Master thesis

Design and Evaluation of an Indoor Localization System using 2.4 GHz LoRa

Ashok Vaishnav

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Kiel University
Department of Computer Science
Distributed Systems Group

Supervisor 1: M.Sc. Oliver Harms
Supervisor 2: Prof. Dr. Olaf Landsiedel

Eidesstattliche Erklärung

Hiermit erkläre ich an Eides statt, dass ich die vorliegende Arbeit selbstständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel verwendet habe.

Kiel, 19. November 2022

Abstract

Localization systems help people navigate (to) unknown locations. Today's technical advancements provides people handheld devices and indoor robots, which increase the popularity of using navigation systems. The Global Positioning System (GPS) is suitable for Line-of-Sight scenarios like outdoor environment and lacks the connectivity in indoor environment. Instead, the LoRa 2.4 GHz is a low power, low cost, and long range technology which features geolocation capabilities. To efficiently use the technology for Indoor Localization, we study its ranging performance with several LoRa modulation parameters considering different scenarios.
In this thesis, we present a ranging evaluation system and indoor localization system. The evaluation system enriches us with suitable LoRa parameter for indoor environments and further used to achieve positioning in indoor localization system. Our evaluation gives a brief perspective about LoRa modulation parameters in different scenarios. Also, the indoor localization system's performance is largely dependent on ranging performance of LoRa devices. Additionally, our evaluation shows that positioning with LoRa 2.4 GHz is reliable while using optimal LoRa modulation parameters.

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Chapter 1

Introduction

We live in a world which is highly advanced in terms of connected devices. There are millions of active wireless in-mobile devices performing their desired tasks. Locating of those devices has become an interesting topic and their ongoing research for obtaining “Geo-positions”. Many existing positioning systems are used for localization of air-crafts, trains, vehicles, e-scooters, cellular phones, etc. using e.g., GNSS technologies. These technologies are limited only to outdoor positioning and do not offer much accuracy in Indoor environment [1]. Therefore, localization/positioning of wireless mobile devices in Indoor environment gains an interest for research which can be useful for localization of devices in buildings, airports, hospital, train stations, supermarkets, warehouses, etc. [2].

In wireless networks, technologies like Wi-Fi, Bluetooth, UWB were explored and have their localization feature implemented, but each of them has their own limitations in terms of range, accuracy, cost and power consumption. There are technologies which uses higher frequency bands and operates in low power conditions and promises long distance communication. LoRa is one of them, and uses 2.4GHz spectrum, which can be an economical solution as LoRa enabled devices are appreciated for their price, range, and power consumption [3]. Semtech's SX1280 is a LoRa module, which is worldwide available and provides a built-in Ranging Engine. Having these modules in a sensor network would support several real world applications in localization of devices in real-time. Therefore, we take an interest to explore Indoor ranging and positioning accuracy of LoRa 2.4GHz using Semtech SX1280 LoRa module.

The approach for the Indoor Localization is a twofold. For the first step, we perform ranging, through which we obtain distance between two different positions. To come out with best distance measurements, we perform some evaluations based on varied network parameters like frequency, bandwidth, and data rate. This evaluation is necessary for wireless devices as there can be ranging error caused by multipath wave propagation through walls, glass objects, reflecting surfaces, etc. in indoor environment [4]. Then in the second stage, we use outcomes from the previous step and estimate location of the object. A localization system is required to have a sufficient number of anchors as a base for applying a localization algorithm. For that, we have a testbed setup which contains our LoRa modules spread over measured distances. Apart from physical architecture, the system must function in a synchronized manner to achieve non-ambiguous communication environment for better stability. Therefore, we use Zephyr OS to withstand our approach for an organized software architecture and efficient resource management [5].

We observed that the inbuilt Ranging Engine with Semtech SX1280 LoRa module does not always result in good ranging values in indoor environment when compared to actual distance. Therefore, a strategy for pre-localization is applied for gathering ranging data by applying permutations and combination on LoRa modulation pa-

rameters like bandwidth and spreading factor in both LoS and NLoS environment. After comparisons, we found that the optimal ranging setting for SX1280 LoRa module at 1600 KHz bandwidth combined with SF_9 spreading factor would result promising with multilateration localization approach.
Our main contributions are:

- We design an Indoor Localization System using LoRa 2.4GHz.
- `github.com/ashokvaishnav708/IndoorLocalizationLoRaProject`
- We evaluate LoRa 2.4GHz Ranging in LoS and NLoS environment.
- We discuss the ranging differences between actual and LoRa measures distances.
- We find an optimal LoRa 2.4GHz modulation parameters for ranging in indoor environemnt.
- We evaluate LoRa 2.4Ghz Ranging in our Localization System.

The remainder of this thesis is organized as follows. Chapter 2 gives the necessary background information on LoRa and several positioning methodologies. In Chapter 3 we show the differences for indoor localization achieved with different wireless technologies and already explored topics for LoRa. Chapter 4 introduces the overall system design and references of the system. Chapter 5 explains the implementation of the Algorithm for our localization System, and we display some visuals and evaluations performed during the building process of our system in Chapter 6. Finally, we wrap up the work with a general conclusion and discussion in Chapter 7.

Chapter 2

Background

We start by introducing the essential terminologies and providing an overview of the operating system we use. Further-more, we provide description of different ranging techniques, positioning methods and ranging functionality with SX1280 transceiver.

2.1 LoRa

LoRa stands for Long-Range and a technology derived from chirp spread spectrum which uses spread spectrum modulation [3]. LoRa technology was developed by a company called Semtech, and it has a wireless protocol designed specifically for long-range, low-power communications and can transmit/receive packets to/from the remote locations [6]. These features make LoRa an effective and ideal solution for IoT and many wireless applications which rely on far distant communication. LoRa devices and the LoRa Wide Area Network (LoRaWAN) standard offers great features for IoT applications, including low power consumption and secure data transmissions. The technology is currently used by various sectors in networking market and provides greater range than regular cellular networks [3]. As shown in figure 2.1, LoRa fills the technology gap of cellular, Wi-Fi and BLE networks that require either high bandwidth or high power, or have limited range or inability to penetrate deep indoor environments [3].

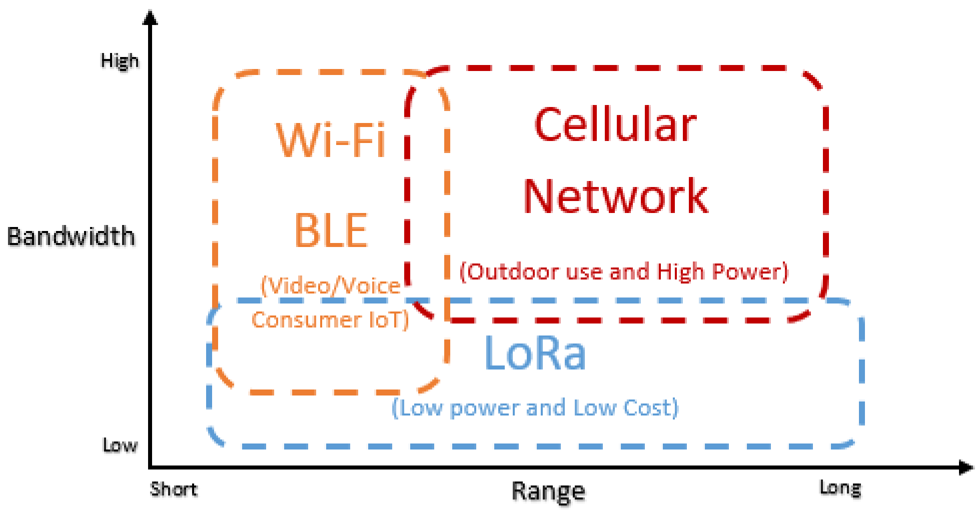


Figure 2.1: Why LoRa over other wireless technologies [3]

2.2 Ranging

Ranging is a process to determine distance between two different geolocations. In wireless technology, a great amount of research has been done for distance estimation. There are several ranging techniques which are used for localization of devices, among which four main techniques are Received Signal Strength (RSS), Time of Arrival (ToA), Time Difference of Arrival (TDoA), and Angle of Arrival (AoA) [7]. Assumptions for these techniques are that, the propagated waves travel with the same velocity as light, and measure the distance accordingly.
An extended version of ToA is RToF which is a similar technique to Time-of-Flight, in which the distance is measured at the sender end and requires relative clock synchronization [7]. This technique is also used by Semtech's SX1280 Ranging Engine.

2.3 Localization/Positioning

There are several methods to estimate the location of an object on a 2d spatial plane. For that, distance is measured between the object and subsequent numbers of Anchor points. The commonly preferred methods for localization are Lateration and Angulation. These methods are applied on a 2d plane with three or more known anchors at fixed locations [8]. Three major positioning techniques are described below.

Trilateration is a geometrical method to determine location of an object which requires minimum three known reference coordinate points and their distances to the object [9]. Distances are considered as radius of circle and the intersecting point between those circle is the object location [10], [11]. For calculus, we get three different equations using Pyhtagoras theorem with radii (distances) and their coordinate points. Solving those equations will provide a point which is referenced as intersection (object location).

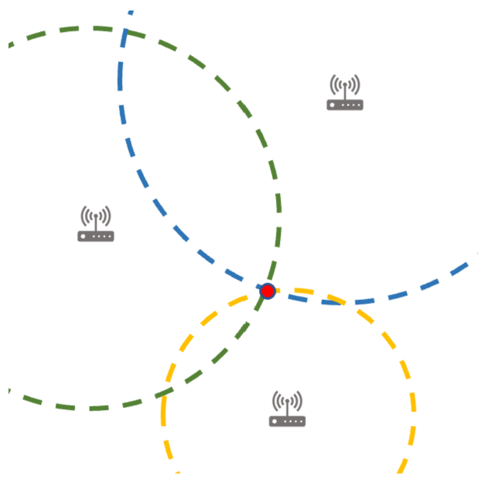


Figure 2.2: Trilateration Positioning Method

Triangulation is an angulation method which requires two or more antenna arrays placed at known locations and distances to each other. Object (mobile node) performs ranging through one of the several ranging techniques and obtains the distance from all available antennas. The location of the object is estimated by the angle formation between the edges connecting the Anchor points and object [10]. This is a complex method as there is the need of antenna arrays to obtain angle, which leads to complex hardware infrastructure [12].

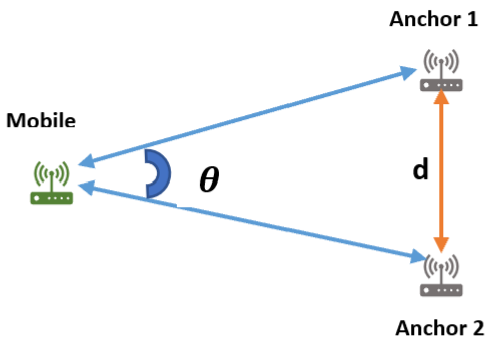


Figure 2.3: Triangulation Positioning Method

Multilateration is also a geometrical method and easiest among other localizations techniques. It is very common to occur errors in ranging process and do not have accurate positioning in other techniques [13]. Multilateration provides the expected location of the object inside a particular area/polygon, which makes it interesting and useful. Multilateration can be applied in systems where there are three or more anchors and after ranging the distances are considered radius of a circles [12]. The coinciding points between the circles describe the location in which the object is present [14].

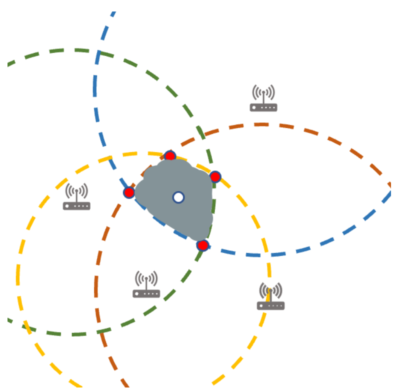


Figure 2.4: Multilateration Positioning Method

2.4 Semtech SX1280 Transceiver

The SX1280 is the silicon developed by Semtech Company. The SX1280 transceivers are used for ultra-long range communication, which uses 2.4GHz band and can insulate heavy interference. Withstanding a high interference makes these transceivers ideal for robust and reliable wireless system [15], [16]. It's the first ISM band module to serve built-in ToF functionality. Within this, it also provides point-to point, multipoint, multi-multipoint clear data transmission among LoRa modules [16]. For different uses and purpose, as shown in the table 2.1, the SX1280 module can be configured with combination of different modulation parameters like bandwidth, spreading factor, and coding rate as needed.

Bandwidth kHz	**Spreading Factor**	**Coding Rate**
BW_1600	SF_5	CR_4_5
BW_800	SF_6	CR_4_6
BW_400	SF_7	CR_4_7
BW_200	SF_8	CR_4_8
	SF_9	CR_LI_4_5
	SF_10	CR_LI_4_6
	SF_11	CR_LI_4_8
	SF_12	

Table 2.1: SX1280 supported Modulation parameters

SX1280 transceiver includes a Ranging Engine which defines the ranging packets and their sequence of exchange between master and slave modules. The header of the ranging packet contains a ranging ID (max 32-bit) for verification of the ranging request. Range information can be accessed at master node.

2.5 ZephyrOS

Zephyr OS is an open source collaborative project which aims small and scalable Real Time Operating System (RTOS) for support of multiple architectures and resource constraint embedded devices [5]. It is released under Apache 2.0 open source license. Zephyr provides a small-footprint kernel with several libraries and General Purpose Input Output (GPIO) polling and interrupt services for slave devices. Zephyr OS provides a Device Driver Model, which further extends the support for available devices as well as future devices. Its driver implementation uses Application Programming Interface (API) for device interaction [17]. An existing set of APIs are reusable for other devices having similar architecture. Device trees are used to describe the hardware, which provides an abstraction layer between device and OS which makes its APIs executable on different hardware platforms. It supports Native Networking Stack protocols for secure and reliable communication [18] and drivers for wide range of wireless technologies like BLE, Wi-Fi, LoRa, etc.

2.6 Semtech SX1280 Ranging Engine

Semtech's SX1280 transceiver has an inbuilt ranging engine designed by Semtech which handles the ranging operations and packets between sender and receiver (also called master and slave). The ranging engine internally ensures the errors fixing caused by delays occurred in the whole ranging process. The ranging Engine is based on RToF concept to perform ranging [19]. The figure 2.5 shows the RToF process and packet exchange between master and slave node.

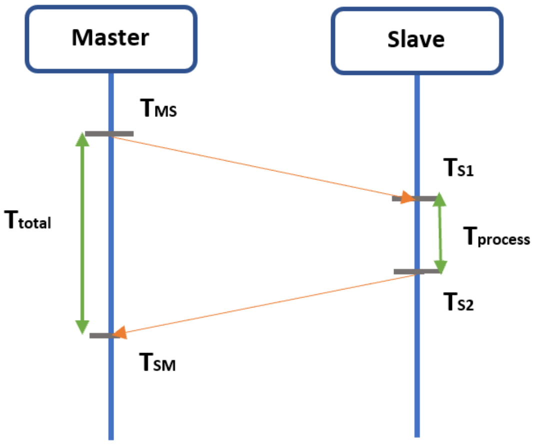


Figure 2.5: SX1280 RToF based Ranging process

The relative time of RToF process is the difference between total time at the master and process time at the slave.

$$T_{air} = T_{total} - T_{process}$$

Distance is then calculates as:

$$d = \frac{c.(T_{air})}{2}$$

2.6.1 Ranging Engine Packet Format

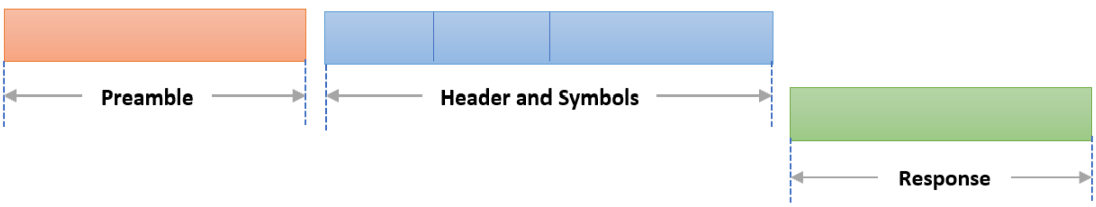


Figure 2.6: An illustration of different sections of SX1280 Ranging Packet [20]

In Semtech's built-in SX1280 Ranging Engine, the devices exchange special packets similar to LoRa packet format, differentiating it with one reserved bit in preamble indicates the ranging packet [20]. The packet consist of three main sections, the preamble. master header & ranging symbols, and ranging response. In the figure 2.6, the blue section indicates the master header which includes ranging ID, which can be configured to 8, 16,24, or 32 bits and ranging symbols. At the slave end, the slave responses with ranging response indicated with green section.

$$T_{sym} = \frac{2^{SF}}{BW}$$

2.6.2 The Ranging Process

The ranging process with SX1280 is described by Semtech[19] is as follows:

1. Master triggers the RToF process and initiates the ranging packet exchange by issuing a ranging request for a unique Slave ID and starts an internal timer.
2. The slave receives the ranging packet and checks the ranging request with its unique ID. If it's valid, then slave starts the synchronization process. Although, the Master and slave never exchange a common absolute time, but slave attaches the time taken to process the ranging request and sends a response back to Master.
3. Finally, upon reception of a response, the Master can deduce the round-trip time of flight from time elapsed.

[Note]: A timeout can be set at both Master and Slave ends.

Chapter 3

Related Work

In this chapter, we look at radio technologies which are already explored for ranging and positioning in indoor environment. This analysis is essential to achieve an optimistic approach for our system and comparisons in the evaluations. Furthermore, we will look at the previous work done on LoRa 2.4 GHz with Semtech SX1280.

3.1 Indoor Localization with other technologies

For leading the world towards smart buildings and automation, many problems arose within tracking location of devices and caught into attention of researchers. Therefore, much research has been done throughout different corners of the world with the available wireless technologies like BLE, Wi-Fi, UWB, RFID etc. as it became hard with satellite localization approaches to locate devices due to signal loss in indoor environment. Thus, we discuss these technologies in this section.

3.1.1 Wi-Fi

In recent years, Wi-Fi technology has become very popular for providing networking facility in buildings and having a well established infrastructure. Therefore, less need for new hardware installation. There are several papers presenting indoor localization using Wi-Fi. There are many ways through which ranging can be achieved in Wi-Fi. RSS is the most widely used methodology to calculate distances between AP and devices in Wi-Fi as it is the easiest method which has purpose to evaluate the signal range in terms of power. In the work [10], authors used Trilateration and fingerprinting based methods to achieve device positioning using the distance estimation method of RSS.
In fingerprinting method, there are offline and online phase, where in offline phase a database is created based on different locations with their respective RSS strength. In the online phase, a live test is run with the device and established APs and measured values are compared with stored values in the database and the device are localized.

3.1.2 UWB

UWB features the most accurate and promising positioning amongst the other available technologies [21]. UWB communication channel is spread over a wide frequency spectrum, which allows the waves to travel effectively through walls and indoor objects even with multipath propagation [22].UWB can be used within TDoA ranging technique and can obtain distance between transmitter and receiver [21]. The authors in [23] uses a two-step approach to obtain indoor positioning where in the second step they estimate position using TDoA ranging technique which is dependent on time synchronization between receiver and transmitter. And therefore, in the step one, they utilize ToA as time estimation algorithm to produce positioning accuracy. Though, UWB is also prone to interference with metallic objects and surfaces and therefore requires more attention with environment objects.

3.1.3 RFID

There is also a well-known localization system which uses RFID tags. RFID receivers can be placed within different corners of the building with tags [24]. Many positioning methods can be applied within RFID, proximity is the mostly used method for obtaining the distance between objects and fixed tags [21]. This is performed by tags emitting different radio frequencies and received by receivers and vice-versa, which uses a predefined frequency and data exchange protocol.

3.1.4 BLE

BLE enabled devices are energy efficient and easy deployment procedures compared to above listed technologies, which makes it interesting to explore for Indoor Localization [24]. BLE can offer ranging with all positioning techniques and later any localization algorithm can be applied to obtain location of the object. Received Signal Strength Indicator (RSSI) is a commonly used method for obtaining distance between BLE tags. The Authors in [25] takes the advantage of channel diversity of BLE and collects RSSI values at different channels and choose either the best RSSI (biggest value) or consider the mean of all values or withMaximum Ratio Combining (MRC) Algorithm for distance estimation. Furthermore, for the position estimation they presented different scenarios and their respective solutions with Trilateration approach i.e., the circles may intersect at a single point (ideal case), the circles intersecting at an area, two circles intersect and one does not, none of the circles intersect.

3.2 Ranging with SX1280 by Stuart Robinson

Stuart Robinson is a researcher who studied Radio Television and Electronics and has not just explored LoRa enabled devices but also wrote Arduino libraries to support LoRa transceivers [26]. Stuart has performed several tests for ranging with SX1280 at different distances in outdoorLoS environment [27], in meters and also in Kilometers. Stuart performed ranging evaluations at 4.4KM up to 40KM and found that the SX1280 transceiver could perform ranging over 40 km range with 4dBm of signal power. When ranging by SX1280 was compared with Google Maps at 40 km distance, it showed +0.2% error, which is acceptable. This suggests that the ranging with SX1280 could reach 80 km in LoS with 10dBm of signal power. The table 3.1 shows the outcomes of short range (in meters) ranging tests.

Actual Distance	Measured Distance
0	4.4M
50M	57.6M
100M	103M
150M	148M
200M	201M
250M	253M

Table 3.1: Difference between Actual and device measured distance [27].

From Stuart's evaluations for short range, we can say that the distance measured by transceiver verses actual distance is very close to similar, and we can motivate ourselves considering SX1280 suitable for indoor like environment.

3.3 Ranging with different LoRa Parameters

LoRa is based on chirp spread spectrum modulation, which makes it robust against interference. Though, several settings with LoRa modulation parameters can significantly affect its wireless performance. In the table 2.1 we have presented the different SF and BW values, which can be used as several combinations to measure the optimal performance of the transceiver in ranging. A similar study is presented in the paper [28]. Authors have performed several tests with different combinations of SF and BW in LoS and evaluated **mean error** considering a 100 meter ranging distance.

100 m	400kHz	800kHz	1600kHz
SF5	106.41	99.00	96.86
SF6	110.20	110.10	98.93
SF7	116.00	106.30	100.35
SF8	124.75	111.40	104.05
SF9	145.75	121.25	109.95
SF10	182.23	143.71	122.15

Table 3.2: 100m mean samples with different BW and SF combinations[28].

In the table 3.2 we can find the evaluated ranging mean samples over actual distance of 100 meters. Evaluations shows that the closest value to the actual distance is with SF 7 and BW 1600kHz, and it is considered optimal combination to perform ranging with SX1280. And Authors found that higher SF does not necessarily provide effective measurements, though it is contradicted in theory. This research work provides an idea to perform similar evaluations to obtain optimal SF and BW for our setup environment and furthermore, we will have several options to choose suitable combination for the application.

3.4 Circle-Circle Intersection

Paul Bourke presented a study for different geometrical figures on his website[29], where he also describes the theory to calculate the intersection points between two circles and possible exception cases where the intersections are not possible. This theory is useful for multilateration method, where we evaluate the intersection between three or more circles.

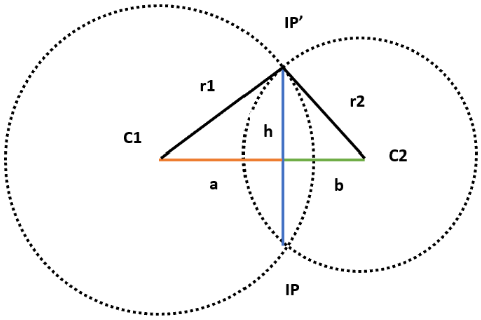


Figure 3.1: Geometrical illustration of two intersecting circles [29].

The theory provides the general solution with two intersection points between two circles `IP & IP'` as shown in figure 3.1:

The intersections are only feasible in two circles if they do not occur in following conditions:

$$dist = ||C2 - C1||$$

- If `dist > r1+r2`, then circles are far apart and do not intersect each other.
- If `dist < abs(r1-r2)`, then one circle is inside another and no intersection possible.
- If `dist = 0` & `r1=r2`, circles are same or on top of each other and infinite intersections.

The above conditions provides no solution for two circles, therefore for a successful intersection calculation any process calculating circles intersection must pass through such criteria.

Chapter 4
Design

This chapter presents the design and key components of our Indoor Localization System with LoRa 2.4Ghz and answers several questions like how we can design such a system, what will be prerequisite for the system, what factors can affect the performance of the system. Before we implement our system, we much ensure the Ranging performance of the LoRa devices. For that, we examine transceiver settings with different LoRa modulation parameters (presented in Chapter 3).
Also, it should be considered that, for indoor environment it is not common to have devices always in LoS especially in corporate buildings, houses, hospitals, etc. As there are possible obstacles with walls, doors, indoor objects, it is a must to examine the effects on ranging in both LoS and NLoS device placement settings.
In general, in the indoor localization system, there are two different roles, the mobile, and anchors. Ranging in LoRa requires unique IDs to work with special ranging packets exchange and ranging request validation in Ranging Engine. So, a mechanism is required to provide the IDs to the mobile device. So we introduce a third role called "central device" to achieve such a functionality for the system.
To this end, we came up with two different systems, one for the evaluation and the another one for localizing, and we also define roles and components required before and during the system execution, which can be seen in figure 4.7.
Also, we need a platform to visualize the pre-evaluation and localization specific data. This aspect can be defined as post-execution of the system, i.e., a Graphical interface where we can see the live execution of the localization system and determined mobile node location.
The following sections will elaborate the systems designs to achieve Indoor Localization System.

4.1 LoRa Modes and Configuration

The LoRa devices can be operated with several modes like LoRa, Ranging, BLE, GFSK, etc. The system functionality can be achieved with normal LoRa and Ranging mode. Before performing any operations, the devices must be configured to their desired Mode of operation. A device cannot simultaneously work with different modes, and therefore the operations has to be sequential with respect to the mode. Another aspect is to configure the devices with optimal LoRa parameters (frequency, BW, SF and CR), which are comprehensively discussed in Chapter 3. For a successful communication between LoRa devices, these parameters must be the same among all the LoRa devices, irrespective of their mode of operation.
In normal LoRa operation mode, the devices can simply transmit and receive packets with payload. While in the ranging, the devices exchange special packets between master and slave to perform only ranging specific operations.

4.2 Ranging Evaluation System

The main aim of this thesis work is to evaluate position of mobile device using LoRa. The system's performance is completely based on how efficiently the device performs the ranging. As the ranging engine provided by Semtech performs the ranging between unique IDs assigned LoRa devices and are referenced as Master and Slave. So the design consist of two LoRa devices, one acting as master and another as slave. We previously discussed LoRa associated parameters in chapter 3 and found that LoRa can operate with several combinations of its parameters, namely frequency, spreading factor, bandwidth, and coding rate. So the design must iterate over each combination and perform minimum 100 ranging operations within each iteration and collect the evaluated distances.

Figure 4.1: Master and Slave devices performs ranging operation. Purple arrow issues a ranging request for slave device at ID2(slave ID), and slave responds with a ranging response back to master with yellow arrow.

4.2.1 Pre-evaluation setup and Environment

For the setup, we place the devices apart at a desired distance to evaluate the ranging with LoRa devices. We choose a desired actual ground distance to have more realistic situation in indoor like environment. Also, to achieve significant results, we must consider regular conditions in indoor environment. As the indoor environment usually have obstacles with walls, doors, reflecting objects, indoor objects, etc. Therefore, the evaluation must be carried out in both LoS and NLoS environment.

Device Placement

We place a pair of LoRa devices in two different corners of the building at a certain distance, each assigned with their unique IDs. Here, the role of IDs is not just to differentiate the devices, but also the Semtech's ranging engine issues the ranging request for a specified ID. Figure 4.1 shows the device holding the ID accepts the request and provides the response back to the device initiating the ranging request, i.e., the master device.

- LoS (`Line-of-Sight`).
- NLoS (`Non Line-of-Sight`).

LoS Environment

In the Figure 4.2, the devices are most likely to be present in the same section of the building, placed 20 meters apart and can have direct contact. The devices are having almost no obstacles in between them. Having LoS environment makes the radio waves reach the destination easier and faster.

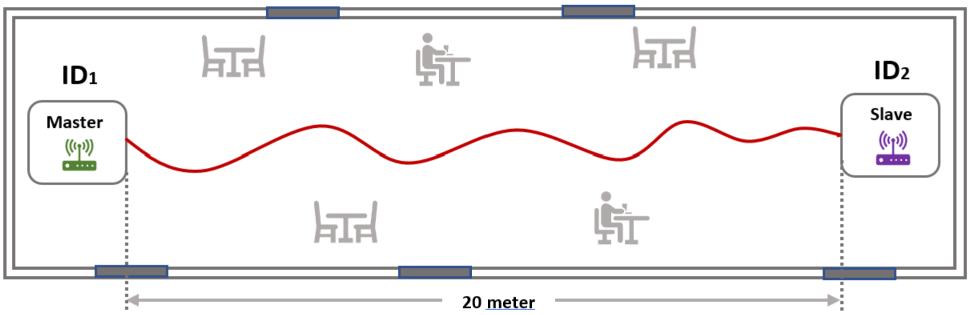


Figure 4.2: Master and Slave devices performs ranging in LoS. Different IDs discriminate the pair.

NLoS Environment

In the figure 4.3, the devices are placed 20 meters apart in different sections of the building and do not have direct contact and therefore, radio waves travel through different paths via reflections from the walls, and objects present in the environment and radio waves reach the destination with a delay compared LoS.

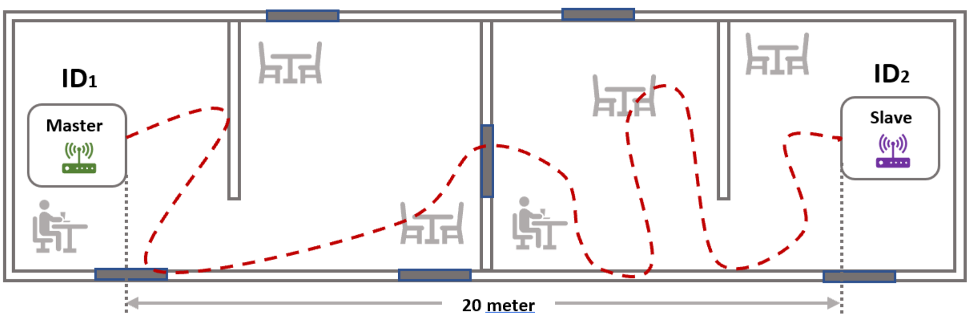


Figure 4.3: Master and Slave devices performs ranging in NLoS. Different IDs discriminate the pair.

The figures 4.2 and 4.3 illustrates the behavior of radio waves in two different environment. Radio waves traveling with delay would produce an estimated distance value greater than the environment having no obstacles. Hence, these differences are necessary to study to come up with best LoRa parameters combination.

4.2.2 Execution Procedure

The system execution begins with setting up devices with their initial modulation parameters for a successful first communication. For normal packet reception and transmission, the devices are configured with LoRa Mode. The system must evaluate each combination of LoRa parameters, so we iterate each possible combination (mentioned in Chapter 3) and perform a Pre-ranging communication process. The figure 4.5 below represents this sub-process execution. This process results in an acknowledgement from the Slave device. On an acknowledgement, we step ahead with

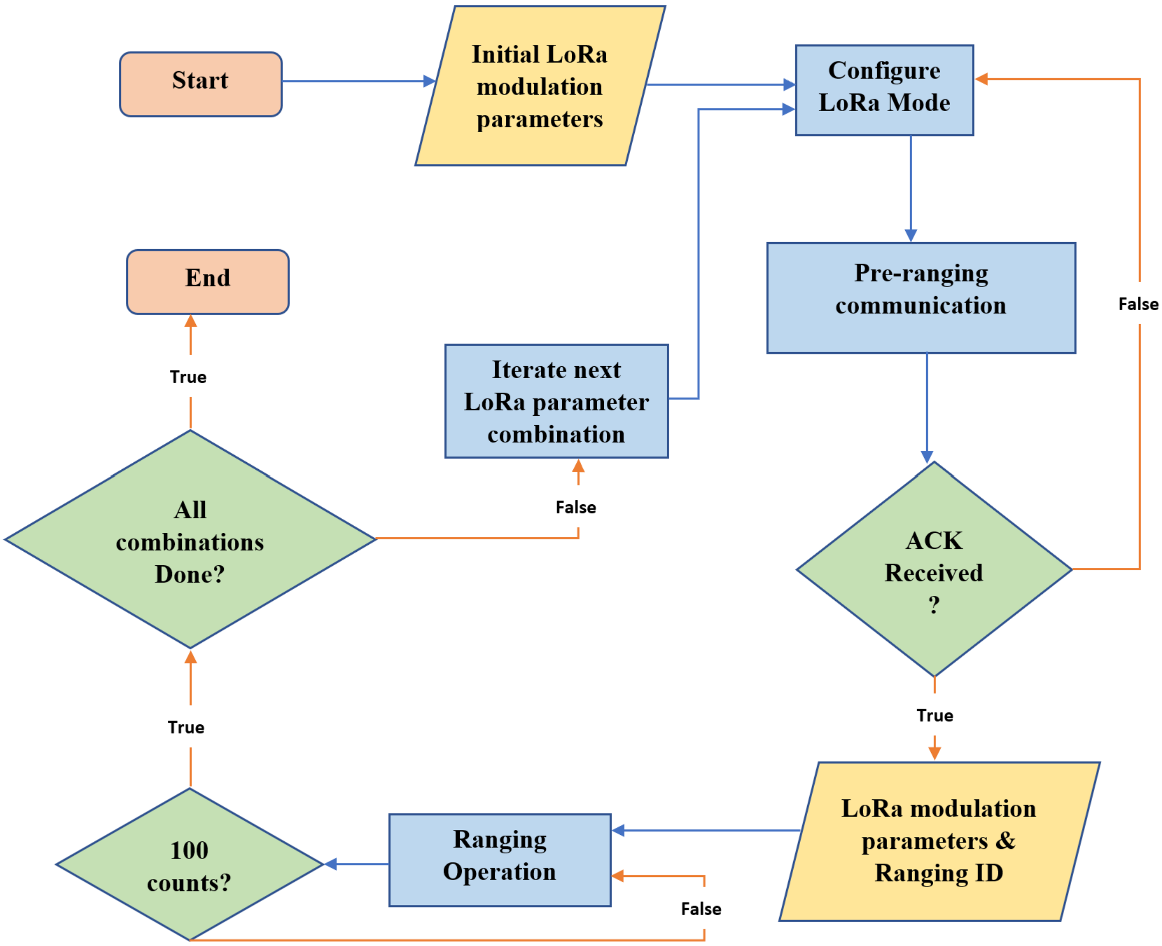


Figure 4.4: Flow diagram illustrating complete execution of Evaluation System. Blue arrows represent procedural flow and orange arrows represent the conditional flow.

the current iterated LoRa parameter combination and start Ranging Operation. An execution of this process in described in figure 4.6 below. For an evaluation, we require a significant amount of ranging samples. So, we loop over Ranging Operation until we reach 100 samples. The system execution ends with iterating last possible LoRa parameters combinations. A complete sequence of execution of the system is described in the figure 4.4 above.
In the complete process, the master device is the control unit of the system, which

triggers all the events. The slave just accepts a specific command on reception of a packet from master and performs the respective operation.
The above-mentioned two sub-processes has its individual role to play in the system. The first one, involves the exchange of information containing LoRa parameters to prepare the device for the Ranging operation. And in the second process, the devices perform the ranging operation. In the sections below, we describe both the sub-processes.

Pre-ranging communication

In this process, the devices exchange the LoRa parameters, namely spreading factor and bandwidth. Initially, devices must operate on the same parameters to keep communication alive and synchronous in the packet exchange process. The master initializes and sends the packet containing LoRa parameters information to Slave with CHNG_PARAMS_PKT for ranging operation and re-configure itself with updated parameters. Simultaneously, the Slave should set itself to Receive Mode to

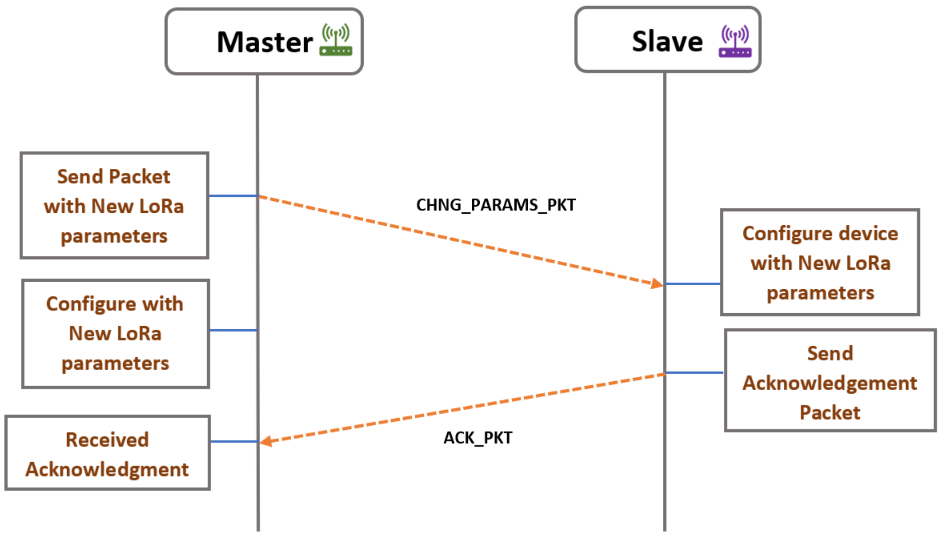


Figure 4.5: A Time-step diagram of devices exchanging LoRa parameters. Orange arrows represent the packet sending and reception between Master and Slave.

receive parameters information. Slave, processes the packet and updates its parameters according to the received packet. And sends back a response with ACK_PKT (acknowledgement) to the master and switches the mode to Ranging.

Ranging Operation

The ranging process involves setting up of LoRa parameters and assigning a unique ID to both slave and master. So, the process starts with configuring the LoRa in ranging mode with LoRa parameters and assigning the ID to the devices. This unique ID can be exchanged in the pre-ranging communication process if not intentionally chosen. Either of the devices must set the ID of another device to avoid ambiguity. Then, the slave must be set to ranging Receive mode to be able to accept

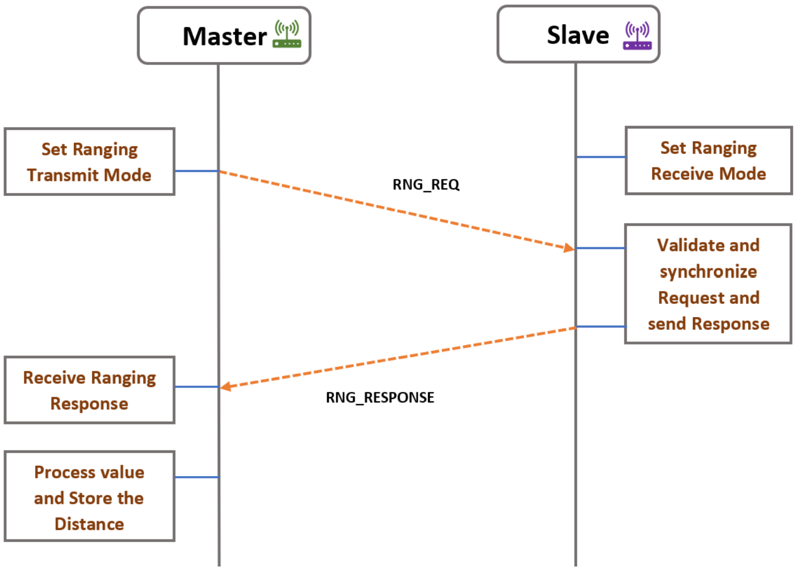


Figure 4.6: A Time-step diagram of devices performing Ranging Operation. Orange arrows represent the special ranging packet exchange between Master and Slave device.

any ranging requests. Now, a master device can initiate a ranging request to perform ranging. After initiating the ranging request, an internal process is started in the Ranging Engine of both devices. A description on working of ranging engine is illustrated in Chapter 2. After the ranging operation, the measured distance is available at the master device and can be stored for visualization or further processing.

4.3 Indoor Localization System

4.3.1 System Architecture

In general, the Indoor Localization System design consist of anchors, mobile node, and a localization technique. We discussed many localization techniques (in Chapter 2), and we chose multilateration to make adjustment with ranging evaluations carried out in the previous step. For using this technique, we require minimum of 3 anchors nodes at known locations and each holding their own unique ranging IDs. in the complete design description, we refer to the LoRa device as node. To be able to perform ranging and localize, the mobile node must have the ranging ID and location of each anchor node. Therefore, we must introduce a new entity called master, which holds the IDs and Coordinates of the Anchors and will also be responsible for communicating with the mobile node whenever a ranging request is initiated. The architecture of the complete system is shown in figure 4.7, where the mobile node emits its evaluated position, which means the localization procedures are performed by the mobile node itself.

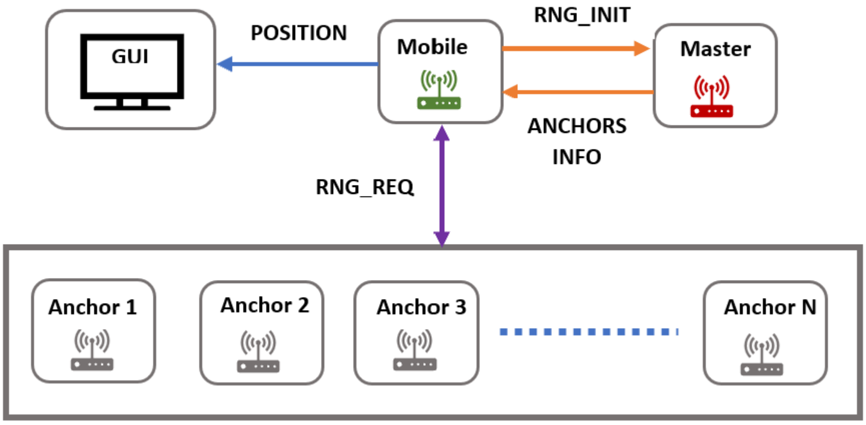


Figure 4.7: The different components of the Indoor Localization System and their connections. It illustrates an array of Anchors, a mobile device and master device. Orange arrows represent pre-localization data exchange, purple arrow to perform ranging, and blue arrow passing estimated position on UART.

4.3.2 Associated Roles of the System

The design for our Indoor Localization System consist of three different Roles. Each role has its own control flow and are independent in their individual execution behavior. Though, the sequence of execution in the complete system illustrates their importance and their significant sub-processes to reach the system's climax. In the below sections, we describe the workflow of individual roles.

Master

Although, the localization system requires just two entities, the one is Mobile (to be localized) and another one is Anchor. The system requires the Anchors' information to be known by the mobile node. Hence, the master node is enriched with all available anchors' information, i.e., Ranging ID and Position (two-dimensional coordinates). The node always has to stay passively active in LoRa Receive Mode and never takes part in ranging process. The node is responsible for accepting the ranging initialization requests from the mobile node. And whenever, it receives such requests, it sends back the response with anchors' information in different packet chunks. And at last it sends a packet says, all information sent. And goes back to Receive Mode and awaits the ranging requests.

Anchor

The anchor node starts by LoRa Ranging Mode configuration and later, set itself to Ranging Receive Mode and awaits the ranging requests at its unique ID. Whenever the node receives the ranging request, the Ranging Engine validates the request and sends back the response. The control starts again and awaits the new requests.

Mobile

The mobile node communicates with both entities, master and anchors. The node begins with configuring itself initially with LoRa Mode and prepares the “Ranging Initialization” packet and broadcasts it in the system and goes to Receive Mode. If there is a master hearing the request, then the Mobile node will receive the Anchors’ information. The node keeps hearing until it receives a final packet from the master with “All information sent”. After that, the node switches to Ranging Mode if it has received three or more anchors information. Otherwise, it initiates the process again. Now, the control iterates over each anchor’s ID and initiates a ranging request at the Anchor’s ID, performs the ranging operation and collects measured distances. Now, the control estimates the location by passing the distances and Location of Anchor’s positions to Localization Algorithm and estimates the Location and passes the location to Universal Asynchronous Receiver Trasnmitter (UART). The process loops again from ranging process keeps evaluating node’s location.

4.3.3 Preparation and Nodes Placement

As we described earlier that, for localizing an object, the system requires a base or few reference positions to consider in a two-dimensional space. We can set up a localization system in a measured space. So, we introduce an array of anchors (minimum three numbers) and place those nodes on specific known locations in two-dimensional coordinates system to build a two-dimensional space environment for the system. We make sure to place anchors in different corners of the system’s space at certain distances to each other for an efficient positioning. The system also has a master node, and this node must be in the communication range of the system’s space, so that it can communicate with the mobile node whenever a mobile node initiates a ranging request. Basically, a master node contains all necessary information about anchors, which are required for a mobile node to obtain the position. A mobile node will be localized if it is present in the system space. Therefore, a mobile node is also required to be present in the system space.

4.3.4 The Execution Procedure

The execution process is completed in two parts, where the first part is data exchange process and second part is to perform ranging operations and localize the device. The first part involves the mobile and master node communication in normal LoRa mode, whereas the second part is ranging communication between mobile node and available anchor nodes. The data exchange is necessary in the system as the localization algorithm will be performed by the mobile node and the algorithm requires location of anchors to relatively estimate position after executing ranging operation with each node. Below sections describe the execution sequence of two sub parts of the system.

4.3.5 Pre-localization process

The process begins with initializing the chosen LoRa modulation parameters from the outcome of Ranging Evaluation System and configuring the devices to LoRa mode. The master node contains the Anchor IDs and their locations, and this information is required only by the mobile node. Therefore, this process happens between master and mobile node. Once, both nodes are LoRa mode configured, the mobile node initiates RNG_INIT request and goes into receiving mode with starting a timer. The master accepts the request and start sending out the information of anchors to mobile node. If the mobile node received all anchor's information, then it starts the subsequent process. If the mobile node does not receive all anchor's or anything from master, it re-initiates the request after a timeframe of timeout and the process starts again.

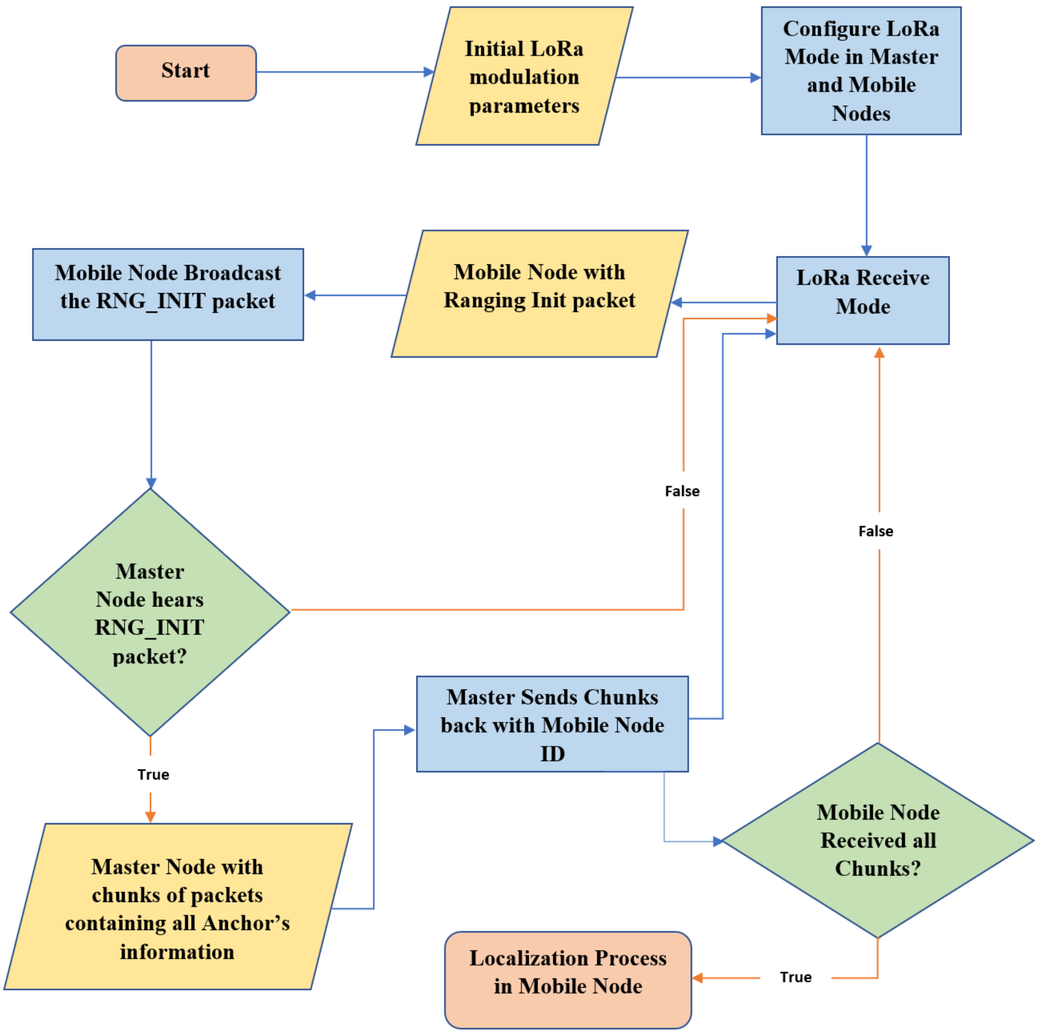


Figure 4.8: A control flow diagram of Pre-Localization Process. The blue arrows represent the regular control flow and the orange arrows represent conditional flow in the system.

4.3.6 Ranging and Localization

In complete Indoor Localization process, the system must work in same LoRa parameter settings and therefore, we do not change the modulation parameter and also proceed for Ranging Mode with same LoRa modulation parameters. The role of master node completes in the previous process and hence, this process involves process execution only on mobile and anchors nodes. Both Mobile and Anchors entities are configured in LoRa Ranging Mode. Since, there are three or more anchors in the system, the process iterates over all anchors with their IDs one by one and performs ranging with each anchor. If the ranging is successful with three or more anchors, then the system performs Localization using Multilateration method with collected distances. In the final step, the estimated location is transferred to UART for visualization process. And the process continues in loop to again perform ranging and subsequent operations, and updates the location on UART.

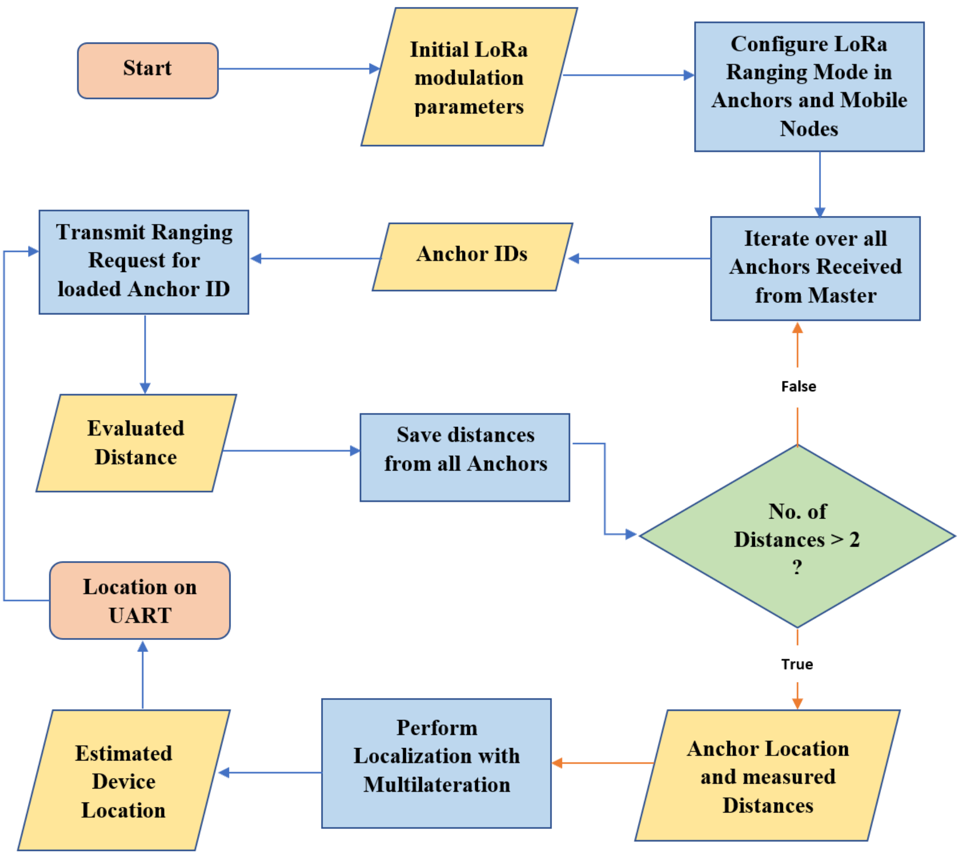


Figure 4.9: A control flow diagram of Ranging and Localization Process. The blue arrows represent the regular control flow and the orange arrows represent conditional flow in the system.

4.3.7 The Localization Algorithm

The algorithm estimates the location of the node in three steps. First, it considers the estimated distances from ranging process as radii of circles and evaluates the all intersection points of the circles. Second, it filters the unnecessary points with efficiency control mechanism. Finally, evaluates centroid of filtered points. And the centroid is considered as Estimated Location. Below we outline the complete algorithm in the Listing 4.1 w.r.t the Figure 4.10. In the Listing 4.1, the algorithm

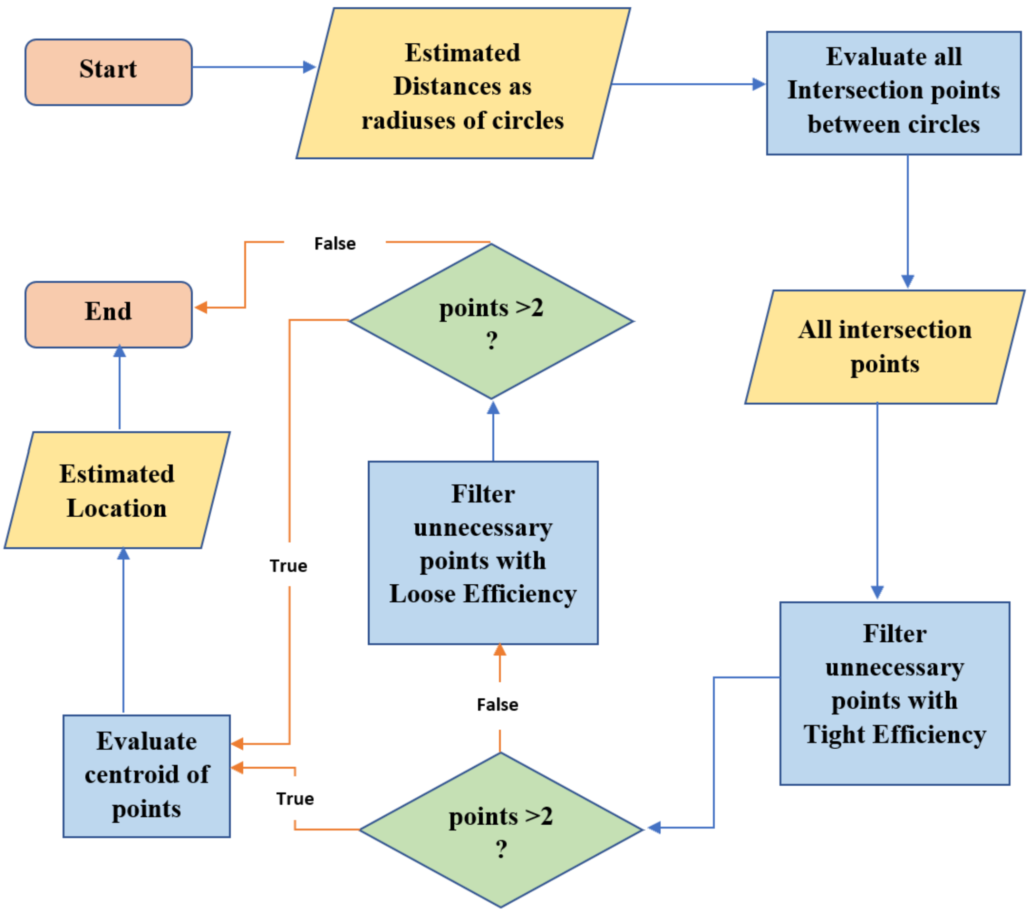


Figure 4.10: A control flow diagram of Localization Algorithm. The blue arrows represent the regular control flow and the orange arrows represent conditional flow in the system.

consists of two major tasks, namely the filter process and centroid estimation. After evaluating all intersection points, filter criteria is to be applied to remove irrelevant intersections. The criteria are based on tight and loose efficiency. With tight efficiency, the filter process considers selecting the intersection points which are covered by all the circles, whereas with the loose, the process considers selecting the intersection points which are covered by one less circle among all circles and hence, decrease the efficiency. Then the algorithm evaluates the centroid of all filtered points by performing the averaged sum of all intersection points and results the centroid as device location.

```
ips := get_all_intersection_points()
efficiency := tight
filtered_ips := filter_intersection_points(ips, efficiency)
count := length(filtered_ips)
if (count > 2) then
    location := calculate_centroid(filtered_ips)
else
    efficiency := loose
    filtered_ips := filter_intersection_points(ips, efficiency)
    if (count > 2) then
        location := calculate_centroid(filtered_ips)
    else
        location  := NULL
return location
```

Listing 4.1: Algorithmic representation of Localization Algorithm.

Chapter 5

Implementation

In this chapter, we discuss the implementation of the design we presented in the previous chapter. We begin with introducing the basic hardware and software components. We also demonstrate the components' integration to reach our design goals. Finally, we will elaborate how we realize the proposed design and its procedures.

5.1 Hardware

We collect different hardware components to start performing our desired operations. Since, the LoRa transceivers are operated by executing several commands according to their tasks, we need a host machine to provide such commands to LoRa transceiver. Therefore, the hardware can be utilized in a pair of transceiver and host machine.

5.1.1 The LoRa 2.4GHz

Semtech's LoRa SX1280 chipset is a transceiver which uses LoRa 2.4GHz spectrum and offers ranging capabilities via an in-built Ranging Engine. The SX1280 transceiver is a command operated device which acts as a slave device and requires a host to provide commands. The SX1280 supports Serial Peripheral Interface (SPI) and UART interfaces to accept commands from the host machine. The figure 5.1, shows the DLP-RFS1280 breakout board which has LoRa SX1280 chipset mounted on it. It is a low cost and easily available device which provides SPI interface for host machine communication.

Figure 5.1: DLP-RFS1280 breakout Board mounted with SX1280 transceiver [30].

5.1.2 The Host Microcontroller Unit(MCU)

We use the Nordic Board nRF52840DK (shown in the figure 5.2) as host machine for providing operating commands to SX1280 LoRa module.It includes an nRF52840

System on Chip (SoC) which has a 32-bit ARM Cortex-M4 running on 64MHz of oscillator frequency. The board is embedded with 1 MB internal flash and 256 KB of internal memory. It can extend the available memory from on board external memory. The development kit has an onboard debugger to ease the firmware development process. The board comes with several SPI ports and one of them can be used for connecting SX1280.

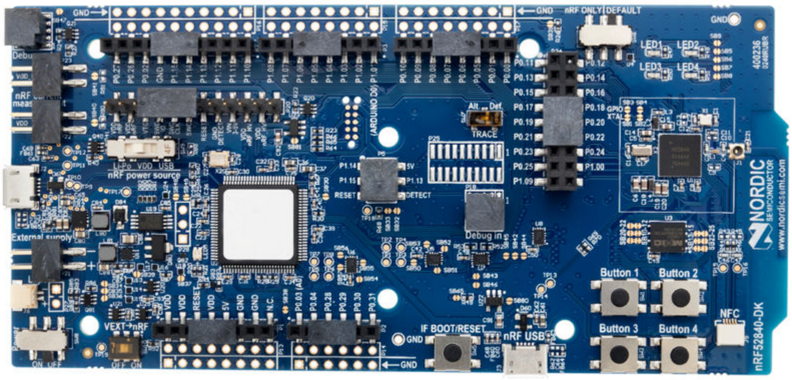


Figure 5.2: The Nordic Board nRF52840DK [31].

5.2 Operating System

For the software support, we use Zephyr OS. We already discussed in Chapter 2, that Zephyr is a small and lightweight Real Time Operating System (RTOS) which provides in-built libraries and supports multiple hardware architectures. The services like, multithreading, interrupt handling, dynamic memory allocation, power management etc. makes it an ideal solution. It implements the access of libraries functionality through API interface. It does support the nRF52840 processor architecture. The kernel of this RTOS requires a description of hardware, which is done by Devicetree source files (dts). The device tree describes the different components of the hardware and implements the property structure. This property expands the further characteristics [32]. A `.yaml` file contains different properties a component can have. Furthermore, the property represents a device whose pins are connected to its respective component's General Purpose Input/Output (GPIO) pins.

5.3 LoRa Integration

5.3.1 Connecting SX1280

For our implementation, we program nRF52840DK to run a sequence of operations. We further extend the hardware by adding the SX1280 LoRa device to the nRF52840DK. We connect the SX1280 transceiver through SPI interface. And for establishing a connection for RTOS, we need to modify the SPI node in the devicetree accordingly. As described in Listing 5.1, specifies the respective pins to use for SPI port 1. Though, the board nRF52840 offers three SPI ports, but we stick to

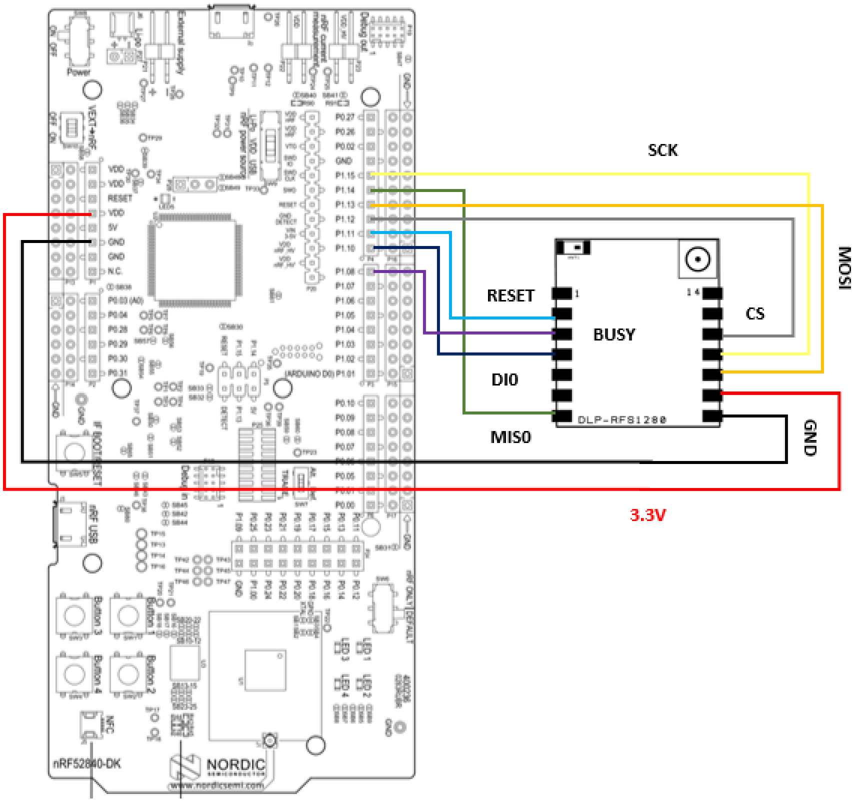


Figure 5.3: Physical connection between nRF52840DK and SX1280 Transceiver.

port 1. Now, we create a LoRa property which will be internally connected to the respective pin address using devicetree specification. We then configure different sub-properties in LoRa to use other interrupt related and device status monitoring pins. Then we specify a devicetree overlay file in which we use the LoRa property and specify the respective pin addresses using devicetree specifications. The figure 5.3 presents the physical connection of SX1280 transceiver to nRF52840DK board's port 1. The SPI signals Chip Select (CS), Master-Out Slave-In (MOSI), MOSI and Serial Clock (SCK) are connected to `P1.12, P1.13, P1.14 and P1.15` respectively. The signal assigned to which states the device status if device is still in execution of previous command. Lastly, we assigned `BUSY, DIO & RESET` to `P1.10, P1.08 & P1.11`. Now, we describe the specific functionality of each pin connected to the port 1.

- A Master-Out Slave-In (MOSI) signal is used for sending data from master to the slave,
- a Master-In Slave-Out (Master-In Slave-Out (MISO)) signal is used for sending data from slave to the master,
- a Serial Clock (SCK) signal for clock synchronization,
- a Chip Select (CS) signal to activate communication between master and slave,
- a BUSY signal is input to master with status if slave still in execution,
- a Digital Input Output (DIO) signal is interrupt signal to master from slave
- a RESET signal is used to reset slave device

```
/ {
    aliases {
        lora0 = &lora;
    };
};

&spi1 {
        sck-pin = <47>;
        miso-pin = <46>;
        mosi-pin = <45>;
        cs-gpios = <&arduino_header 16 GPIO_ACTIVE_LOW>;

        lora: sx1280@0 {
                compatible = "semtech,sx1280";
                reg = <0>;
                label = "sx1280";
                reset-gpios = <&arduino_header 15 GPIO_ACTIVE_LOW>;
                dio-gpios = <&arduino_header 14 GPIO_ACTIVE_HIGH>;
                busy-gpios = <&arduino_header 13 GPIO_ACTIVE_HIGH>;
                spi-max-frequency = <1000000>;
                power-amplifier-output = "pa-boost";
        };
};
```

Listing 5.1: Devicetree overlay file defining the connection of SX1280 to SPI1 port of nRD52840DK [33]

5.3.2 LoRa Ranging

Here we explain the code mechanism that enable the device to define Master and Slave roles with IDs and perform ranging operations. Zephyr provides a LoRa driver functionality in API manner via a header file, which we include in our source code. These APIs abstract the actual implementation of LoRa transceiver. To use the API, we must initialize the LoRa radio device with reference to the devicetree. Next, we create a pointer to the device and define the LoRa parameters like frequency, bandwidth, spreading factor, coding rate and power in a configuration struct.
Now, we can configure the device mode to `Ranging Mode`. Within this, we also specify the respective ranging ID and Role for the device. Device transmitting ranging must have role Master and device receiving ranging must have Slave Role. Now, the device is all set for performing ranging operations. Every time we receive or transmit the ranging, the corresponding function also need device pointer and a timeout. Here, we also have an option to specify the ranging ID. function. The function for transmitting the ranging awaits for response and returns a struct containing ranging status, measured distance value and RSSI value. The function for receiving ranging stays in receive mode until timeout or if received any ranging request.

5.4 The Indoor Localization System

In this section, we will explain the code structure for Indoor Localization System which performs location estimation using three different entities, namely master, anchor, and mobile. For firmware development, we use Zephyr OS. Code for firmware and drivers in Zephyr are written in C language. Even with the limitation, that C language does not support classes and objects, the Zephyr offers the libraries access via API interface and provides a programmer friendly environment. Furthermore, we also illustrate commonly used scripts by master and mobile entities, which are programmed in C with Zephyr OS. For the location visualization, we use a host computer running a Python script.
The whole Indoor Localization System code is available at:

`github.com/ashokvaishnav708/IndoorLocalizationLoRaProject`

5.4.1 Operations & Payload Structure

```c
// Operations
#define RANGING_INIT 0x00
#define RECEIVE 0x05
#define START_RANGING 0x07
#define ALL_DONE_PKT 0x06
#define ANCHOR_PKT 0x10
#define CORNER_PKT 0x12
#define NONE 0xFF

struct __attribute__((__packed__)) Coordinates
{
    bool flag; //  Validated Coordinates if TRUE else not validated
    float x;
    float y;
};

struct __attribute__((__packed__)) Payload
{
    uint32_t host_id;
    uint8_t operation;
    struct Coordinates coords;
};
```

Listing 5.2: Common set of Code for Master and Mobile.

5.4.2 Master

The Master contains information of all available Anchors in the system. The information like Raging ID and Coordinates. The Master is always configured for normal

LoRa mode, in which it can just send and receive packets and therefore never takes part in the ranging process. The execution begins with initializing SX1280 LoRa device. Then the control assigns the LoRa modulation parameters like frequency, spreading factor, bandwidth, and coding rate for `LoRa-config`. Then through the API, `lora_config` the normal LoRa mode is configured. After the Mode configuration, the control enters the infinite loop. In the Loop, each operation is selected on the basis of `switch statements` on local `operation` variable. By default, the device is set to `Receive Mode`. Whenever it receives a `RANGING_INIT` operation with payload, the control save the `request_id` and initializes the Test setup's Corners & Anchor's information in the Payload and broadcasts (send) them one by one in different chunks. At last, it prepares the payload with `ALL_DONE_PKT` with saved `request_id` and broadcasts to acknowledge the device from which it received the request. Finally, control loops back to `Receive Mode` and awaits further requests.

5.4.3 Anchor

The Anchors are standalone devices, which are actively ready to perform ranging receive operation within its start. The Ranging ID of the Anchor is the 32-bit converted ID of the host device. The execution begins with collecting the Ranging ID of the host device. Now the control proceeds with initializing SX1280 LoRa device with LoRa modulation parameters. Then the control configures the LoRa device to `Ranging Mode` as slave role and assigns the Ranging ID. The control enters the infinite loop and sets the LoRa device to Ranging Receive mode. Whenever a ranging request is received at specified `Ranging ID`, the device performs the ranging response and control returns back to the loop and awaits further ranging requests.

5.4.4 Mobile

The Mobile device implements the complete logic of device location estimation. The mobile node hops between two different modes of LoRa. Initially, when it collects the Anchor's information and later, when it performs the ranging operations. The execution begins with the mobile device assigning a 32-bit ID to itself. Now, the control proceeds with initializing SX1280 LoRa device with LoRa modulation parameters. Then the control configures the LoRa device to `LoRa Mode` to transmit and receive normal packets. The control enters the infinite loop which has `switch statements` on local `operation` variable. By default, the device is set to `Receive Mode`, with 1 second of timeout. Whenever timeout occurs, the `operation` variable is assigned `RANGING_INIT` operation. Then the control goes over loop and switches to the `RANGING_INIT` case. In this case, the device prepares the payload with `RANGING_INIT` operation & its 32-bit ID. Then device broadcasts the packets and goes to `RECEIVE MODE` and awaits with 1 second timeout for Test setup's corners and Anchor's information. In case, it does not receive anything from master then after timeout process starts again. The device implements a Dynamic Queue in Linked list structure to store anchor's information and has `distance` variable which can further store measured distance via ranging operation. Once it received all anchor's information, the device switches to `Ranging Mode` via `START_RANGING` operation case, and performs the ranging with each anchor. Here, we can define the `sample-count` to perform number of ranging with each node according to `sample-count` and we take average sum of each successful ranging sample as our estimated distance (meters). Now, the control proceeds for Localization Algorithm and estimates the location if there are minimum 3 successful anchors ranging and loops the ranging and localization process.

5.5 The Localization Algorithm

The Localization Algorithm is based on multilateration approach, where we first estimate a specific overlapping area and the centroid of the area is considered an estimated location. As shown in the Figure 5.4, the algorithm begins with iterating the Anchor's queue list one by one in nested manner to calculate intersection points between each circle formed by estimated distance as radius. The algorithm implements a Dynamic Queue in linked list structure to store the intersection points. When there is a duplicate intersection point, the queue does not allow adding that point. Therefore, the algorithm robust against data redundancy. Now, the next step

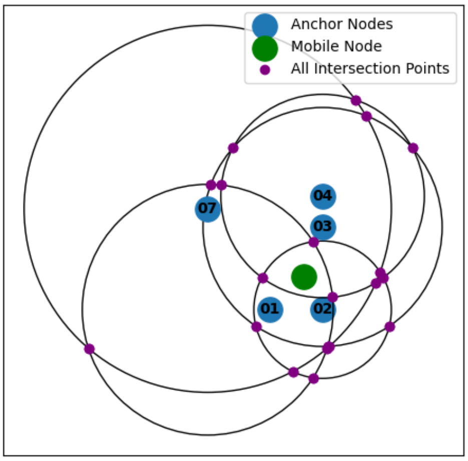
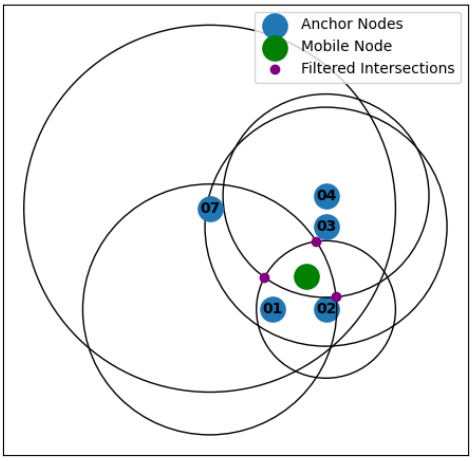


Figure 5.4: All circles intersection and their intersection points.

is to filter all unnecessary intersection points and get a polygon, i.e., consider only the points which forms the common overlapping section. This is done via `error_factor` criteria. The criteria also defines the algorithm's efficiency mechanism, namely tight and loose efficiency. If the `error_factor` is 0 then it is tight efficiency, in which the algorithm filters only points which are inside all circles. Whereas, if `error_factor` is 1 then it is loose efficiency, in which the algorithm to filters points which are inside `N-1` circles, where `N` is a total number of circles available. Figure 5.5, shows the filtered intersections with tight efficiency.
Now, after the filter process, the center point of the overlapping section is considered as the estimated location, i.e., the centroid of the polygon. It is evaluated as the average sum of filtered intersection points. The Figure 5.6, presents the estimated point exactly on the mobile node.



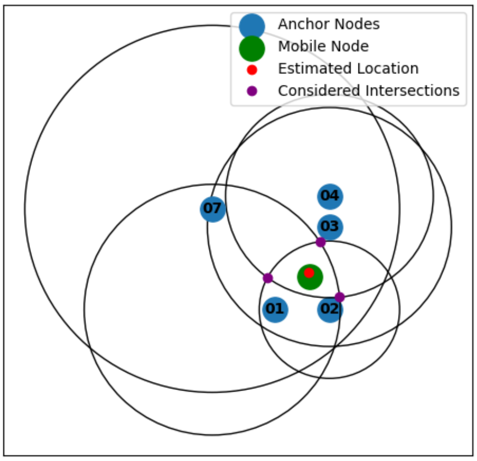


Figure 5.5: Filtered intersection points. **Figure 5.6:** Estimated Location.

Chapter 6

Evaluation

In this chapter, we will discuss the outcomes from the Ranging Evaluation System and Indoor Localization System. In general, we discussed two scenarios for the system, i.e., LoS and NLoS environment. Here, we distinguish between these two scenarios in which we placed our devices executing their desired tasks and evaluate the ranging performance for each combination of LoRa parameters. With three different bandwidths and six different spreading factors combinations, we configure Master and Slave devices and perform minimum 100 ranging operation between them, and keeping them 20 meters apart from each other. We always set coding rate to 4/5 with 2445000000 Hz (2.4 GHz spectrum) of frequency. Furthermore, we will discuss the results achieved on behalf of Ranging Evaluation System. For the Indoor Localization System, we will place several nodes on fixed measured locations and create a base map or a test bed setup. We will discuss several aspects which affects the overall system's performance and quality of estimated location.

6.1 LoRa as a Receiver

LoRa module's behavior as a receptor allows devices to overhear the incoming packets irrespective of its configured mode. Therefore, to resolve the issue of overhearing, the LoRa devices returns with an 8-bit IRQ_STATUS register. It's value defines what kind of packets has received with predefined filter values. It's value also verifies if the packet is correctly received or not. A filter can be applied to check if the received packet is RNG_REQ packet or normal packet. With RNG_REQ, a filter can be applied to verify if the request is issued for this device's ID or not. And handles the validation and discarding process for ranging packets.

6.2 Ranging Evaluation System

Before we finalize our Indoor Localization System's methodology, we conduct some experiments considering the general indoor setting, i.e., the environment, and see how well ranging is performed by devices. A good accuracy is when values are close to the actual ground truth. LoRa SX1280 can operate with several modulation parameters like frequency, bandwidth, spreading factor, and coding rate. The parameters, bandwidth, and spreading factor majorly affects the packet reception and transmission delays which implies variation in distance measurement. Indoor environment usually consist of many objects, doors, and glass objects and therefore, it is not always a LoS scenario. We proceed with conducting experiments in two different scenarios, LoS and NLoS with different combination of LoRa parameters and outcome with optimal LoRa parameters for Indoor Ranging.

6.2.1 Line-of-Sight (LoS)

The Table 6.1 shows the LoRa measured distance values with several combinations of LoRa parameters in LoS scenario at 20 meters of actual ground truth. We create a three-dimensional graph as shown in figure 6.1, which represents an overview of the distance error between LoRa measured and actual distance. With an overview, we can guess that in LoS setting, most of the parameter combinations performs the over-ranging with 20 meters of actual distance.

20 m	**400kHz**	**800kHz**	**1600kHz**
SF5	27.67	27.53	33.48
SF6	26.23	29.52	37.11
SF7	25.42	28.71	37.18
SF8	28.21	31.23	33.19
SF9	27.67	30.15	26.95
SF10	24.78	32.40	22.10

Table 6.1: Estimated distance samples with different BW and SF combinations in LoS at 20 meters actual distance.

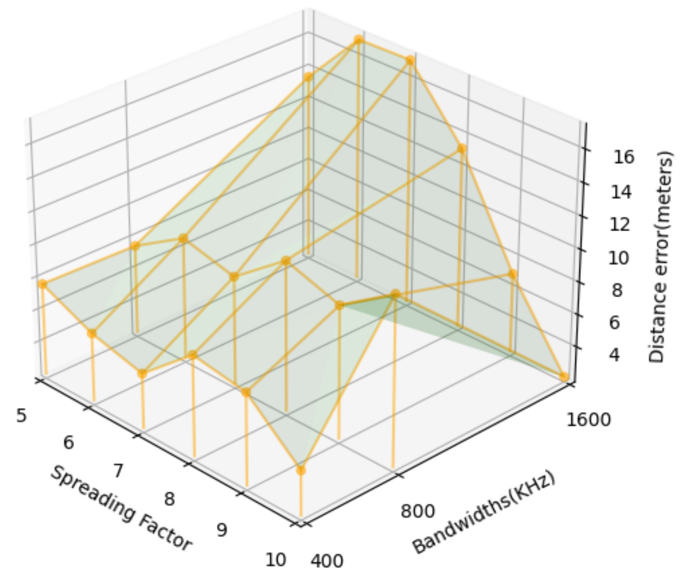


Figure 6.1: A three-dimensional overview graph representation of Distance Error with respect to Bandwidth and Spreading Factor combinations in LoS scenario.

Looking at individual bandwidth graph, we observe that with `BW 400KHz & 800KHz`, the error rate is greater than 5 meter. An optimal combination will be the one which has distance error close to value 0. As we can see in the figure 6.1, there is one combination with `BW 1600KHz & SF 10` which is close enough to zero and have measured distance `22.1 meter`. Therefore, we consider `BW 1600KHz & SF 10` LoRa parameters as the optimal for LoS setting.

6.2.2 Non Line-of-Sight (NLoS)

The Table 6.2 shows the LoRa measured distance values with several combinations of LoRa parameters in NLoS scenario at 20 meters of actual ground truth. Likewise, in the LoS test-case, we create a similar three-dimensional graph as shown in the figure 6.2, which also represents the overview of the distance error between LoRa measured and actual distance. With this overview, we can guess that in NLoS setting, there are some parameter combinations to performs the under-ranging with 20 meters of actual distance.

20 m	400kHz	800kHz	1600kHz
SF5	31.91	23.61	34.32
SF6	28.75	28.80	40.20
SF7	27.04	31.73	39.77
SF8	22.98	34.93	34.16
SF9	13.07	33.62	25.96
SF10	6.535	13.47	17.35

Table 6.2: Estimated distance samples with different BW and SF combinations in NLoS at 20 meters actual distance.

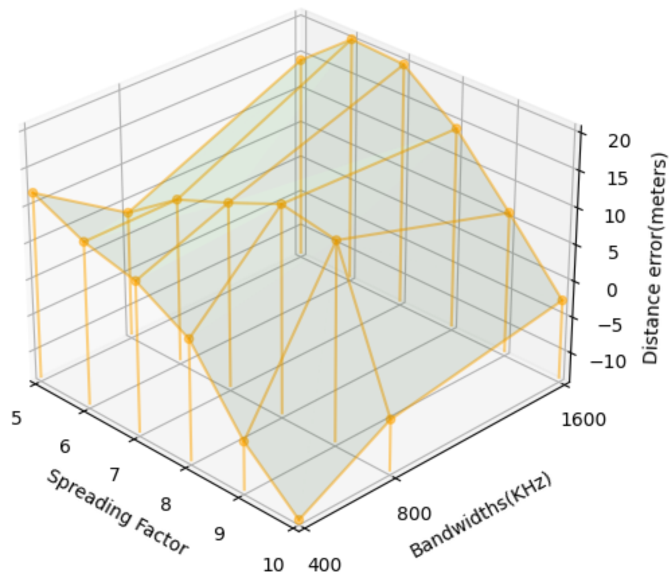


Figure 6.2: A three-dimensional overview graph representation of Distance Error with respect to Bandwidth and Spreading Factor combinations in NLoS scenario.

With a similar point of view for NLoS evaluated individual graph, we observe that with `BW 400KHz & 800KHz`, the error rate either greater than 5 meter or below 0. An optimal combination will be the one which has distance error close to value 0. As we can see in the figure 6.2, there is one combination with `BW 1600KHz & SF 10` which is close enough to zero and have measured distance `17.35 meter`. Therefore, also for NLoS scenario, we consider `BW 1600KHz & SF 10` LoRa parameters as the optimal for LoS setting.

6.2.3 LoS & NLoS brief Comparison

In LoS and NLoS scenarios, we found a common optimal LoRa parameter combination, i.e., `BW 1600KHz & SF 10`. But with this common optimal parameter, the scenarios LoS and NLoS has different error factors. For LoS the error factor is `2.10` and for NLoS the error factor is `-2.65` and therefore, there can be chances of having over-ranging and under-ranging situation when LoS parameters tested with NLoS setting and vice versa.

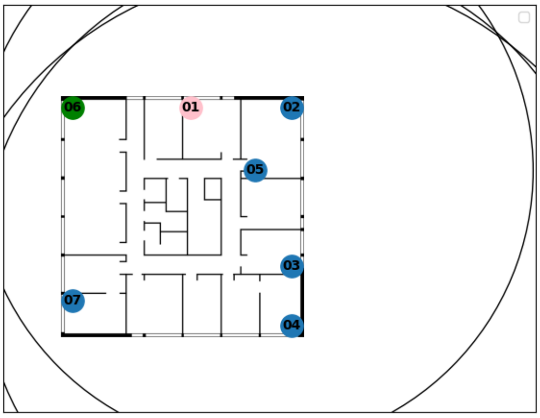


Figure 6.3: Ranging Test with Node in NLoS scenario. The green spot represents the Master node and Blue spots Anchors.

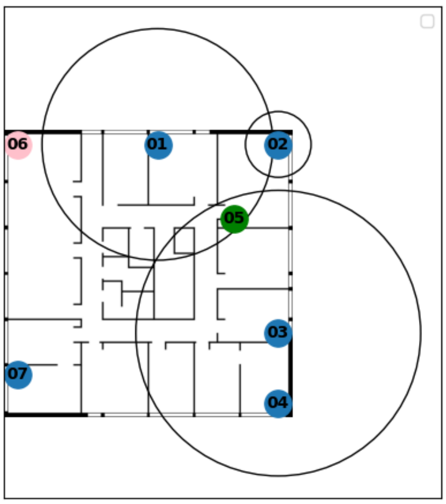


Figure 6.4: Ranging Test with Node in LoS scenario. The green spot represents the Master node and Blue spots Anchors.

The figures 6.3 & 6.4 shows the ranging test and proves the above-mentioned situation of over-ranging and under-ranging for LoS and NLoS in their compliment scenarios. We figured out that the evaluated optimal LoRa parameters combination did not perform ranging suitable for indoor environment.

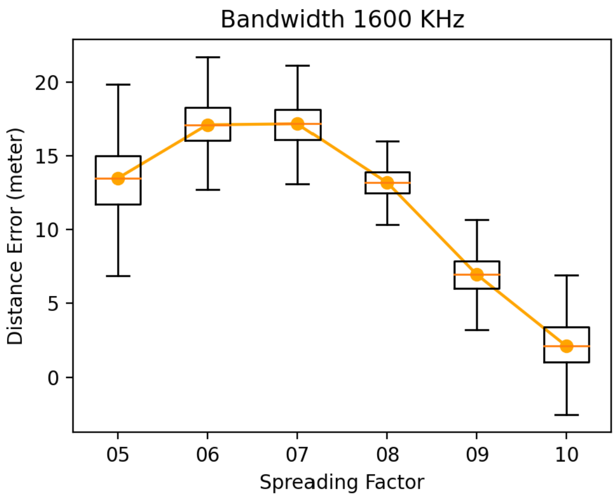


Figure 6.5: SFs with BW 1600KHz.

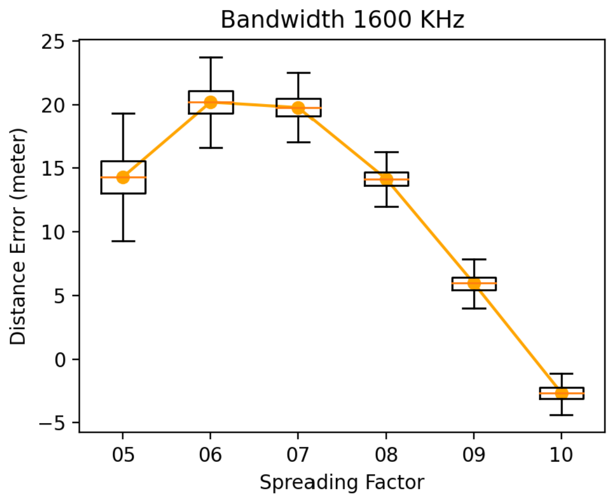


Figure 6.6: SFs with BW 1600KHz.

Now, we take a brief comparison for the evaluation and again check out the figures 6.1 & 6.2 for LoS and NLoS. We see that, none of the distance values are found exactly equal to the actual distance and therefore, ranging with SX1280 LoRa do not guarantee an accuracy. Still, we can seek for precision and reliability on the basis of similarity comparisons efficiently. We perform individual bandwidth based comparisons and seek for the similarities so that the devices would provide similar ranging values.In figures 6.5 & 6.6 we observe that the `BW 1600KHz` with `SF 09` has the most similar error factors and having similar distances with not significant difference for both LoS and NLoS scenarios. Therefore, we update the optimal LoRa parameter combination to `BW 1600KHz & SF 09`.

6.3 Indoor Localization System

As we discussed in the chapter 4, that the Localization system can be tested on the basis of the optimal outcomes from Ranging Evaluation System. Now, we have optimal LoRa parameter combination in which we saw similar behavior performed by the devices. Our further tests will be performed considering the optimal LoRa parameter combination, i.e., `BW 1600KHz & SF 09`. A Localization System requires a real-world test setup in an Indoor Environment to function. In this section, we see the device setup and localization accuracy and quality with different scenarios. Furthermore, we will also discuss the system dependencies.

6.3.1 The System Setup

The Indoor Localization System requires a base setup which should have minimum three LoRa Anchor nodes placed at the known location and a Master Node in communication range. Therefore, we require a testbed setup having nodes placed with measured physical distances. The Figure 6.7, is the floor plan of the testbed having different nodes placed at fixed and measured distances. The visible nodes are configured with LoRa modules attached with their respective host MCU. The blue nodes represent all the available Anchor nodes, Pink node represent a master node and Green node is the mobile node (node to be localized). Although, the roles for the nodes can be changed for evaluation of different test cases. All further evaluations will be with testbed setup (Figure 6.7) for our Indoor Localization System.

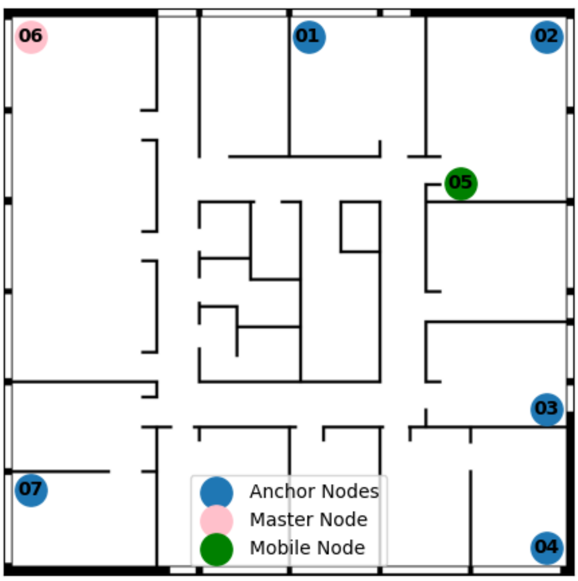


Figure 6.7: Floor plan of the testbed at Kiel University.

6.3.2 Ranging Quality

The localization of a node is dependent on how well the ranging has been performed. Also, a localization is good estimated if there are a maximum number of circles participating in intersection and overlapping. And more intersection points implies more data, which helps the `multilateration algorithm` estimate a good location. Therefore, we discuss the localization based on ranging quality performed by devices.

Good Ranging

A good ranging is said in case where mobile node estimated the distance equal or close enough to the actual distance. As shown in the figure 6.8, the `node 05` is the mobile node and performs the ranging with `node 01, 02 & 03`. The estimated distance values from Anchors in this case are very close to the respective actual distances to the Mobile node (`node 05`). And hence, the estimated location shown with red dot is very promising.

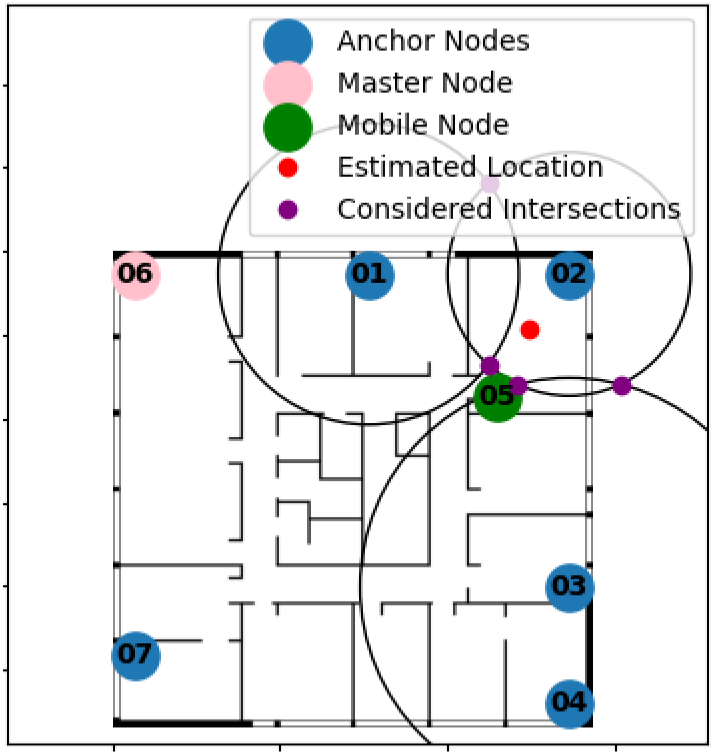


Figure 6.8: An example illustrating Good Ranging situation.

Bad Ranging

A bad ranging refers to the situation when there is no appropriate ranging performed among the devices and circles formed with their distances as radius do not intersect at all. As shown in the Figure 6.9, we again try to perform localization with similar situation as last section, and observed that the evaluated distances were not even close to mobile node and therefore, do not have any circles intersecting. The algorithm only works when it has intersections points with minimum of three circles, as there are two intersection points between two intersecting circles and there is an ambiguity between choosing the one among two intersection points. The scenario shown in the above-mentioned figure will result with no localization.

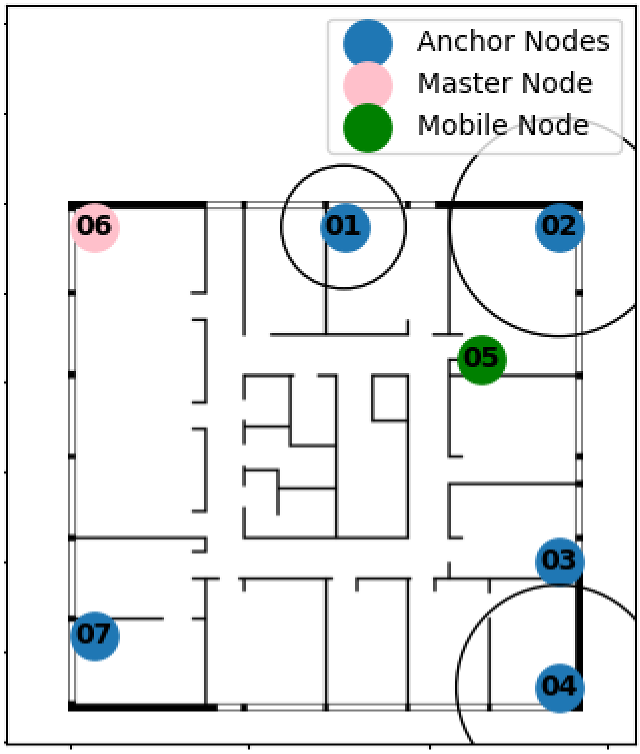


Figure 6.9: An example illustrating Bad Ranging situation.

6.3.3 Efficiency Control

The multilateration algorithm is embedded with an Efficiency control mechanism, in which the `error-rate` defines two different efficiency, namely Tight and Loose Efficiency. We discussed its working in Chapter 5, that Efficiency control mechanism is key for filtering process for intersection points. With the `Tight` efficiency, it considers the intersection points which are commonly present in all the circles and the `Loose` efficiency considers the intersection points present in one less than the maximum number of circles and therefore, chooses the more intersection points and looses little efficiency. The Tight and Loose Efficiency is defined by `error-rate=0` and `error-rate=1` respectively.

Tight Efficiency

In the Figure 6.10, we are trying to locate `node 04` and only three intersection points (purple colored) are chosen for evaluating location and estimates location (red colored) which is very close to the `node 04`. These intersection points are selected by the filter process with `error-rate=0` which means selected points lie in all circles formed by the estimated distances with respective Anchors.

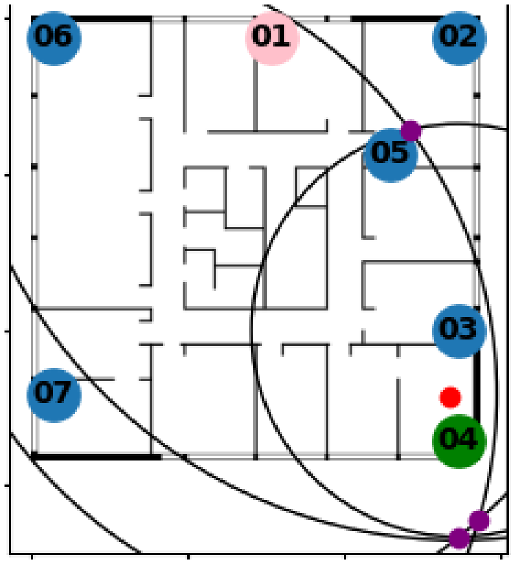


Figure 6.10: Localization with Tight Efficiency

Loose Efficiency

In the Figure 6.11, we consider the same case and same data, but this time with we try to locate `node 04` with `Loose` efficiency, i.e., `error-rate=1`. We observed that there were more intersection points are chosen by filter process as with `Loose` efficiency the filter process also considers the points which are also under one less circle as with `Tight` efficiency. As the result, the estimated location (red colored point) slightly moved away from the `node 04`. Even with the loose efficiency, the algorithm provides the promising estimated Location.

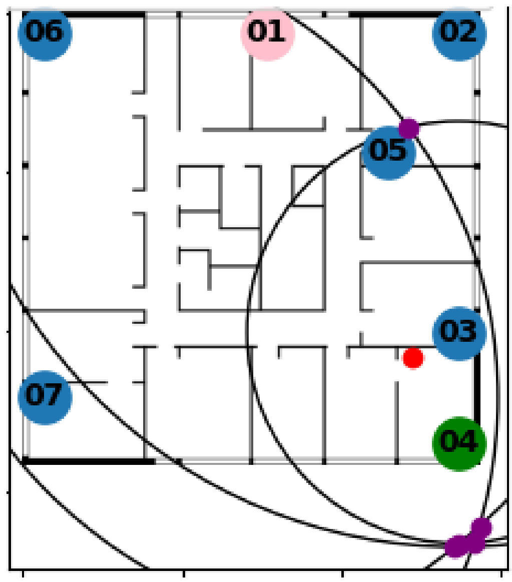


Figure 6.11: Localization with Loose Efficiency

6.3.4 Algorithm Efficiency in different cases

Case 1: The Best Case Scenario

In the Figure 6.12, the ranging performed by the `node 05` with Anchors is slightly higher than the actual distance, that means there will be circles overlapping situation. The algorithm of the system filtered the intersection points and resulted in three intersection points remaining, which defines the common overlapping area. Therefore, the algorithm estimates the location exactly on the node's actual position. The combination of slightly higher distance and three filtered intersections is seen as the best scenario in which the algorithm estimates the accurate location.

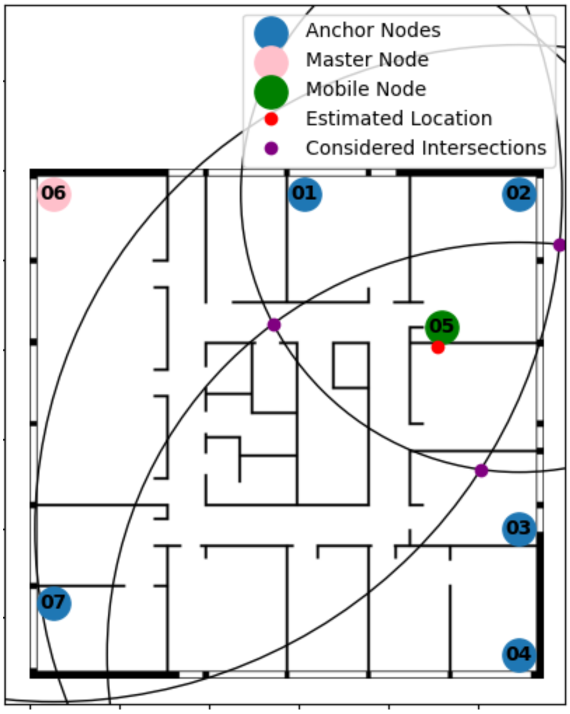


Figure 6.12: Localization, with Best Case with three intersection points after filtering.

Case 2: Intersection Points

In the Figure 6.13, we try localizing the `node 03`. After ranging, there are four filtered intersection points from filter process outcomes. In the previous case, there were three filtered intersection points formed a triangle like structure and found the center of the geometrical figure as location. Likewise, in this case also with four intersections a polygon formation is considered and simply finding a centroid would be the estimated location. The algorithm applies centroid evaluation for all the filtered intersection points irrespective of their quantity and therefore, the centroid is the estimated location of the `node 03`. We observed that, even with more intersection points, the algorithm still promises a good location.

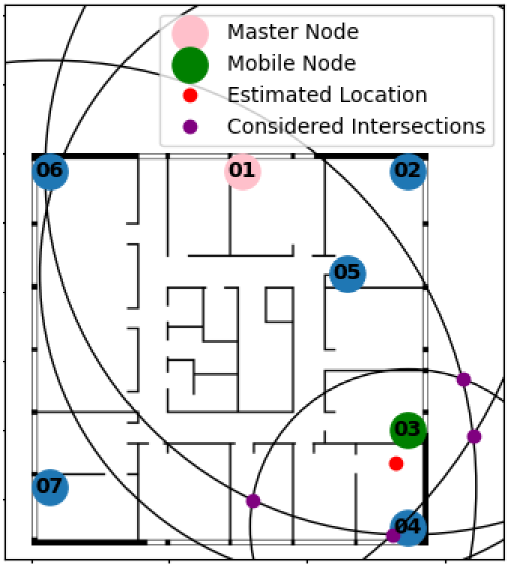


Figure 6.13: Localization with more than three intersection points after filtering.

Case 3: Non-Intersecting Circles

The Figure 6.14, illustrates a strange and interesting case, where we locate `node 05`. The ranging performed between locating node and Anchor `node 03` is exactly the same as actual distance. But for `node 01` & `node 02`, the ranging is slightly less than the actual distance. Therefore, not all circles formed by the distance values intersect with each other. But one circle with `node 02` is commonly intersecting with other two circles, and we get distinct intersection points. In this case, the algorithm does not filter these distinct points and estimates a location for `node 05` which is a good estimation.

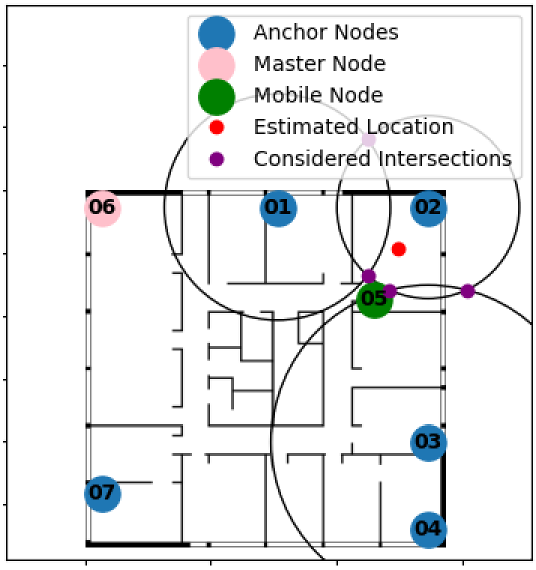


Figure 6.14: Localization when not all circles intersecting.

Case 4: The Outliers Scenario

In Figure 6.15, we try locating `node 06`, and observed the ranging values are significantly larger than actual distance and resulting into the possibility of having intersections mostly outside the space. Anyway, the algorithm did withstand the outlier situation and estimated a location which is not promising enough but can provide information about node presence in one section of the space.

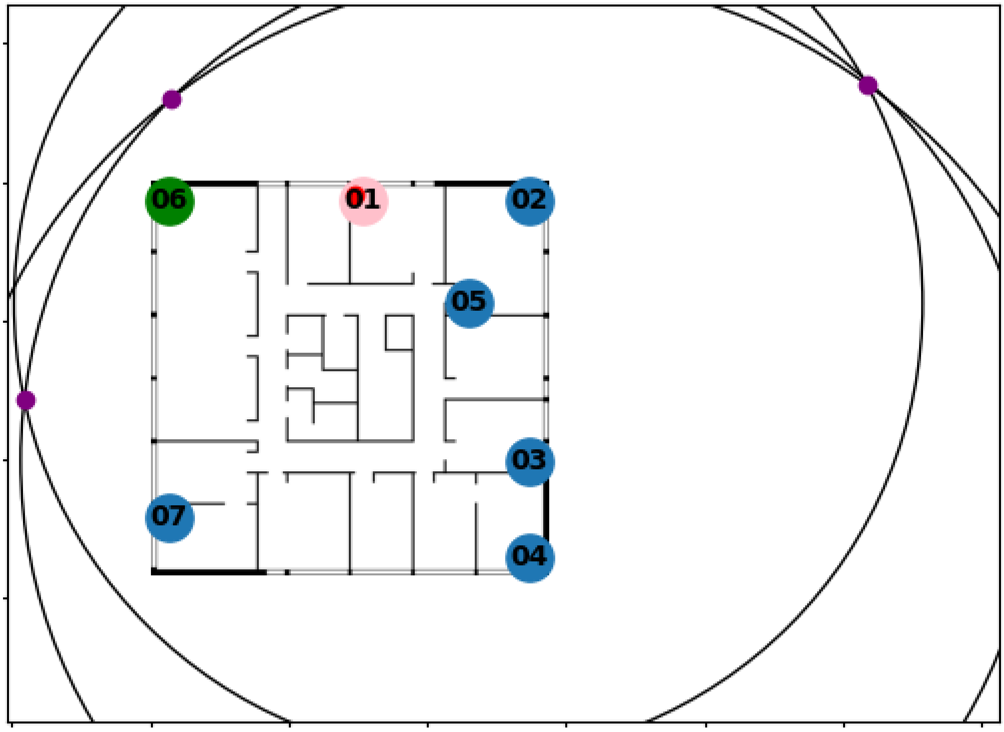


Figure 6.15: Localization with outliers (Over-Ranging).

6.3.5 Evaluation Conclusion on Localization System

We carried out several tests within our Indoor Localization System, considering several test cases to check the efficiency of the algorithm. As we mentioned earlier that the location estimation is purely dependent on how good ranging has performed. During the tests, we saw that we had very accurate results with measured distance data almost equal to real ground truth and even with the cases where estimated distances were slightly larger than actual ground truth. There were some cases where we observed very promising results with nodes having different behavior (some nodes performed under-ranging) and not all circles intersecting with each other, i.e., no particular overlapping area among circles. Also, the algorithm did withstand the outliers cases where, it estimated the location a bit far but provides the information about device present in which section of the map. Within multiple samples, we also observed that the localization algorithm tolerance for a good location estimation is when over-ranging is 5 meters or below. And even at worst, the algorithm gives an idea about the section of the space in which the device lies.

Chapter 7
Conclusion

One main objective in this thesis is to develop an Indoor Localization System with LoRa 2.5Ghz. Our basic idea for the design contains three different entities: the master, the mobile, and the anchor. The master's purpose is to provide information like IDs and positions of all anchors present in the system to mobile. Anchor's just stays in ranging mode. The mobile then broadcasts the localization request and sequentially starts ranging and localization process once it gets the anchor's information from the master.
In our Localization System's algorithm, we used a multilateration positioning technique, as the evaluations shows the over-ranging results, and the fact that multilateration is used in such scenarios. Furthermore, we evaluate the localization algorithm in different test case scenarios with tight and loose efficiency. We observed that the system could provide the promising location estimation with good ranging results. While, the quality of ranging has a large impact on estimating location. In the system, the ranging at its worst with over-ranging would still present the portion of the space where the device lies.
The other objective in this thesis is to evaluate LoRa 2.4 GHz for it's ranging capabilities. We observed that the LoRa parameter significantly affects the ranging performance. The evaluation with 20 meters of distance shows that LoRa 2.4 GHz can result in good distance estimation with combination of bandwidth 1600 KHz with high spreading factors. We also observed enormous impacts with other factors like LoS and NLoS scenarios, which affects the ranging performance even with optimal LoRa parameter combinations and results in situation like over-ranging and under-ranging. Therefore, it is recommendable to perform such evaluations and use positioning techniques which are capable of withstanding such conditions for Indoor Localization Systems with LoRa 2.4 GHz.
The evaluations from previous research will rarely apply exactly to our system's work environment. Nevertheless, they can present a direction and flow. Consequently, it would benefit deciding positioning techniques for building a Localization System using LoRa 2.4 GHz and also to learn more about the indoor environment setting and several test cases which may offer new possibilities.

7.1 Future Work

The outcomes from the Indoor Localization System can be taken a step higher by applying machine learning approaches on estimated locations. Keeping a track of the hopping locations with creating history and observe the behavior comparisons with actual location, would open possibilities for new estimations. An approach similar like fingerprinting can help estimate location more precisely with the data of a complete experiment.

Our evaluations were based on distance values carried out with SX1280's ranging engine. The transceiver also provides a RSSI value within each ranging operation. Combining the obtained RSSI and ranging engine's results could be explored for evaluating ranging with LoS and NLoS with different LoRa parameters combination. And can be tested within our existing indoor localization system.
Our Indoor Localization System outputs the estimated device location. Apart from LoRa devices, a user interface application presenting a map and featuring a live location update can fulfill a purpose similar to navigation system.
We designed the system localizing devices in two-dimensional space using LoRa 2.4 GHz. It might be interesting to design and evaluate a similar system using LoRa 2.4 GHz for a three-dimensional space.

Acronyms

AoA Angle of Arrival 4

API Application Programming Interface 6

BW Bandwidth ix

BLE Bluetooth Low Energy v

CS Chip Select 27

DIO Digital Input Output 27

GPIO General Purpose Input Output 6

GPS Global Positioning System iii

LoRaWAN LoRa Wide Area Network 3

LoS Line of Sight vi

MRC Maximum Ratio Combining 10

MOSI Master-Out Slave-In 27

MISO Master-In Slave-Out 27

MCU Microcontroller Unit vi

NLoS Non-Line of Sight vi

RFID Radio Frequency Identification v

RSS Received Signal Strength 4

RSSI Received Signal Strength Indicator 10

RToF Round-trip Time of Flight vii

RTOS Real Time Operating System 6

Bibliography

[1] T. T. Khanh, V. Nguyen, X.-Q. Pham, and E.-N. Huh, *Wi-fi indoor positioning and navigation: A cloudlet-based cloud computing approach—human-centric computing and information sciences*, Jul. 2020. [Online]. Available: https://hcis-journal.springeropen.com/articles/10.1186/s13673-020-00236-8.

[2] Y. Cui, Y. Zhang, Y. Huang, Z. Wang, and H. Fu, "Novel wifi/mems integrated indoor navigation system based on two-stage ekf", *Micromachines*, [Online]. Available: https://www.mdpi.com/2072-666X/10/3/198.

[3] *What is lora®?* [Online]. Available: https://www.semtech.com/lora/what-is-lora.

[4] X. G. Qiang Liu XiuJun Bai and S. Yang, *Lora rtt ranging characterization and indoor positioning system*, 2021. [Online]. Available: https://doi.org/10.1155/2021/5529329.

[5] T. L. Foundation, *Zephyr os*. [Online]. Available: https://zephyrproject.org/learn-about/.

[6] M. Team, *Introduction to lora technology – the game changer*, Aug. 2016. [Online]. Available: https://www.digikey.de/en/maker/blogs/introduction-to-lora-technology.

[7] H. Liu, H. Darabi, P. Banerjee, and J. Liu, "Survey of wireless indoor positioning techniques and systems", *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, vol. 37, no. 6, pp. 1067–1080, 2007. DOI: 10.1109/TSMCC.2007.905750.

[8] H. Obeidat, W. Shuaieb, O. Obeidat, and R. Abd-Alhameed, "A review of indoor localization techniques and wireless technologies", *Wireless Personal Communications*, vol. 119, Jul. 2021. DOI: 10.1007/s11277-021-08209-5.

[9] V. ilçi, V. Gülal, R. Alkan, and H. Çizmeci, "Trilateration technique for wifi-based indoor localization", Oct. 2015.

[10] A. E. M. E. Ashry and B. I. Sheta, "Wi-fi based indoor localization using trilateration and fingerprinting methods", *IOP Conference Series: Materials Science and Engineering*, vol. 610, no. 1, p. 012 072, Sep. 2019. DOI: 10.1088/1757-899x/610/1/012072. [Online]. Available: https://doi.org/10.1088/1757-899x/610/1/012072.

[11] P. Cotera, M. Velazquez, D. Cruz, L. Medina, and M. Bandala, "Indoor robot positioning using an enhanced trilateration algorithm", *International Journal of Advanced Robotic Systems*, vol. 13, no. 3, p. 110, 2016. DOI: 10.5772/63246. [Online]. Available: https://doi.org/10.5772/63246.

[12] *Radio frequency ranging for precise indoor localization.* [Online]. Available: https://edoc.hu-berlin.de/bitstream/handle/18452/19525/dissertation_sark_vladica.pdf?sequence=3.

[13] S. Pande and K. S. Ibwe, *Robust trilateration based algorithm for indoor positioning systems.* [Online]. Available: https://www.ajol.info/index.php/tjs/article/view/212601.

[14] B. Cook, G. Buckberry, I. Scowcroft, J. Mitchell, and T. Allen, "Indoor location using trilateration characteristics", Jan. 2005.

[15] *Sx1280.* [Online]. Available: https://www.semtech.com/products/wireless-rf/lora-24ghz/sx1280.

[16] Z. Zhang, S. Cao, and Y. Wang, "A long-range 2.4g network system and scheduling scheme for aquatic environmental monitoring", *Electronics*, vol. 8, p. 909, Aug. 2019. DOI: 10.3390/electronics8080909.

[17] *Device driver model.* [Online]. Available: https://docs.zephyrproject.org/latest/kernel/drivers/index.html.

[18] *Zephyr project—nordic semiconductor.* [Online]. Available: https://developer.nordicsemi.com/nRF_Connect_SDK/doc/2.0.0/zephyr/introduction/index.html.

[19] Semtech, *An introduction to ranging with the sx1280 transceiver.* [Online]. Available: https://semtech.my.salesforce.com/sfc/p/#E0000000JelG/a/44000000MDiH/OF02Lve2RzM6pUw9gNgSJXbDNaQJ_NtQ555rLzY3UvY.

[20] *Semtech sx1280 datasheet.* [Online]. Available: https://semtech.my.salesforce.com/sfc/p/#E0000000JelG/a/2R000000HoCW/8EVYKPLcthcKCB_cKzApAc6Xf6tAHtn9.UKcOh7SNmg.

[21] A. Alarifi, A. Al-Salman, M. Alsaleh, *et al.*, "Ultra wideband indoor positioning technologies: Analysis and recent advances", *Sensors*, vol. 16, pp. 1–36, May 2016. DOI: 10.3390/s16050707.

[22] M. S. Svalastog, *Indoor positioning—technologies, services and architectures*, Jun. 2007. [Online]. Available: http://urn.nb.no/URN:NBN:no-15083.

[23] M. Segura, V. Mut, and C. Sisterna, "Ultra wideband indoor navigation system", *Radar, Sonar Navigation, IET*, vol. 6, pp. 402–411, Jun. 2012. DOI: 10.1049/iet-rsn.2011.0352.

[24] A. Kalbandhe and S. Patil, "Indoor positioning system using bluetooth low energy", Dec. 2016, pp. 451–455. DOI: 10.1109/CAST.2016.7915011.

[25] V. Paterna, A. Calveras, J. Aspas, and M. Bullones, "A bluetooth low energy indoor positioning system with channel diversity, weighted trilateration and kalman filtering", *Sensors*, vol. 17, p. 2927, Dec. 2017. DOI: 10.3390/s17122927.

[26] S. Robinson, *What is lora ?* [Online]. Available: https://stuartsprojects.github.io/WhatisLoRa.html.

[27] R. Stuart, *Semtech sx1280 2.4ghz lora® ranging tranceivers*. [Online]. Available: https://stuartsprojects.github.io/2019/04/26/Semtech-SX1280-2-4Ghz-LoRa-ranging-tranceivers.html.

[28] F. Rander Andersen, K. Dilip Ballal, M. Nordal Petersen, and S. Ruepp, "Ranging capabilities of lora 2.4 ghz", in *2020 IEEE 6th World Forum on Internet of Things (WF-IoT)*, 2020, pp. 1–5. DOI: 10.1109/WF-IoT48130.2020.9221049.

[29] *Circles and spheres*. [Online]. Available: http://paulbourke.net/geometry/circlesphere/.

[30] SX1280, *Dlp-rfs1280 lora rf transceiver module—dlp design | mouser*. [Online]. Available: https://www.mouser.de/new/dlp-design/dlp-design-rfs1280-rf-module/.

[31] N. Semiconductors, *Nrf52840 dk*. [Online]. Available: https://www.nordicsemi.com/Products/Development-hardware/nrf52840-dk.

[32] Zephyr, *Devicetree howtos*, Feb. 2022. [Online]. Available: https://docs.zephyrproject.org/3.0.0/guides/dts/howtos.html.

[33] L. Hass, *2.4 ghz lora in smart buildings: Driver development for zephyr os and comparison with ble*. [Online]. Available: https://www.ds.informatik.uni-kiel.de/en/teaching/bachelor-and-master-theses/completed-master-and-bachelor-theses/2021_bachelor-thesis_Lukas-Hass.pdf.

Appendix A

Additional evaluation plots

A.1 Ranging Evaluation System

A.1.1 LoS

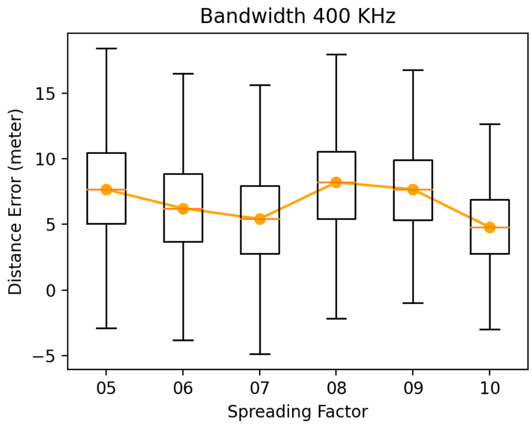


Figure A.1: SFs with BW 400KHz.

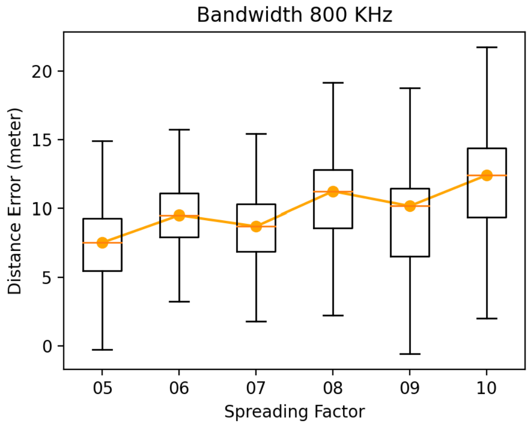


Figure A.2: SFs with BW 800KHz.

A.1.2 NLoS

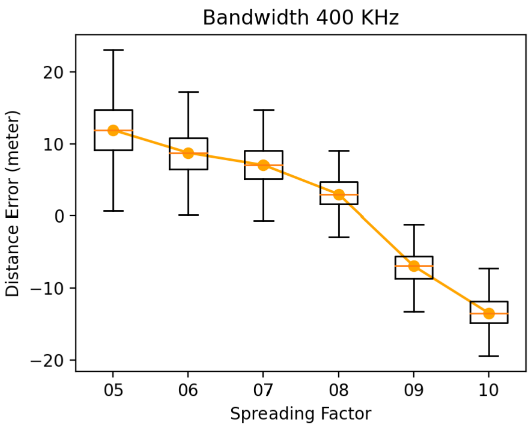


Figure A.3: SFs with BW 400KHz.

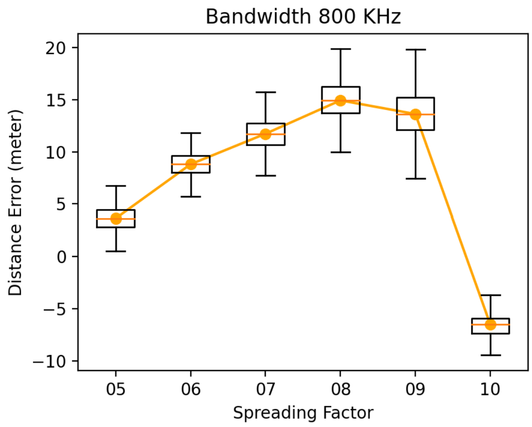


Figure A.4: SFs with BW 800KHz.

A.2 Indoor Localization System

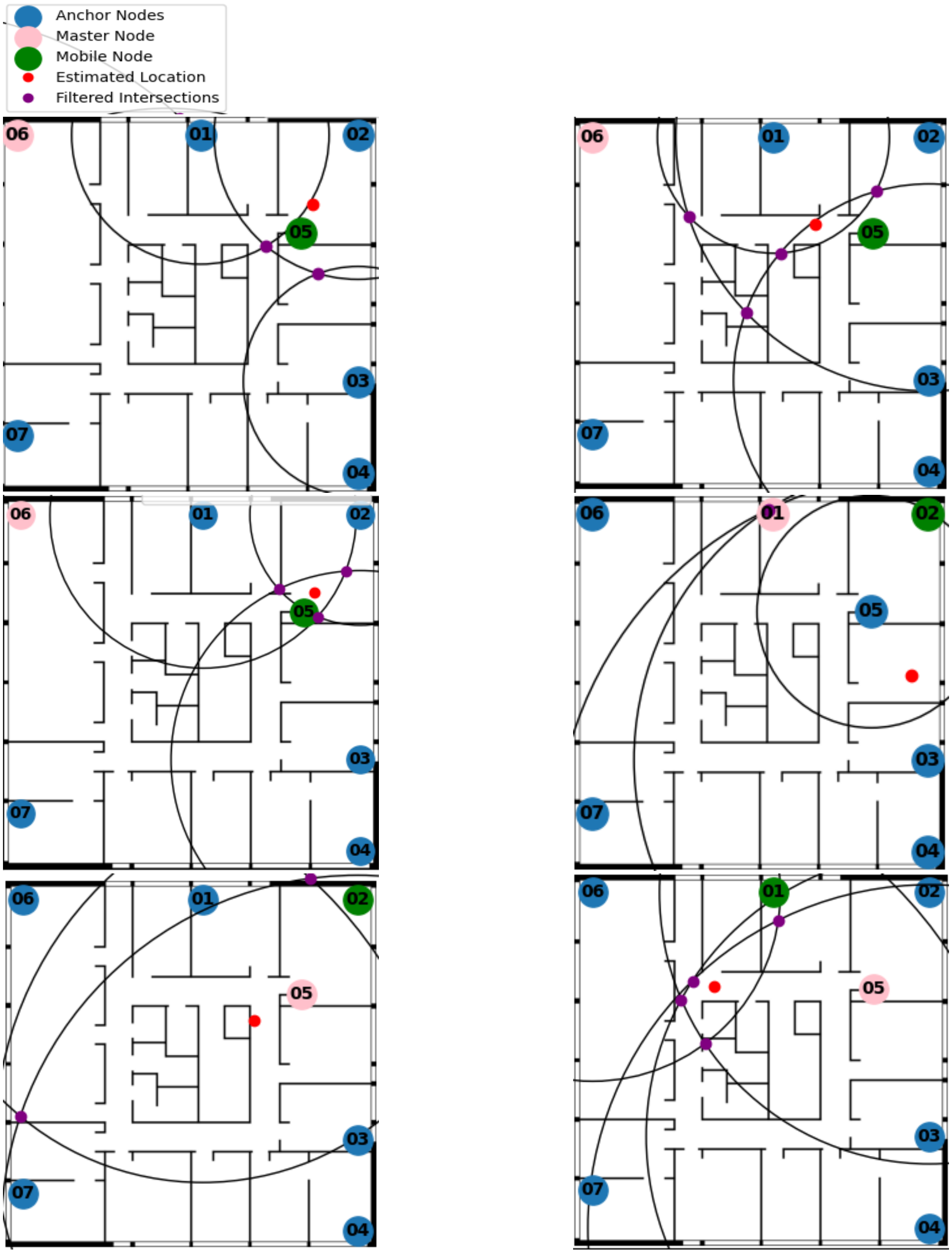


Figure A.5: Several cases with different Mobile Node Position.