# A RSSI Locating Algorithm for Multi-Robot System

A Thesis Presented

by

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to

The Graduate School

in Partial Fulfillment of the

Requirements

for the Degree of

**Master of Science**

in

**Electrical Engineering**

Stony Brook University

**December 2013**

**Stony Brook University**

The Graduate School

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Abstract of the Thesis

**A RSSI based Locating Algorithm for Multi-Robot System**

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**2013**

An algorithm based on Received Signal Strength Indicator (RSSI) is designed for locating a wireless signal source in Multi-Robot System (MRS). Mobile robots are initially assigned to different locations. They are either sending or sensing wireless signals. The purpose of the algorithm is to establish communication among robots by locating the signal sources. Three main behavior modes of a robot are proposed for the algorithm skeleton through behavior-based analyzing. A log-distance path loss model is adopted for representing Received Signal Strength Indicator (RSSI) on a grid map. The locating process is a gradient-based motion control which refers to the RSSI measurement in the grid map. We simulated the locating algorithm in Matlab. The result of the simulation demonstrates a good locating result in a RSSI map without fading effect. In a RSSI map with Rayleigh fading, multiple movements and variations in step size are integrated into the algorithm to cope with measurement errors by the fading effect of the RSSI.

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## Acknowledgments

I express my deepest gratitude of thanks to my thesis advisor Professor Xin Wang for her support, guidance and positive suggestions throughout my graduate program and in completing this thesis. Her previous research has already given me a good start. Without her support and help, it would have never been possible to overcome the various challenges.

I would like to express my gratitude to Professor Lei Zuo for agreeing to review my thesis in such a short notice. I really appreciate your help.

I would also like to thanks to my team members Zhe Yan, Jiawei Chen, Hanho Lee, and DaegeunYoon who give me suggestions from time to time. It's a great experience to work with you.

I would like to express my deepest gratitude my beloved fiancée Yur in China for her consistent support and encouragement.

# Chapter 1 Introduction

## 1.1 Background

Multi-Robot System (MRS) is a system which consists of multiple mobile robots collaborating to execute tasks. Each robot in MRS has its own capabilities of sensing, actuation, computation and communication[1]. A MRS has numbers of applications, e.g. surveillance and environment monitoring, to emergency handling, e.g. disaster rescue, from scientific activities, e.g. space and deep sea exploration, to military operations, e.g. de-mining and battle field scouting, etc.

Compared with an independent robot, a MRS can have higher flexibility, efficiency and reliability, e.g. accomplishing a single task much faster, executing tasks beyond the limits of single robots, providing parallel mobile sensing and processing, handling a variety of tasks, performing a complex task with a team of simple robots rather than a costly super robot, being less influenced by the failure of any individual robot, etc. Existing research [2] has shown that MRS can get performance gain through efficient coordination than multiple independent robots during the process of task.

## 1.2 Architecture of MRS

There are two major architectures in MRS, centralized and distributed. In our research, we choose the distributed architecture.

### 1.2.1 Centralized Architecture

Figure 1.1 shows a centralized architecture. A single robot that works as commander owns other robots' information. Robots can be considered as nodes which communicate each other through this headquarter node. The benefit of the centralized architecture is the conveniences of getting and maintaining multi-robot information. All robots' information can be accessed and controlled through the center node. However, this is also a weakness of the architecture. The commander is critical to the whole network. If that robot fails, the whole network crashes. Lack of flexibility is also a drawback for a centralized architecture. One robot always needs to reach each other through the commander robot in the network.

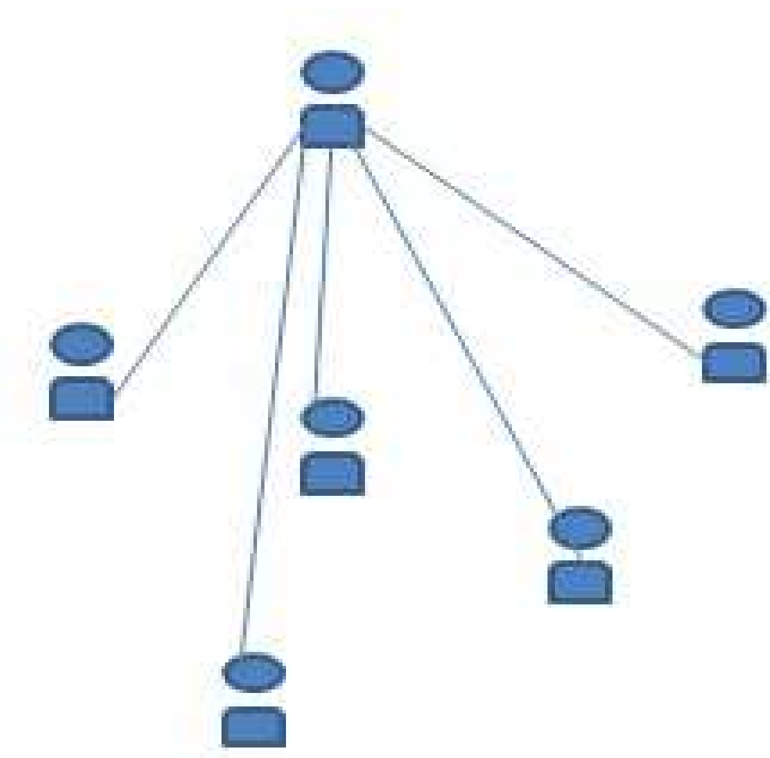

Figure 1.1 Centralized Architecture

### 1.2.2 Distributed Architecture

Figure 1.2 shows a distributed architecture. All robots are in equal position in the distributed architecture. They all organize themselves and connect to their neighbor directly. They plan their own action based on information from neighboring robots [4]. This architecture has some advantages compare with the centralized architecture. It is failure tolerant. One failure robot will not affect other robots in the network. The architecture is more flexible.

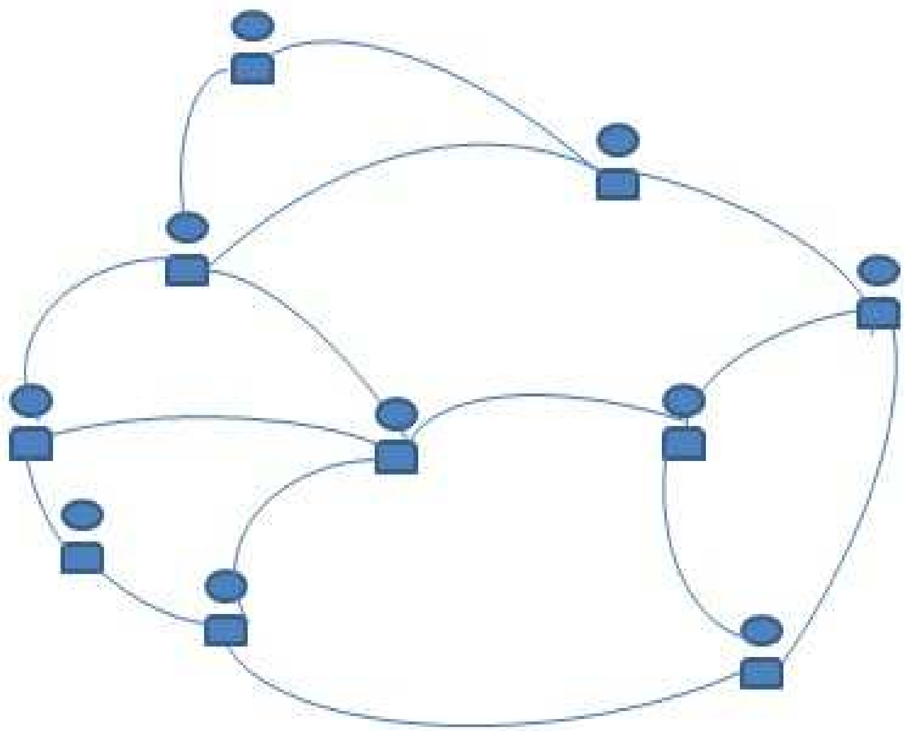

Figure 1.2 Distributed Architecture

# Chapter 2 Motivation and Problem

## 2.1 Motivation and Objective

Communication plays an important role in cooperation between multi robots during the process of task implementation. Although many researches have been published in this area, professor Wang's report[1] pointed out the lack of researches on establishing and recover communication. Existing multi-robot coordination studies generally assume the availability of wireless connections or initial connections. Some major challenges like signal propagation condition, robots with no initial communication and requirement for high-bandwidth transmission among mobile robots remain unaddressed.

In this paper, we research on how to establish establishing communications among robots with no initial communication. The purpose of the research is to establish communication in a MRS by utilizing the mobility of mobile robots.

## 2.2 Problem Formulation

### 2.2.1 Signal Strength Control in Establishing Communication

Initially, there is no communication among robots in the MRS. Robots initiate their tasks at random locations. If the robots are getting close and strong signals, they can start communicate without moving. However, some robots cannot communicate because of the weak signals. In that case, the robots can increase its signal coverage by increasing its signal strength or moving closer to others. We assume two robots can communicate when they received certain level signal strength. The problem of establishing communication becomes the control of increasing received signal strength to a certain level which can be successfully decoded.

### 2.2.2 Motion Control in Establishing Communication

In previous research[1], a Dual-Ranges communication was introduced by professor Wang to further clarify this problem. Two channels are used in different application. For Data transmission, it needs high throughput and more reliable transmission. A high frequency and high transmission rate channel is used. This is defined as data channel. On the contrary, for simple message transmission between robots, high throughput is now necessary. A channel with low frequency and low transmission rate is used. We called it beacon channel which cover longer transmission range.

In each channel, there are sensing range and transmission range. Given the maximum transmission power, the sensing range is approximate two times as the transmission range. This is our coarse-grained assumption. The precise ranges relations need to be determined in the future experiment. A receiver can only sense signals in the sensing range. If robots want to establish communication, they need to enter into the transmission range to get stronger signals. Two channels with two ranges are consists of four ranges as shown in Figure 2.1.

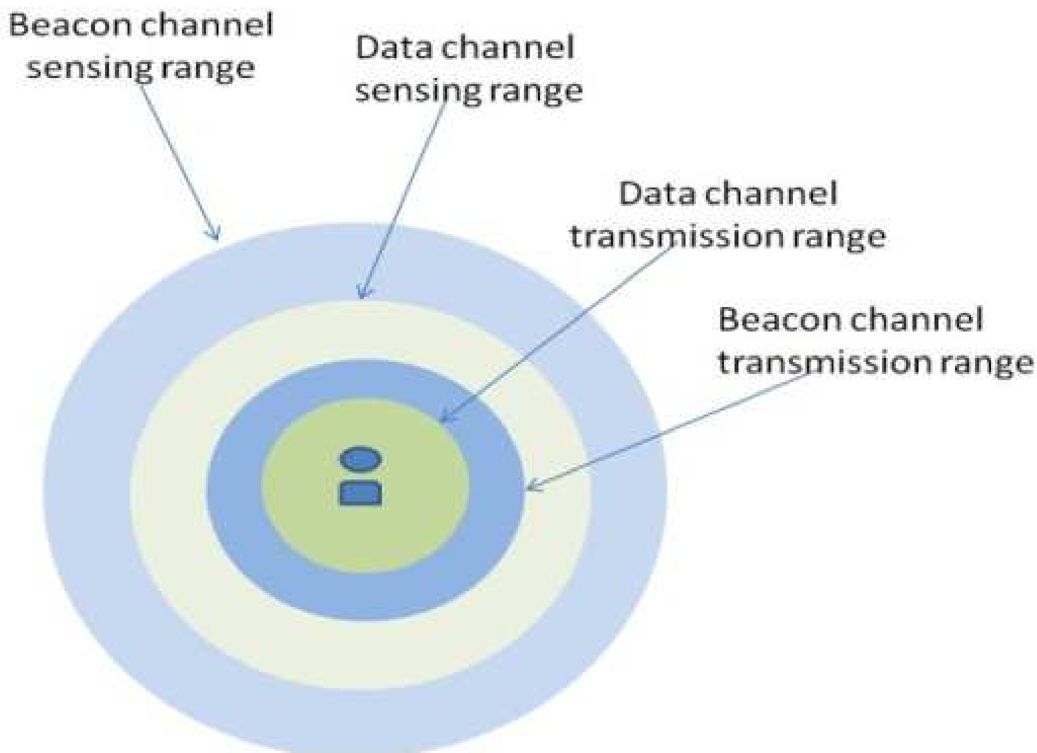


Figure 2.1 Data/Beacon channel transmission/sensing range

Dual-Range model further narrows our first step of establishing communication into controlling the robots to move into the transmission range. If robots can get close enough to each other, robot can establish communication and transmit data.

With initializing communication, a network can be further built. Robots organize themselves in the coverage network[3]. In our research, we consider the ad-hoc network in which there is no base station for robots.

### 2.2.3 Localization in Motion Control

In the process of controlling the robot moving into the transmission range, a robot needs to know other robot's location or the location of higher signal strength.

Locating a wireless signal source has been researched in many papers. Song's paper [4] category this topic into three research fields including Radio frequency(RF)-based localization, simultaneous localization and mapping (SLAM), and occupancy grid methods. In RF-based localization, a location system can utilize the signal strength to estimate distance or angles. Radim Zemek's paper[5] compared those techniques including time of arrival (TOA), time difference of arrival(TDOA), angle of arrival (AOA), and Received signal strength indicator (RSSI). It addressed the requirements of synchronization and additional receiver hardware in TOA, TDOA and AOA techniques. In our research, we also adopt RSSI technique considering on its simplicity. RSSI suffers from signal fading problem and it does not provide as accurate measurement as TOA and TDOA due to those effects[5]. In the field of SLAM, Dieter Fox's paper[6], Sebastian Thrun, Wolfram Burgard and Dieter Fox's book[7] made a thoroughly research in this field. However, this method needs large amount of measurements from different sensors like laser range sensor, GPS. In our research case, the purpose is not to build up a precise map. Our purpose is to establish communication through localization. So we use RF-based method for its simplicity and no need of advanced hardware.

# Chapter 3 Algorithm Design

## 3.1 Behavior Analysis

The algorithm to be designed mainly copes with three limitations: an unknown environment, robots scattered in different place and no initial communication with other robot.

We first list and analyze a list of behaviors of a robot in the Multi-Robot System. In each behavior, there are different operation modes. I plan to design a role based algorithms for those functions.

This behavior-based concept is inspired by Julian de Hoog's paper[8] in 2009. The concept of behavior-based formation control for Multi-Robot System was first proposed by Balch and Arkin in their paper[9] in 1998. Julian de Hoog further proposed a role-based exploration in 2009. In his paper, He defines two roles in that paper: explorer who searches unknown areas and relay that relays explorer's information to a central station. In implementation process, Julian introduces a role swapping mechanism in simulation and implementation. However, Julian's paper focuses on a rescue application in which robots take off from the same known point. In our case, robots start from random point. We also don't have the central base station, all the information is distributed in individual robot.

In our research, we divide the behaviors of our robot into three categories. They are exploration, establish communication, and maintain communication.

In the exploration behavior, a robot doesn't sensed signals. It explores unknown areas and stores the waypoints trying to find other robots or groups. The other case in exploration behavior is a group of robots explore unknown areas. In the group, the robots already have communication. We define the two cases as single exploration and cluster exploration. In cluster exploration, the robots in the whole group can move together or a robot in the group can temporally moves out of the communication range of the cluster. The latter case is a more flexible way to communicate. In our research, we first approach the single exploration problem.

1. Exploration:
    a. single exploration
    b. cluster exploration
    c. single reaches out of range and then comes back to cluster

In the behavior of establishing communication, there are communications between single robot to single robot, single robot to a cluster and a cluster to a cluster.

2. Establish communication:
    a. one to one
    b. one to cluster
    c. cluster to cluster

In the behavior of maintaining communication, robots can keep in the beacon range or keep in a fixed distance from other robots.

3. Maintain communication:
    a. keep in the beacon range
    b. keep in the fixed distance

The behaviors can be presented in the Figure 3.1.

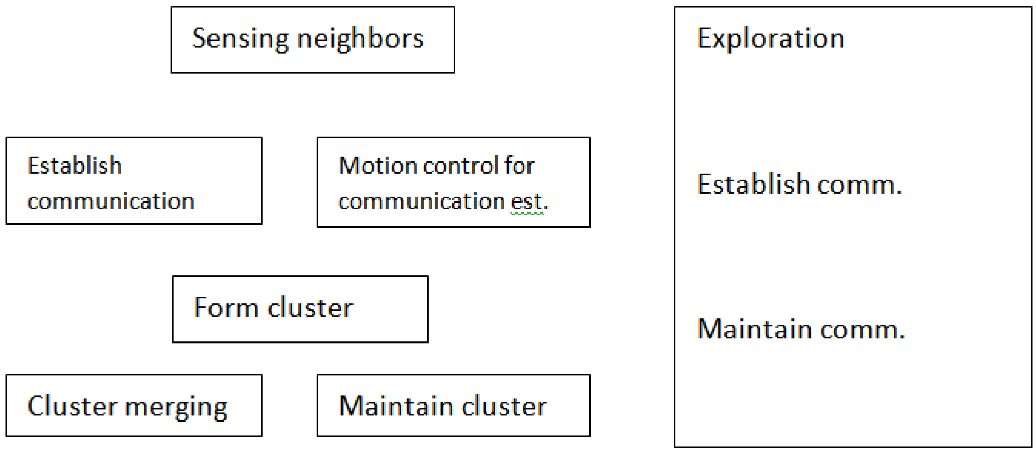


Figure 3.1 Robot Behavior

Data communication is implied in the behaviors of establishing and maintaining communication. Two robots can communicate directly if they are in the communication range. They can also send a message to a third robot to relay the information. The third robot is called step stone or messenger depends on its mobility.

Data communication

a. direct communication
b. step stone
c. messenger

## 3.2 Behavior Mode

Based on the behaviors analysis, three main roles are defined. Multiple functions are contained in each role. In a given period, a robot just executes functions in its corresponding role. The robot switches into another role when its condition changes. The main algorithm shows in Figure 3.2.

```
initialization;
while no signal sensed do
    Explorer Mode;
    if sensed signal then
        if RSSI < TH then
            Locator Mode
        else
            Communicator Mode
        end
    end
end
```

Figure 3.2 The Main Algorithm

### 3.2.1 Explorer Mode

- Explore unknown area
- Sensing neighbor robots

### 3.2.2 Locator Mode

- Estimate directions and distance of signal source
- Establish communication

### 3.2.3 Communicator Mode

- Messenger
  - Step stone
  - Relay
- Leader
  - Lead the cluster
- Follower
  - Follow leader's command

## 3.3 RSSI Model

Received signal strength indicator (RSSI) is a measurement of the power present in a received radio signal[10]. Through the relation between distance and received signal strength, we can estimate distance from a transmitter to a receiver given received signal strength. Based on the calculated distance, we can further determine direction by heuristic move or triangulation methods to locate the signal source.

### 3.3.1 Fading

Although simplicity is an important advantage of RSSI method, there are also some fading factors to be considered. There are short term fading and long term fading. The short term fading consist of Rayleigh or Rician fading. The Rician fading fits the propagation condition which existing a line-of-sight (LoS). Rayleigh is more suitable for simulate the fading without a LoS condition. Rayleigh fading is a special case of Rician fading[11]. The propagation of wireless signal is influenced by multiple fading phenomena, like reflection, diffraction and scattering effects (Figure 3.3).

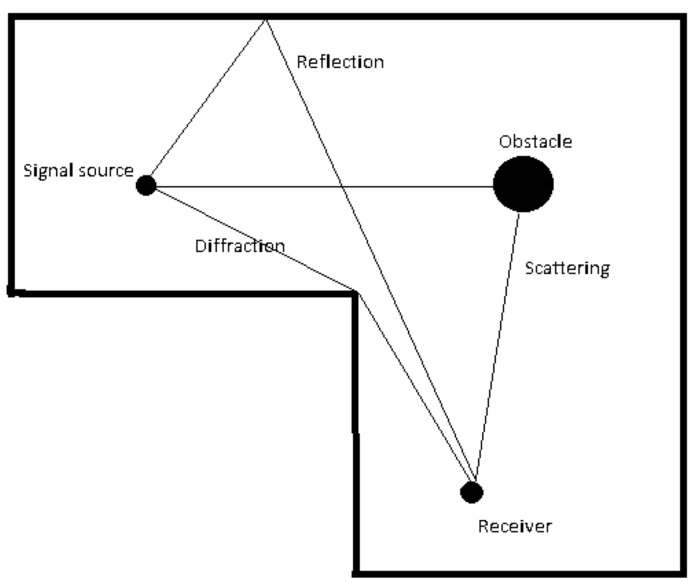


Figure 3.3 Multipath Fading

Those factors introduce uncertainty to our RSSI, and further affect the preciseness of RSSI location methods. In fact, RF-based methods all needed to consider on this affect. On one side, we need to model the RSSI signal and fading effects in order to perform better control of our robots motion. In our research, we will mainly consider the Rayleigh fading. Our robots work in an indoor environment which has no good LoS.

### 3.3.2 Log-Distance Path Loss Model

The other fading effect long term fading is usually the gradual power loss because of the distance between transmitter and receiver. This effect is simulated by a log-normal distribution. We adopt the log-distance path loss model in our research. It is a general propagation model used in modeling wireless communication propagations. We got the parameters from the papers like [12], [13]. Received signal strength can be calculated from this model. It models the signal attenuation with distance between transmitter and a given point. In book[14] , it is expressed by

$$\mathbf{PL(d)\ =\ PL(\boldsymbol{d_0})\ +\ 10nlog\frac{d}{\boldsymbol{d0}}\ +\ \boldsymbol{X_{\sigma^2}}} \quad 3\text{-}1$$

In paper[11], the right side of equation contains Gr and Gt which are receiving and transmitting antenna gains. We don't consider them since it will not affect our algorithm and simulation. In fact, the equation of considering only long term fading is the equation (3-1) without the term $X_{\sigma^2}$. The short term fading is taken into account by adding the $X_{\sigma^2}$ .

In this equation (3-1), PL (d) is the path loss at distance d from signal source. The parameter $d_0$ is the reference distance. Parameter n is the attenuation exponent which depends on environment. $X_{\sigma^2}$ is a Gaussian random variable, with zero mean and variance $\sigma^2$. It describes the effect of shadowing effect caused by obstacles in the environment. In our simulation case, we first assign this parameter to 0 without considering the effects of short term fading like reflection, diffraction and scattering effects.

Values of parameters are defined in Table3.1 referred on paper [12] [13] .

| Wireless Tech | Pt(dBm) | $P_{d0}$ (dB) | $d_0$(m) | n |
|---|---|---|---|---|
| Wi-Fi | 7 | 40 | 1 | 2.9 |

Table3.1 Parameters of Log-Distance Path Loss Model

Once we can calculate pass loss value PL (d), we can calculate RSSI by

$$\mathbf{Pr(d) = Pt - PL(d)} \qquad \mathbf{3\text{-}2}$$

In equation (3-2), Pt is the transmitting power of signal source, and Pr is the RSSI at the distance d from signal source. We plot a graph in Matlab to represent a relation between RSSI and distance at a transmitting power of 7dBm. The maximum distance is 20m. Figure 3.4 is the RSSI plot without fading effect. Figure 3.5 is the RSSI plot with fading effect which is simulated by $X_{\sigma^2}$.

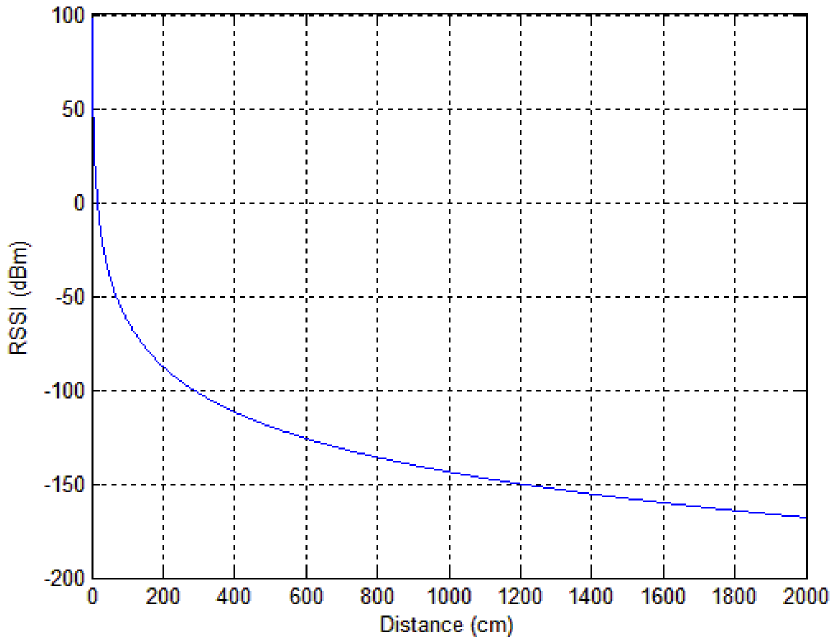


Figure 3.4 RSSI without Fading

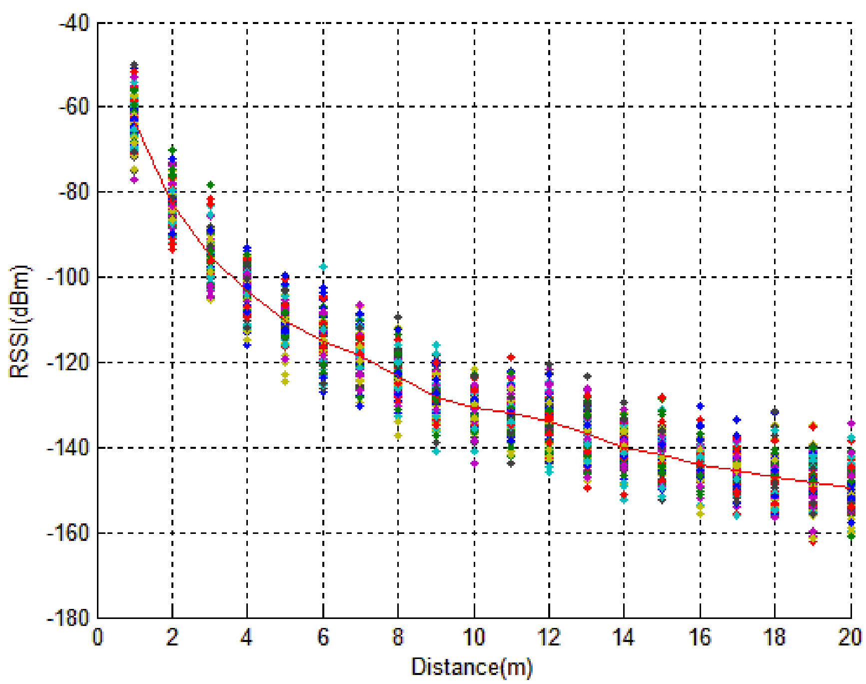


Figure 3.5 RSSI with Fading

The red line in Figure 3.5 is the average RSSI in every location. There are 100 measurements in each location.

## 3.4 Algorithm Detail

In the initial version of our algorithm, the case is simplified by fixing up one robot to be a signal source. The other robot is taking the role of searching the signal source. We call the first robot locator and the other robot source in the following context.

This is a simplification case of rendezvous strategy. If there is only one locator moving, there is no issue of resolving the rendezvous place between locators. The time synchronization is also not existed. In Roy and Dude's paper[15], the agreement on rendezvous place and time synchronization have been researched. When there are two locators, two robots need to agree on the meeting place. Sometimes robot has different individual map. The meeting place determined by one robot may not explored by other robot. The reason for this problem is that robots initially are random walk and stores its own waypoints. It's a typical distributed system. In this system, time synchronization is also a problem needed to be considered on. In our research, we mainly research one locator with multiple sources scenario.

The reason of the simplification is to let us focus more on the locating problems. We want to get a stable location algorithm by starting our research from a basic case to a complicate case in the future. Our problem has been transformed into a typical locator –source case.

### 3.4.1 No Signal Sensed

A robot behaves in explorer mode when there is no signal sensed. In explorer mode, the robot is searching the unknown area by random walk. Meanwhile, it actively checks RSSI in the location and stores corresponding location into its waypoint list. For the sources, they are robots which are transmitting through beacon sensing channels. The maximum transmitting power of the source also guarantees its best signal coverage which facilitates locators to sense its signal. This is the setting when both source and locator are still not formed into a network. Currently, we assume sources are static. Explorers in random walk always check their stored waypoints to choose an unknown location as the next waypoint. When the explorer senses RSSI of new waypoint reaching the threshold value, the explorer switches into the locator mode and further verifies the direction and position based on the RSSI.

In the exploring mode, explorer can also walk in a casting way which proposed by professor Wang in the report[1].Casting is similar to a four- leaf walking way. Comparing to a random walk, it casts into four directions in a certain walk way which shows in Figure 3.6.

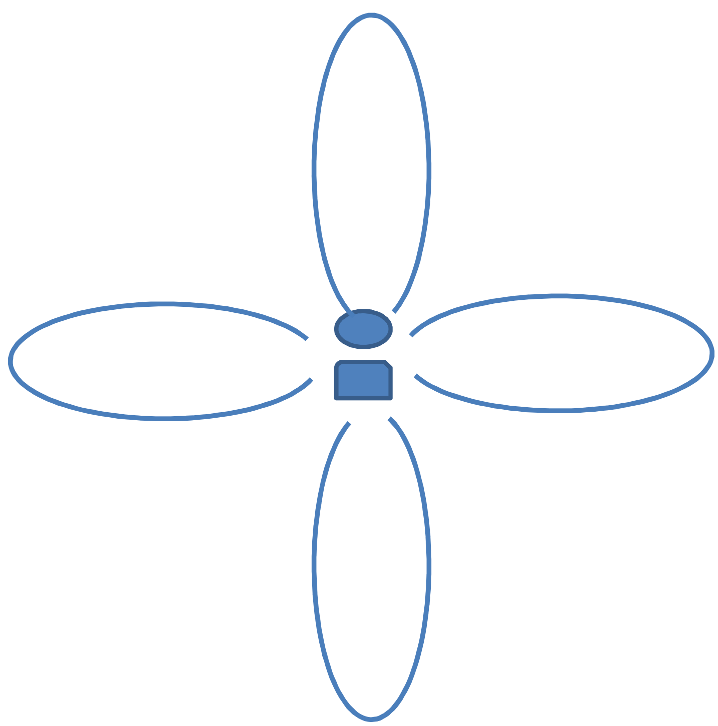

Figure 3.6 Casting Way

### 3.4.2 Sensed Signal in a Perfect RSSI Map

In a locator mode, a robot estimates the signal source distance by calculating RSSI which generated in our log-distance path loss model. However, the robot can only infer the signal source is on the circle whose radius equals to the calculated distance. In other words, the locator does not know the direction of the source. Apparently, it's not enough for a robot to locate the signal source by only referring the distance. The direction of the signal source is also needed to locate the source.

In log-distance path loss model, we can know the RSSI is stronger at the place closer to the source if the fading effect is not considered. However, in real wireless environment fading and shadowing effects cannot be ignored. Here we first consider on the perfect RSSI map which means the fading parameter $X_{\sigma^2}$ in the equation (3-1) equals to 0. Later, we will add this effect.

In a perfect RSSI map, one way for getting direction is utilizing mobility of the robot. The robot can move into four directions and to choose the direction with highest RSSI value. Our team proposed a better way to figure out this without moving the robot. In its configuration, four antennas are equipped on the four corners of a robot. Through the differences of the RSSI on four antennas, the robot can identify the maximum RSSI antenna as the direction of the signal source. The assumption here is the signals strength received at long distance would be lower than the ones received at close distance. Our log-distance path loss model can guarantee the assumption if the fading effects is not considered into the model.

With the determined direction and distance of the signal source, robot can be controlled to move at a given step size towards the source direction. Then it stores the waypoint and senses the RSSI in the new position. This is an iterated process. The robot can move iteratively until its sensed RSSI reaching the threshold we preset. It means the robot already entered into the communication range. In this phase, locator switches into communication mode. It can establish communication since the RSSI is strong enough.

The detailed algorithm is written in Figure 3.7.

```
initialization;
while no signal sensed do
    random walk;
    store the waypoints;
    while signal sensed do
        if sensed signal then
            if RSSI < TH then
                direction ← Max(RSSI(up, down, left, right));
                estDistance = PathlossMode(RSSI);
                Move(direction) at stepSize;
            else
                establish communication with signal source robot;
                break;
            end
        end
    end
end
```

Figure 3.7 Algorithm detail

### 3.4.3 Sensed Signal in a Non-Perfect RSSI Map

As mentioned in previous section, fading and shadowing effects cannot be ignored in our RSSI map. In our research, we need to consider on multipath fading. We mainly consider Rayleigh fading.

Since fading impacts the RSSI maxima values, we need to move the robot at a larger step or to make robot random walk for measuring multiple RSSIs. The measurements of RSSI might have several maximums. Robot can traverse all the possible points and to choose the maximum RSSI as the next location. The method is inspired by the Magnus's paper[16]. In Magnus's paper, the minimum number of measurements has been researched to get a tradeoff between the measurement and motion. The relationship of distance and fading is also researched. One important inspiration is that we can adjust the step size to avoid the deep fading points. The deep fading effect happens almost at every half-length wavelength place of the wireless signal. In our research, we can equip our four antennas separated by at least half of the wavelength of wireless signal. In motion control part, the robot is controlled to move at a step size at least higher than half of the wavelength. Instead of measuring just one location, the robot needs to move multiple places and then go back to the location of highest RSSI as its next waypoint. In simulation part, we will simulate this strategy.

There is another special case needs to be considered in the process of location. The locator can be a deadlock case when it is in the center of multiple sources distributed at symmetric locations. It shows in the Figure 3.8. Locator is in the center while four sources distributed at four corners. In this case, locator sensed the same RSSI in four directions. Even it increase its step size, it can still not sensed the difference among the four RSSI. We proposed a step count for limiting the locating phase. When the step count reaches to the limit, robot switches into explorer mode and random walk to escape the center of symmetric sources.

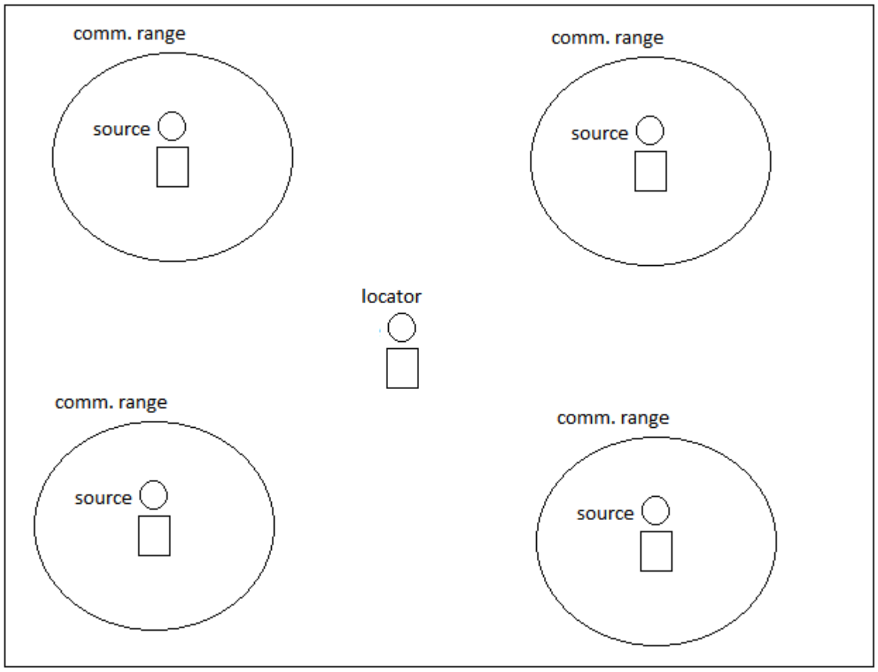


Figure 3.8 Symmetric Case

# Chapter 4 Simulation

Our goal is to find the performance relation among different algorithms, and we also interested in the number of robots and the performance variations.

## 4.1 Configuration

We simulate two robots case in Matlab. In this scenario, one robot is called source which is sending out signals as a signal source. The other one is called locator which is sensing the signal and approaching the signal source. Our environment is a 50*50 ($m^2$) grid map. We assign the source in the center of the grid, the position of (25, 25). The locator is assigned randomly in the map.

We defined a grid map to represent the RSSI of a given signal source in each grid. The RSSI is calculated by equation (3-1) in Chapter 3. The relationship between distance and RSSI can be easily seen from the RSSI plot. Figure 4.1 shows RSSI gradually decrease as the distance from source increasing. In this phase, the wireless fading effects are not considered yet. The greatest height and red color in the center indicate the highest RSSI since source is assigned in the center of the map. This RSSI signal map is the reference for location of source. The locator mainly locates the signal source according to the RSSI in the map.

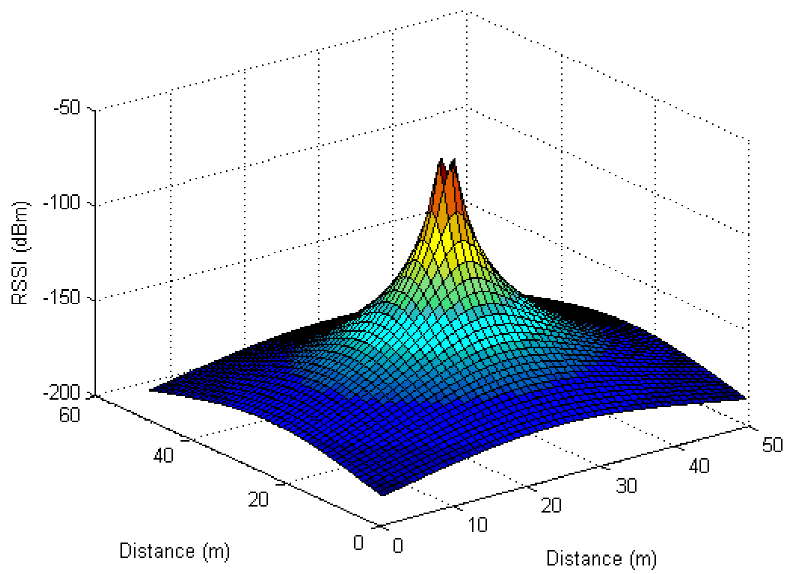


Figure 4.1 RSSI map of single robot (3-D view)

We also show this RSSI map in a 2-D plot in Figure 4.2.

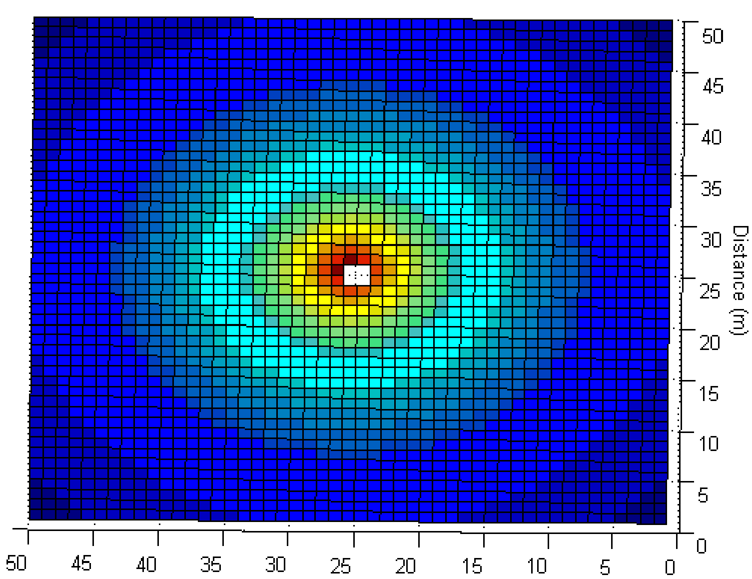


Figure 4.2 RSSI Map of Single Robot (Top View)

Similarly, RSSI values for multiple sources can be a representation of average RSSI from multiple sources. We simulate a five robots case. The plot in Matlab can be seen in the Figure

4.3. The next step is to update RSSI in the whole map with multiple robots moving. While the robots moving, the RSSI updates dynamically.

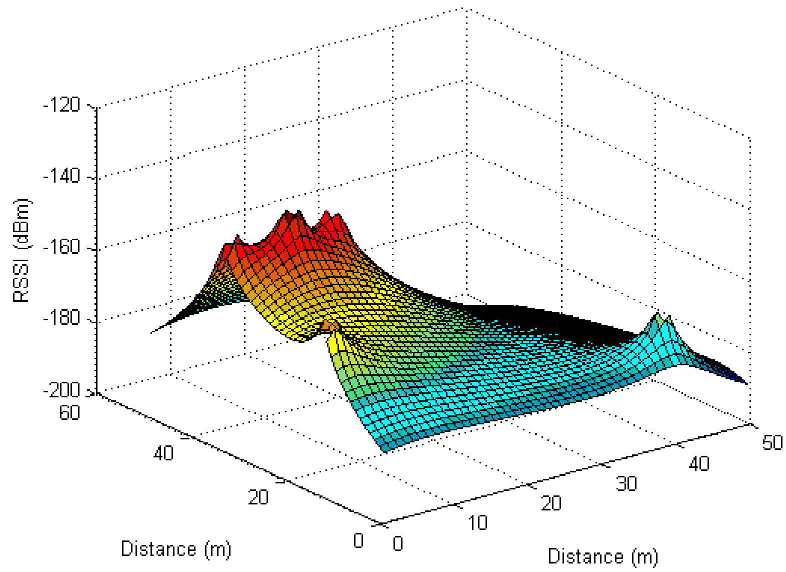


Figure 4.3 RSSI of Five Robots

The top view of the plot shows in Figure 4.4.

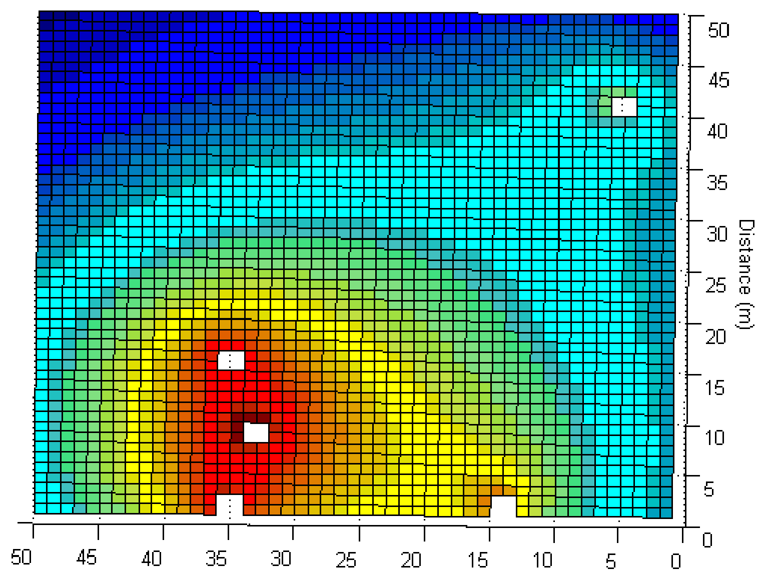


Figure 4.4 Top View of RSSI Map of Five Robots

In real application, Rayleigh fading effect is added into the RSSI calculation. We plot the RSSI map with fading effect in Figure 4.5.

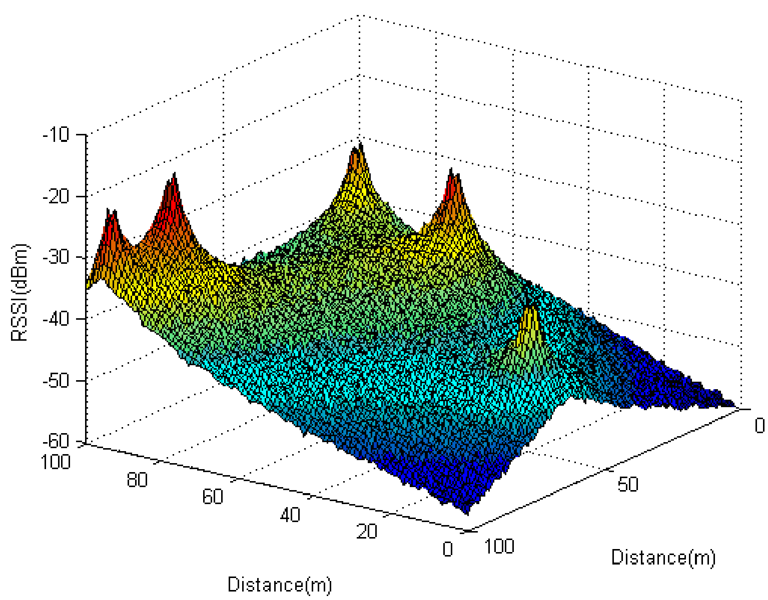


Figure 4.5 RSSI of Five Robots (With Rayleigh Fading)

The top view of the plot shows in Figure 4.6.

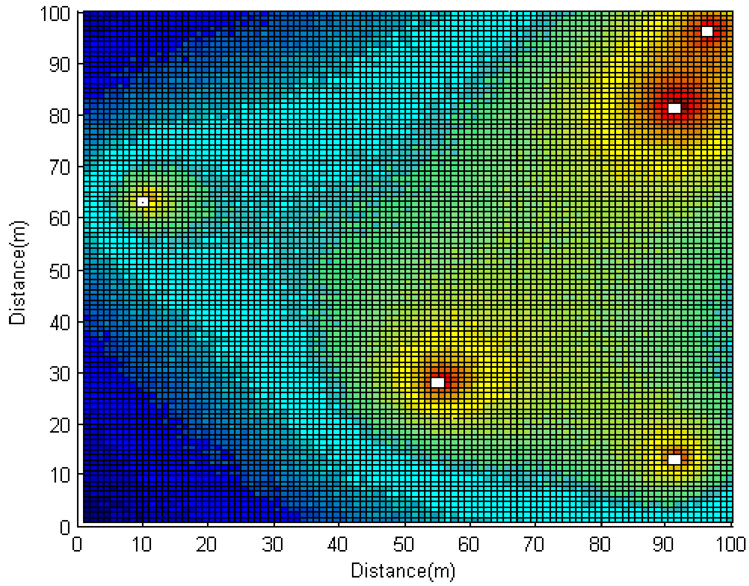


Figure 4.6 Top View of RSSI Map of Five Robots (With Rayleigh Fading)

## 4.2 Simulation Result

### 4.2.1 Locating a Signal Source in a Non-Fading RSSI Map

When the RSSI signal map is built up in the environment, robot can be simulated to locate a signal source. In Figure 4.7, a locating robot picks one of four directions and moves at a fixed step size. It compares the RSSI value in the new location to the one at previous location. If the RSSI is higher, the new location is chosen. The robot moves to the new location and adds new location into its path tree. Path tree which contains the way points of robot moved is a data structure stored in each robot. If the RSSI in the new location is lower than the previous one, robot will go back to the previous position to choose another direction. If RSSI values in four directions are all lower than the one at previous point, it will choose the direction of the greatest RSSI value from those four directions. Robot moves to the new direction at a double increased step size. This iterate steps is set up a maximum steps to prevent from infinite loop.

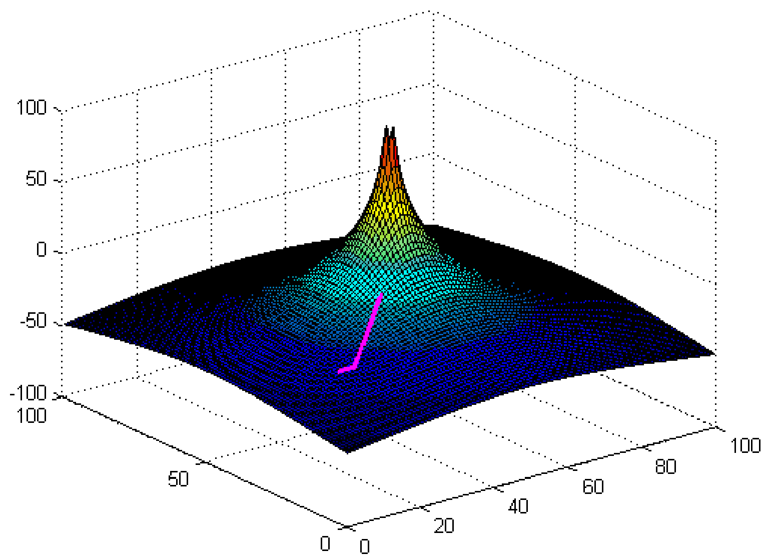


Figure 4.7 Single Source Locating

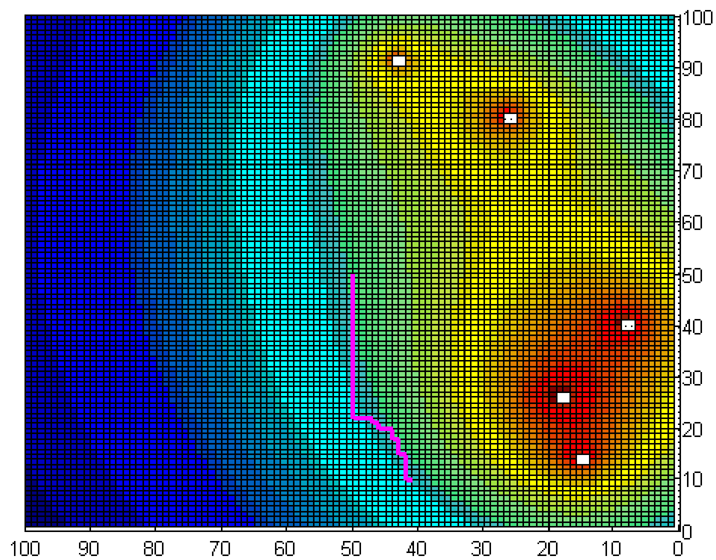


Figure 4.8 Multi-Source Locating in a RSSI Map without Fading

In Figure 4.8 five robots are static signal source which represented as white cells in the RSSI map. The red color indicates the stronger RSSI strength. Locator begins its location at the center (50, 50) of the Map. The result shows locator approaches the three signal sources which have higher average RSSI value than the two signal sources on the upper right side. Locator moves in the gradient ascending direction until its sensed RSSI reaches the threshold. Figure 4.9plots the path without showing the RSSI map.

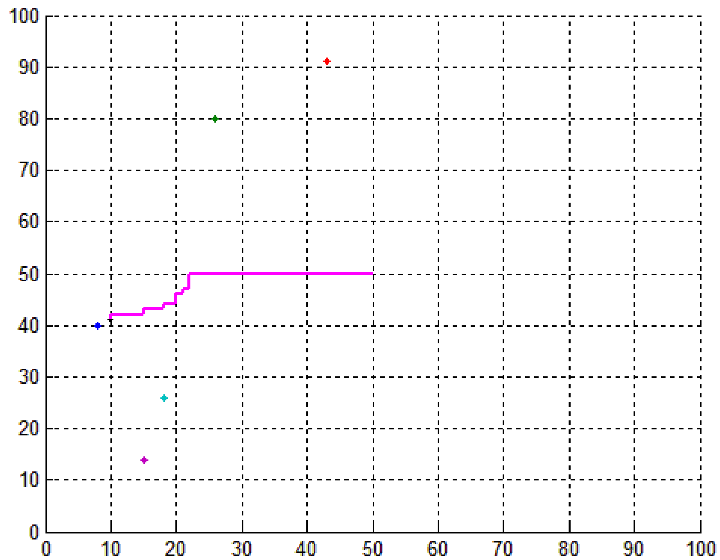


Figure 4.9 Multi-Source Locating in a RSSI Map without Fading (No RSSI Map Representation)

### 4.2.2 Locating a Signal Source in a Fading RSSI Map

In a RSSI map with Rayleigh fading effect, our algorithm makes locator measuring multiple RSSIs by tentatively moving into four different directions. The step size is set to be at least half length of wavelength. In our simulation, the size of map is 500 cm. We found the robot can locate the signal source when the step size is set to higher than 10% map size. We simulated a signal source location case when the step size is step up to 50cm in Figure 4.10. The result shows the robot starts locating at the lower right corner. The source in the center of the map is located by the robot. The locator overcomes the fading effect during the locating source.

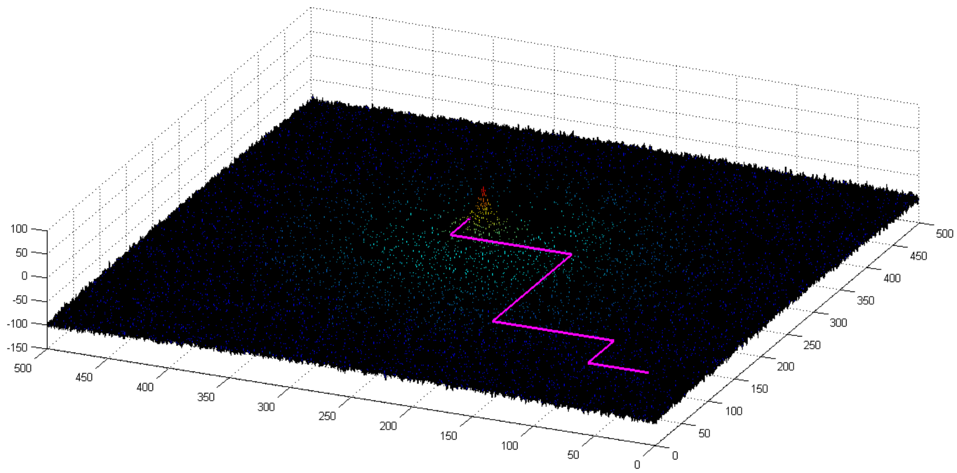


Figure 4.10 Locating a Source in a RSSI Map with Fading

# Chapter 5 Conclusion and Future Work

Simulation results show a good location in a perfect RSSI map based on our algorithm. In the Single source locating case, Figure 4.7 shows the locating robot approached successfully to the signal source in the center. It stops when its RSSI reached communication threshold. In other words, the locator has entered into the communication range of the signal source. In multi-source locating scenario, Figure 4.8 and Figure 4.9 demonstrate locator in the center has moved into the communication range of right three signal source robots. It also meets our model. The reason is the average RSSI is greater than other areas in the map.

The results of location in a RSSI map with fading effect are largely affected by the step size and number of measurements. When the step size set up higher than 10% of map size, the robot can locate the source in a single source location case.

The future work is needed to further research on more fine quantity of step size and number of measurements. It is also possible to utilize other effective way like probabilistic methods, machine learning methods to overcome the location failure introduced by fading effects.

The other thing could be done in the future is to implement real test data to optimize our RSSI mode parameters in order to better fit to our case.

In multi-source locating case, we can iterate the locating process to formulate networks among robots when they establish communication.

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