sources of error in RSSI-based location estimation can be divided into three main categories: hardware-related errors, the limitations of the location-estimation algorithm itself, and the effect of environment. We can start with the uncertainty associated with the transmitted signal strength. The transmitter is expected to transmit a signal of a prespecified strength. However, the transceivers built for low-cost, short-range wireless networking normally have only a simple output power control mechanism, and the hardware manufacturers only guarantee a range of output power when a specific output power setting is selected.The properties of the antenna itself can further degrade the accuracy of the transmitted signal power. The radiation pattern of an antenna is not omnidirectional and the transmitted signal strength at different directions and with different orientation of the antenna can vary considerably. The main challenge in RSSI-based location tracking is its high sensitivity to the environmental changes. Generally, RSSI measurement, noise filtering, and revision are required for distance estimation using RSSI. Given that RSSI does not decrease linearly with distance, the error in a distance which is estimated based on RSSI increases with increasing the measured distance.

2.2 Mathematical Filters

For countering the dynamic behaviour of RSSI, various filters like Mean Filter, Gradient Filter and Kalman Filter are available.

2.2.1 Mean Filter

On the unsound assumption that RSSI values follow Gaussian distribution, we take mean of certain number of RSSI values **σ**, and calculate standard deviation **μ** by the formula:

$$\mu = \sqrt{\frac{|RSSI - \sigma|}{N}}$$

Then we take the middle part of Gaussian function by calculating $\boldsymbol{\mu + \sigma}$ and $\boldsymbol{\mu - \sigma}$. However, these values of RSSI do not always accurately reflect the dynamic behaviour of RSSI, caused by a variety of factors such as multipath and non-line-of-sight (NLOS) propagation in an indoor environment.

2.2.2 Gradient Filter

The gradient of the RSSI is defined over a coverage area scalar field that is a two dimensional space with a real RSSI value associated to each point inside the field. Associated to this scalar field is a vector field defined by the gradient of two different values of RSSI in the scalar field. The gradient of RSSI varies over time and space, that is, if the tag changes its position in the scalar field the gradient will vary, and if the tag is stationary, the RSSI changes over time and hence the gradient will also change. The basic working of this filter is to add up all previous values and take its mean. Then we add the velocity by subtracting previous two readings. This gives us the predicted distance. However there is always scope for error. Finally estimated distance is equal to the sum of predicted distance and error multiplied by a factor (which is less than 1).

2.2.3 Kalman Filter

Distances calculated in indoor environments are affected by noise. A Kalman filter is capable of filtering sudden changes in a signal during signal estimation based on preceding signals. Kalman filter estimation process is based on a feedback loop control system, which first estimates the process's state at a point in time and then obtains feedback from actual measurements. This feedback measurement is used to adjust the model parameters for the next estimate. The model assumes that the state of a system at a time k has evolved from the prior state at time k-1 according to the equation,

$$X_k = A.X_{k-1} + B.u_k + w_{k-1}$$

$$Z_k = H.X_k + v_k$$

It means that each $\mathbf{X_k}$ *(our RSSI values)* may be evaluated by using a linear stochastic equation *(the first one)*. Any $\mathbf{X_k}$ is a linear combination of its previous value plus a control signal **u** and a process noise **w** *(which may be hard to conceptualize)*. Remember that, most of the time, there's no control signal $\mathbf{u_k}$.The second equation tells that any measurement value is a linear combination of the signal value and the measurement noise, **v**. *They are both considered to be Gaussian*. The entities **A**, **B** and **H** are in general matrices.

The table 2.1 shows simplified versions of Kalman equations for this application.

Here, $\hat{X}$ is estimated RSSI,

P is error covariance which is initialized to be 1, R is measurement noise which is initialized to 0.001 in our case,

K is Kalman gain and z is measured RSSI

Time Update *(prediction)*	**Measurement Update** *(correction)*
$\hat{x}_k^- = \hat{x}_{k-1}$ $P_k^- = P_{k-1}$	$K_k = \dfrac{P_k^-}{P_k^- + R}$ $\hat{x}_k = \hat{x}_k^- + K_k(z_k - \hat{x}_k^-)$ $P_k = (1 - K_k)P_k^-$

Table 2.1 Simplified Kalman Equations

$\bar{\hat{X}}$ and $\bar{P}$ refer to the rough estimations in RSSI and error respectively. The **Kalman gain** is the relative weight given to the measurements and current state estimate, and can be "tuned" to achieve particular performance. Higher the Kalman gain, more weight is given to measured value than estimated value and vice versa.

Since the Kalman filter implemented is a linear one, so it works only for stationary targets. In case of dynamic ones, complex extended/unscented Kalman filters are required. Also, the RSSI fluctuation noise is not Gaussian in distribution which implies that the Kalman filter is obviously not optimal. It is observed that these existing methods may not perform sufficiently well in ever-changing dynamic indoor environments.

3. Proposed Method

3.1 WiFi-based Positioning

This section describes the proposed distance estimation framework, which is based on the RSSI values of mobile hotspot. Here, the anchor nodes are three Wemos D1 R2 Mini (ESP8266 modules) and target nodes are cell phones with active hotspots. The anchor modules first scan all the networks available and list them in a file 'ssid_list'. The anchors measure RSSI of those networks and apply Kalman Filter on them. Filtered RSSI values are converted to distance and are sent to a computer using MQTT protocol. The computer then calculates the location of the target by trilateration algorithm.

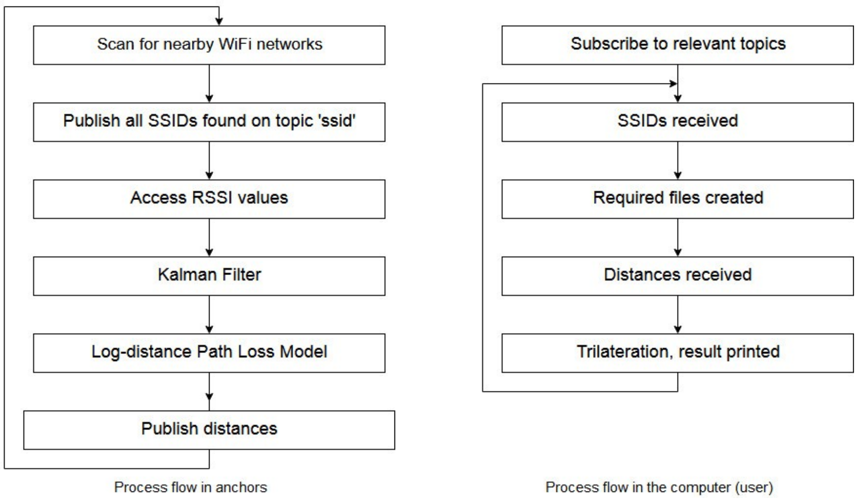

Figure 3.1 Flowchart of Proposed Method

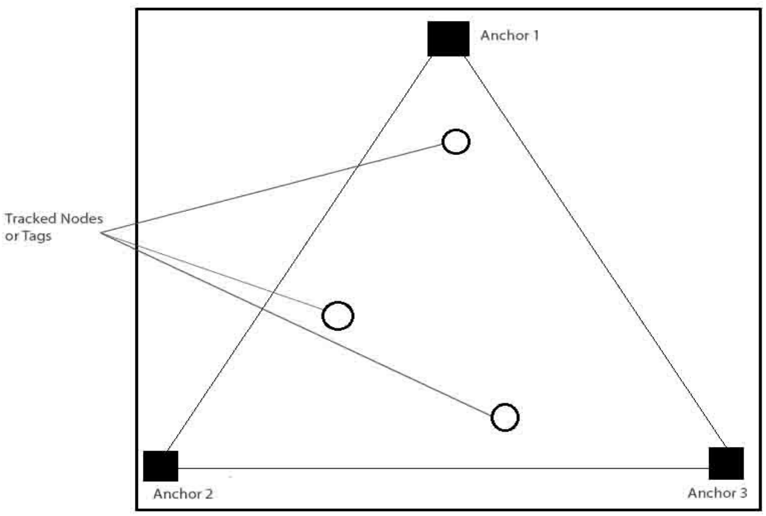

Figure 3.1 Layout of Proposed Method

3.2 Hardware:

Features of WEMOS (ESP8266 module):

1. 11 digital input/output pins, all pins have Interrupt / pwm /I2C/one-wire supported (except D0).
2. 1 analog input (3.2V max input).
3. A Micro USB connection.
4. Compatible with MicroPython, Arduino, NodeMCU.

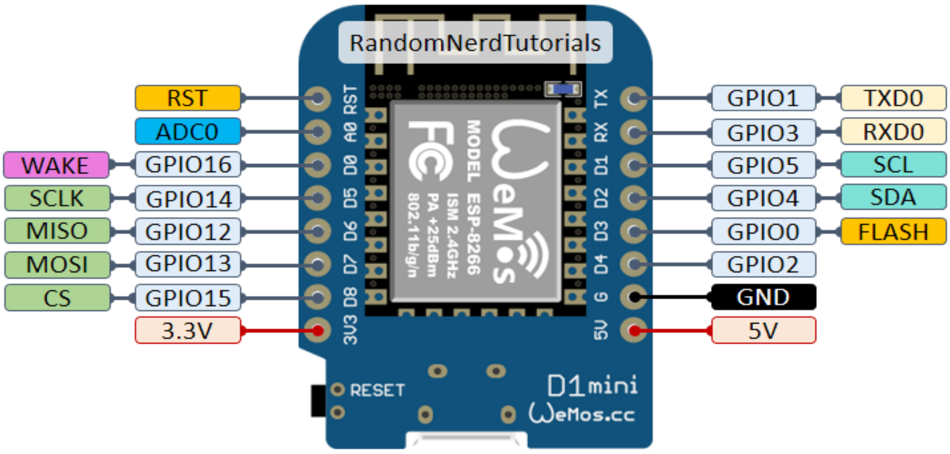

Figure 3.2 Wemos Pin Diagram

3.3 Software

The following software and libraries were used in this project:

1. Platformio extension on Visual Studio Code for writing code for Wemos (ESP8266).
2. Arduino Core Framework for the code for Wemos (ESP8266).
3. PubSubClient Library by Nick O'Leary for implementing MQTT on Wemos (ESP8266) (https://github.com/knolleary/pubsubclient).
4. Paho MQTT Client for implementing MQTT on computer (https://pypi.org/project/paho-mqtt/).
5. Matplotlib library for plotting graphs of RSSI and distance (https://matplotlib.org/).

3.4 RSSI-Distance Model

This is a method to find distance from received signal strength. Power of any signal at a particular distance from the source is the difference of Transmitted Power and Power lost. By Friis's equation is:

$$P_r = P_t G_r G_t (\text{wavelength})^2 / (4 \pi L)^2 d^n$$

Where P_r =Power Received,

P_t=Power Transmitted,

G_r=antenna gain at receiver (mostly 1),

G_t=antenna gain at transmitter (mostly 1),

L=hardware losses (mostly 1),

d =distance from source and

n =path loss exponent

Taking 10log on both sides,

$$\text{P.L. (RSSI)} = 10\log(P_t / P_r)$$

Taking standard RSSI at 1m = txPower

RSSI = txPower – 10nlog(d) + C

- Shadowing effect: Obstacle for every path is different, so loss suffered or increases in signal strength for each path will be different. The above constant C is standard deviation also written as X_d.

This model is suitable for both indoor and outdoor environments.

$$X_d(d) = ad^3+bd^2+cd+e$$

a,b,c,e are undetermined coefficients whose values are adjusted dynamically according to environment.

- Fading: It is rapid fluctuations of amplitude, phase, and delays of signal over short interval of time or distance.

Hence distance d is given by,

$$d = 10^{(\text{txPower - RSSI}) / 10n}$$

3.5 Message Queuing Telemetry Transport (MQTT):

MQTT is a client-server publish/subscribe (or pub/sub) messaging transport protocol. The pub/sub pattern provides an alternative to the traditional client-server architecture. The pub/sub model decouples the client that sends a message (the publisher) from the client that receives the message (the subscriber). The publisher and subscriber never contact each other directly. The connection between them is handled by a third component (the broker). The job of broker is to filter all incoming messages and distribute them correctly to subscribers. The publisher publishes the message on a topic to which the subscriber subscribes. MQTT topics are a form of addressing that allows MQTT clients to share information.

Quality Of Service (QOS) - 0 is used while transmission of message. One access point is arbitrarily chosen to provide internet access to all anchors for implementing MQTT.

3.5.1 Publishing End (Anchor):

An anchor (Wemos ESP8266) scans all the available access points and publishes their SSIDs on topic *'ssid'*. Then as explained earlier the anchor finds the raw RSSI value of each access point, applies Kalman Filter to it and using Log-Distance Path Loss model, converts it into distance. Thus the distance of the APs from each anchor a1, a2 and a3 are obtained. Now these distances are published on topic *'a1'* , *'a2'* and *'a3'* according to the respective anchors in a message that consists of two parts - SSID and distance. The format of the message is

SSID:DISTANCE

The PubSubClient library requires the message to be in the form of a character array in C.

3.5.2 Subscribing End (Computer):

A computer subscribes to the topics *'ssid'*, *'a1'*, *'a2'* and *'a3'*. It first creates a file containing all the SSIDs using the messages received from the topic *'ssid'*. Three directories named 'a1', 'a2' and 'a3' are initially created by the user and inside them, files are created for each SSIDs. When a message on topics *'a1'*, *'a2'* or *'a3'* arrives, the first part (SSID) is read and the second part (distance) is then stored in the file assigned for that SSID.

3.6 Trilateration

Trilateration is a mathematical technique of determining the position of an object (tag), given its distances from fixed, known points. This technique is also used in Global Positioning System (GPS) but it can be applied to any positioning system.

In this application, anchors act as these fixed points. The distance of an AP (tag) from every anchor is obtained from the RSSI method as explained above, and using MQTT, these distances are relayed to and orderly stored in the computer. The distance of the tag from an anchor allows us to ascertain that (considering that the anchor and the tag are in the same plane) the tag lies somewhere along a circle of radius equal to that distance and with centre as the anchor. From distances received from multiple anchors, it is possible to find the exact position of the tag i.e. the point of intersection of the circles. In practice, this intersection will be a region rather than a single point owing to limits of practical accuracy.

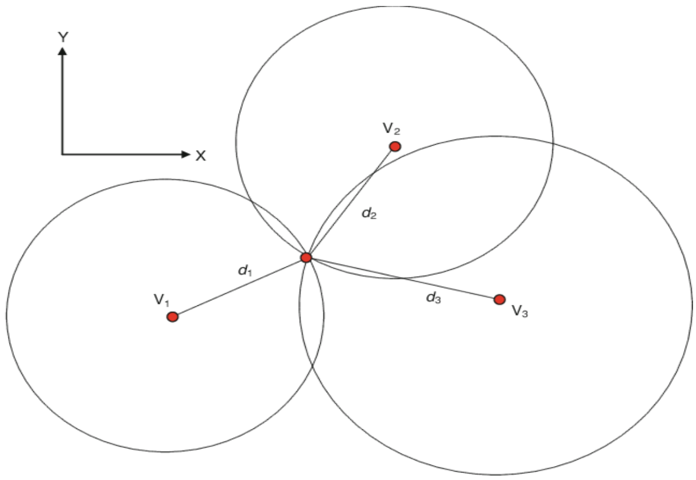

Figure 3.3 Trilateration

4. Experimental Results and Analysis

Using the aforementioned concepts, methods, and communication protocol, position estimation was achieved to an accuracy of about half a metre in a chosen region, with three anchors and multiple access points. Throughout this project, multiple methods of estimating the position and filtering the RSSI values were explored and considered. Out of all the position estimation methods, Signal Strength of Arrival (SSOA) was selected due to its simple implementation, minimal hardware requirements and hardware availability. Of the various filters considered in this project, practically, Kalman Filter gave the best results as shown in the graph in figure 4.1.

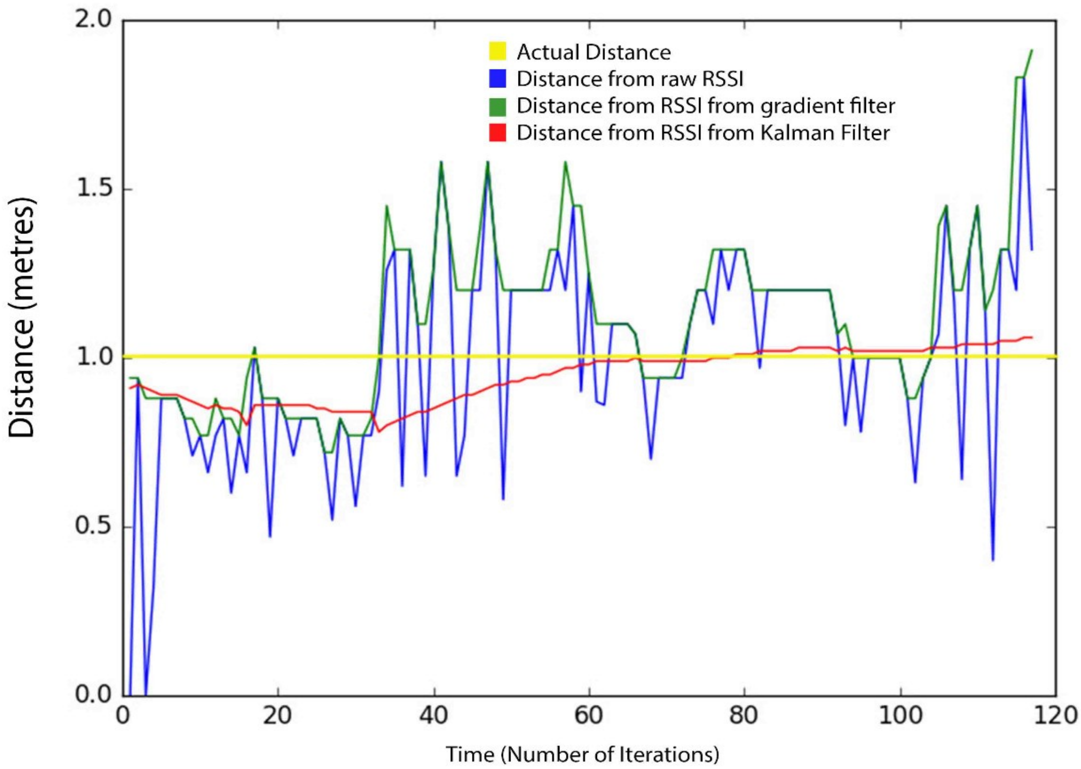

Figure 4.1 Experimental Results at 1m distance

Further, using the inherently simple MQTT protocol for achieving communication between the computer and anchors, distance of each access point from the anchors was sent to the computer. Finally, the computer determined the positions of APs (x and y coordinates) as output.

5. Conclusion and Future Work

RSSI is a highly fluctuating (even when the target does not move) and an unreliable input for positioning systems. However, it is possible to get good results even from this unreliable input using various filters like Kalman filter. RSSI reliability can be further improved by selecting better hardware that has more reliable RSSI output. Path Loss models, particularly Log-Distance Path Loss model facilitate the calculation of distance between the transmitter and the receiver using RSSI.

Such a Wi-Fi based positioning system has numerous significant applications, particularly in indoor environments where GPS fails. The applications of an indoor positioning system combined with a fast and reliable intercommunication system ranges from object or person tracking to even swarm robotics, in which multiple robots work together to achieve a goal. While considering the implementation for indoor positioning systems, it is vital to consider the economic perspective. Positioning using Wi-Fi and RSSI is advantageous from this perspective, since it requires no additional expensive hardware.

The proposed method is implemented only for stationary targets, as of now. Moreover, it is difficult to accurately fit the RSSI distance model with the logarithmic distance loss model due to the complex electromagnetic environment in the room. In future, we aim to implement this method for dynamic targets with higher accuracy in positioning, even with changing environment.

This source code for this project can be accessed from the following GitHub link:
https://github.com/akshatshah21/positioning-using-wifi