Detecting the DOA for Robots with Wireless Antennas

Jiejie Wei*, Bumsik Kim† and Zhe Yan†

Department of ECE, Stony Brook University

NY,Stony Brook, 11790

Email: *jiejie.wei@stonybrook.edu, † bumsik.kim@stonybrook.edu‡ zhe.yan@stonybrook.edu

***Abstract*—The technology of robot grows everyday, which leads the need for a good design in their localization. Our project is to develop algorithms and protocols for the localization of sensors and mobile robots. The main problem is to find the direction and distance of the robot. We will use Multiple Signal Classification(MUSIC) algorithm to determine the direction of arrival(DOA) of robots, and we will estimate the distance between each of the robots based on the path loss of our received signal strength. Noise during the signal processing will be considered during our simulation. In our first semester of research, we are going to simulate the random location of robots and test the power received in ideal case.**

I. Introduction

A. Background

There are many robots created to improve quality of our life, one of the robot example is Roomba. Roomba is a series of autonomous robotic vacuum cleaners sold by iRobot. Roomba features a set of basic sensors that enable it perform its tasks. For instance, the Roomba is able to change direction on encountering obstacles, to detect dirty spots on the floor, and to sense steep drops to keep it from falling down stairs. [1]

Fig. 1. Roomba

However, when multiple Roomba robots are used, it is hard for them to avoid collision and communicate with each other, so the AI of robots that can localize themselves can make a great contribution. What's more, we may want to easily find a specific room location even when we are not familiar with the place. We can navigate our outdoor position with GPS, but it is hard for us to know our indoor position with our smart devices. All of these problems lead to the topic on how to implement the localization of our robots.

In terms of localization, our method is to find direction first and measure the distance along with the direction. There are several algorithms of direction of arrival, we choose to use MUSIC algorithm , stands for MUiltiple SIgnal Classification, one of the high resolution subspace DOA algorithms, which gives the estimation of number of signals arrived, hence their direction of arrival. Compare with other algorithm, it is able to estimate frequencies with accuracy higher than one sample, because its estimation function can be evaluated for any frequency. This is a form of superresolution. MUSIC estimates the frequency content of a signal or autocorrelation matrix using an eigenspace method. This method assumes that a signal, $x(n)$, consists of p complex exponentials in the presence of Gaussian white noise. Given an $M \times M$ autocorrelation matrix, $\mathbf{R}_x$, if the eigenvalues are sorted in decreasing order, the eigenvectors corresponding to the p largest eigenvalues (i.e. directions of largest variability) span the signal subspace. The remaining $M - p$ eigenvectors span the orthogonal space, where there is only noise. Note that for $M = p + 1$, MUSIC is identical to Pisarenko harmonic decomposition. The general idea is to use averaging to improve the performance of the Pisarenko estimator. The equation of MUSIC will be described later. Figure 1 shows the MUSIC algorithm. [2] [3]

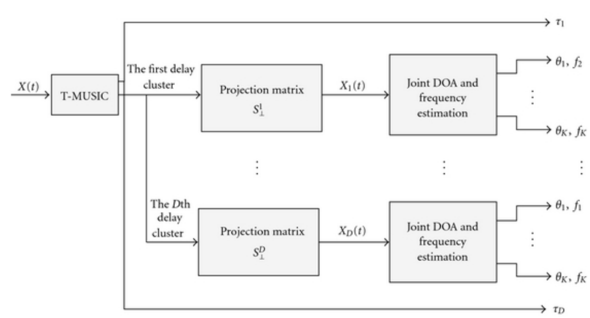

Fig. 2. MUSIC algorithm chart

After the procedure of DOA, we will estimate distance based on path loss with noise of Rayleigh fading and Gaussian white noise. Path loss is the reduction in power density of an electromagnetic wave as it propagates through space.

This term is commonly used in wireless communications and signal propagation. Although path loss may be due to many effects, such as free-space loss, refraction, diffraction, reflection, aperture-medium coupling loss, and absorption, we decide to use simple version of pass loss equation without considering so many effects, which is commonly used and called free space propagation. The simplified equation will be described later. Figure 2 shows the characteristics of wireless channel related to path loss vs. distance. [4] [5]

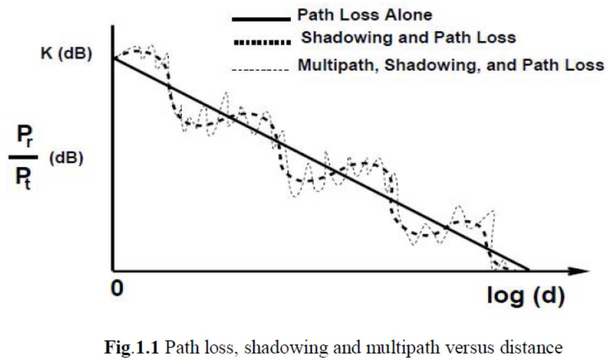

Fig. 3. Path loss vs. distance

In terms of noise simulation, we decide to use the effect of Rayleigh fading,a statistical model for the effect of a propagation environment on a radio signal, such as that used by wireless devices. Rayleigh fading models assume that the magnitude of a signal that has passed through such a transmission medium (also called a communications channel) will vary randomly, or fade, according to a Rayleigh distribution the radial component of the sum of two uncorrelated Gaussian random variables. Rayleigh fading is most applicable when there is no dominant propagation along a line of sight between the transmitter and receiver. In addition to Rayleigh fading noise, we also add Gaussian white noise, which is also known as normal distribution white noise. It is very commonly used in signal processing because of the central limit theorem, it states that averages of random variables independently drawn from independent distributions converge in distribution to the normal, that is, become normally distributed when the number of random variables is sufficiently large. A random variable with a Gaussian distribution is said to be normally distributed and is called a normal deviate if mean of the distribution is 0 and its standard deviation is 1. [6] [7] [8]

B. Related Work

Daniel B. Faria, published a report, ”Modeling Signal Attenuation in IEEE 802.11 Wireless LANs”, presented experimental data that validates the use of the log-distance model both inside and outside a standard office building. In his project, path loss models are used to approximate signal attenuation as a function of the distance between transmitters and receivers, being an important building block for both research and industry efforts. Based on experiments with

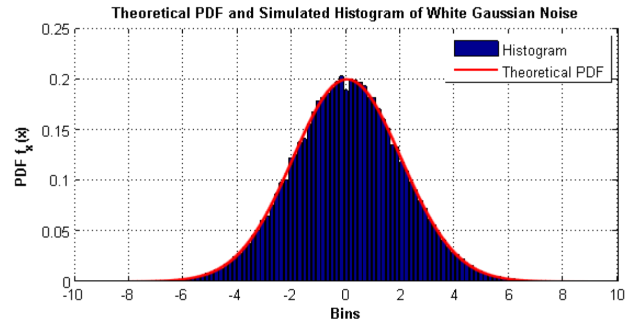

Fig. 4. Distribution of White Noise

off-the-shelf 802.11 hardware, they had shown that the log-distance path loss model with log-normal shadowing can be used to estimate signal attenuation both inside and outside an office building with moderate accuracy. As a result, we will not consider the environment effect of indoor and outdoor in our project. [9]

R.C. Smith and P. Cheeseman in 1986, and the research group of Hugh F. Durrant-Whyte in the early 1990s, proposed an algorithm called simultaneous localization and mapping (SLAM),which is the computational problem of constructing or updating a map of an unknown environment while simultaneously keeping track of an agent’s location within it. [10]

Leonard, J.J. and Durrant-Whyte, H.F., proposed a report of mobile robot localization by tracking geometric beacons in 1991. The algorithm is based on an extended Kalman filter that utilizes matches between observed geometric beacons and an a priori map of beacon locations. Two implementations of this navigation algorithm, both of which use sonar, are described. The first implementation uses a simple vehicle with point kinematics equipped with a single rotating sonar. The second implementation uses a ‘Robuter’ mobile robot and six static sonar transducers to provide localization information while the vehicle moves at typical speeds of 30 cm/s. [11]

II. Overview

Signal will fade during the transmitting and power will somewhat loss no matter what kind of transmitter be used. As a result, we can estimate the distance between the receiver and transmitter if we know the properties of the wireless signal. Meanwhile, the phase of signal will shift when receiver get a signal, which related to their direction of arrival. In this case, out project decide to use the MUSIC algorithm and path loss to estimate direction and distance between multiple robots.

Due to the interaction of noise, one of the biggest challenge is to recover the original signal with considering white noise and Rayleigh fading noise. To easily understand the effect of these noise, the following figures are the simulation of some common signals when addictive noise is applied. Figure 4 is a sine wave without applying any noise

Figure 5 is normal Rayleigh fading noise.

When we apply this noise to sine wave, the signal will look

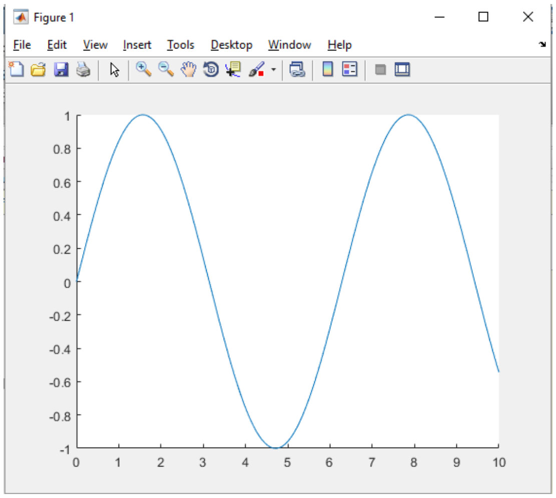

Fig. 5. sin waveform

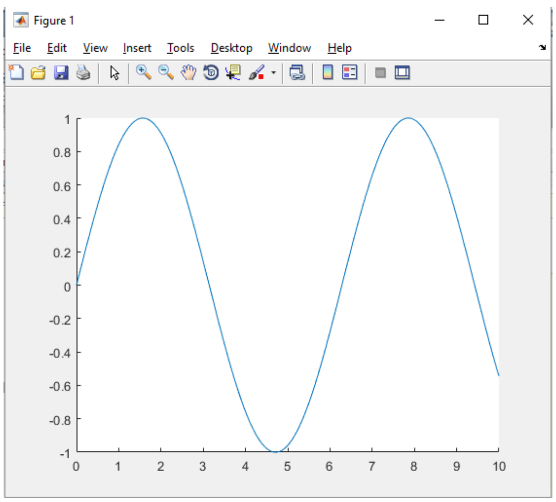

Fig. 6. sin waveform

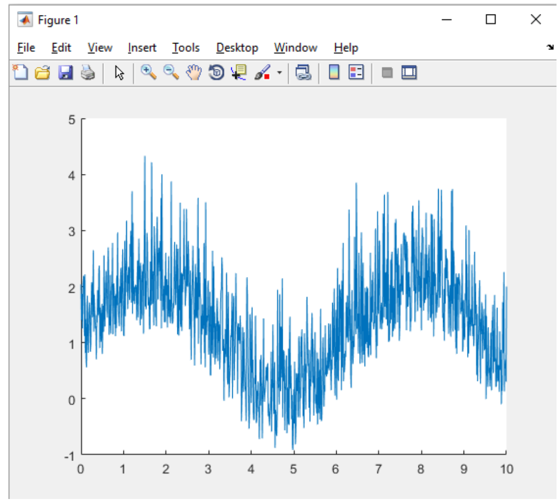

Fig. 7. sin waveform added with Rayleigh fading noise

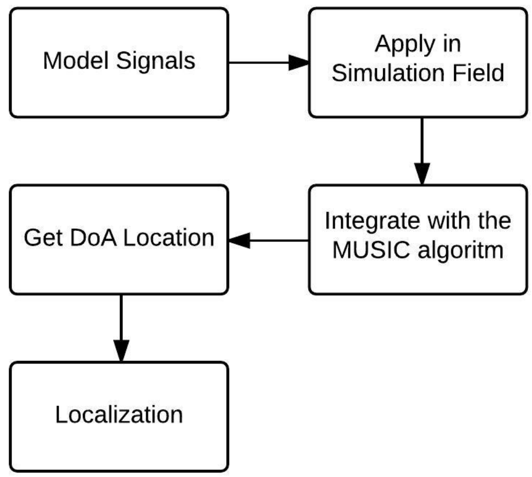

Fig. 8. Simulation Procedure

like figure 6. Rayleigh fading noise is much larger than white noise.

To simulate our signal processing, we are going to use Matlab to model signals and apply them in simulation field, then we will integrate them with MUSIC algorithm and finally get DOA location, which will be described in detail later.

III. Methodology

A. Simulation Procedure

We introduce the overall simulation procedure to achieve our goal. The basic idea of the simulation is to verify and visualize the theories we use. We firstly set signal models to be used to measure waveform and signal strength. Path Loss, Gaussian white noise and Rayleigh fading are used in this step. Secondly, we design a model of robots that has a transmitter and receivers, and simulation field where the robots are placed and our algorithm are applied. Then we apply MUSIC algorithm to estimate the DoA.

In the simulation is designed to see locations of robots and estimated distance by signal strength measured by robot's receivers. The location of the robots and some ranges from the robot are marked. The simulation assumes that field is a 2-D space that ranges 1000 meters by 1000 meters. The robots consist of a transmitter and four receivers with a interval of 0.6 meters. The marked range from robots are 200 meters and 100 meters and 20 meters representing the sensory range and the communication range, the rejection range respectively.

The simulation is written in MATLAB. The simulation consists of five files:

- simulation.m
- Robot.m
- Tranceiver.m
- simulation.m
- getSignalStrength.m
- drawCircle.m.

The drawCircle.m is used to draw circles on the simulation

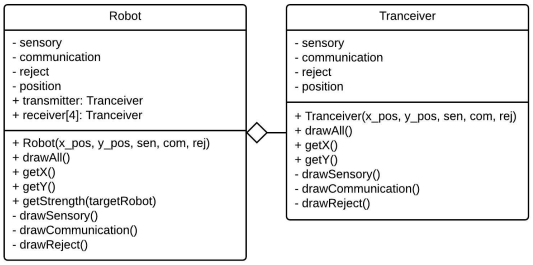

Fig. 9. Class Diagram of the simulation

field to visualize the ranges of robots.

The getSignalStrength.m defines our signal model and accepts a distance value as an argument then returns a value of signal Strength. The model of signal will be discussed later.

Tranceiver.m defines the model of the signal transmitter and receiver using class. This class has four kinds of class member: sensory, communication, reject, and position. The class member sensory, communication, and reject are floating points in meters, representing those name of range. The class member position represents four antennas location of a robot.

Robot.m defines the class of the robot that has five instances of Tranceiver class:one is for transmitter and the other four is for receiver. This class has a method getStrength() that takes another instance of Robot and calculate signal strength between two robots.

Fig. 10. Roomba

B. Signal Modelling

In our signal modelling, we need to test the proper value of SNR, Rayleigh factor for our simulation. According to our test, the maximum proper value of Rayleigh factor is 0.0007 with 90% (18 out of 20 cases) of success. A success means that all differences of every robot's true DOA and noised DOA are less than 45 degrees. Other values larger than 0.001 will decrease the success probability. This value can be lager as

		Transmmiter Robot			
		Robot1	Robot2	Robot3	Robot4
Receiver Robot	Robot1	0	222.1875	23.9063	284.0625
	Robot2	56.2500	0	56.2500	57.6563
	Robot3	201.0938	305.1563	0	278.4375
	Robot4	146.2500	220.7813	81.5625	0
	Robot5	1.4062	286.8750	2.8125	333.2812
	Robot6	46.4062	257.3438	36.5625	341.7188
	Robot7	95.6250	250.3125	87.1875	30.9375
	Robot8	81.5625	33.7500	66.0938	64.6875
		Robot5	Robot6	Robot7	Robot8
	Robot1	182.8125	234.8438	220.7813	229.2188
	Robot2	113.9062	102.6563	73.1250	187.0312
	Robot3	165.9375	227.8125	202.5000	255.9375
	Robot4	106.8750	135.0000	229.2188	210.9375
	Robot5	0	329.0625	302.3438	284.0625
	Robot6	135.0000	0	347.3437	282.6563
	Robot7	130.7813	32.3437	0	188.4375
	Robot8	85.7813	108.2812	12.6563	0

TABLE I

NUMBERS ARE DOA REPRESENTED IN DEGREES. 0 MEANS ROBOT IS RECEIVING ITS OWN SIGNAL.

0.0010 if we apply a low-pass filtered function to the signal. However, it will slow down our test speed, so we decide to use not filtered version of code as speed and cost trade-off. The minimum acceptable SNR is 34 with 90%(18 out of 20 cases) success. SNR stands for signal noise ratio which will be explained later.

When we apply pmusic function to get DOA of each receiver robot from its transmitter robot, we can have the following table as reference:

C. Formula

The equation of path loss is:

$$L(d) = 10 * n * log_{10} d + C \tag{1}$$

where L is the path loss in decibels, n is the path loss exponent, d is the distance between the transmitter and the receiver, usually measured in meters, and C is a constant which accounts for system losses.

In our model, we use a reference distance and signal strength to get the signal strength:

$$p_L(d) = L(d_0) - 20log_{10}(d/d_0) \tag{2}$$

where d_0 is the reference distance of an antenna, $L(d_0)$ is the signal strength at d_0. The value of d_0 and $L(d_0)$ depends on characteristic of an antenna.

The Gaussian White Noise has the probability density function p_G of a normal distribution with random variable x in our case is:

$$p_G(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{x^2}{2\sigma}} \tag{3}$$

where σ the standard deviation. The standard deviation in our model depends on performance of antenna, which can be represented as Signal-to-Noise Ratio (SNR).

The Rayleigh fading is the effect when there are objects like wall in the field that scatter the radio signal. The Rayleigh fading has a model with Rayleigh distributed probability density function, that is:

$$p_R(r) = \frac{2r}{\Omega} e^{-r^2/\Omega},\ r \geq 0 \tag{4}$$

where R is random variable, and Ω is the mean value of square of r: $\Omega = E(R^2)$.

To sum up, the received signal strength of the receiver antenna is:

$$p(d) = p_L(d) + p_G(x) + p_R(r) \tag{5}$$

where $L(d)$ is the path loss, $p_G(x)$ is the Gaussian White Noise, and $p_R(r)$ is the Rayleigh fading.

If $\mathbf{v}_i$ are the noise eigenvectors and

$$\mathbf{e} = \begin{bmatrix} 1 & e^{j\omega} & e^{j2\omega} & \cdots & e^{j(M-1)\omega} \end{bmatrix}^T. \tag{6}$$

Then the frequency estimation function for MUSIC is:

$$\hat{P}_{MU}(e^{j\omega}) = \frac{1}{\sum_{i=p+1}^{M} |\mathbf{e}^H \mathbf{v}_i|^2}, \tag{7}$$

Spectral density estimation is to estimate the spectral density

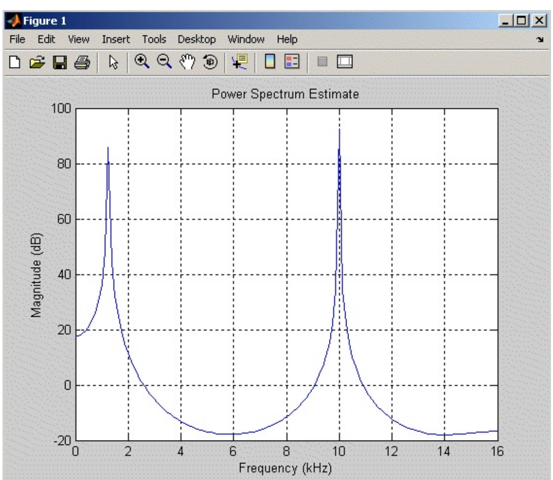

Fig. 11. Power Spectrum Using MUSIC

of a random signal from a sequence of time samples of the signal. In our case, the maximum value of $hatP_{MU}$ converted to degrees is the DOA of robots.

IV. Evaluation

We conduct a simulation using the procedure described above. We put four robots in the simulation field and draw three range, representing the sensory range, communication range, and rejection range, for each robots. We draw straight lines between robots with the average signal strength of four antenna of robots between them instead of the signal strength of each robots for a better visualization. In this simulation we assumed following:

- The frequency of the transceiver is at 2.4 Gigahertz range.
- Each robots is using different frequency channel so that each signal cannot interfere another.
- The reference distance of the transceiver is 1.8 meters and the receiving power at the reference distance is -27.25 decibel. The standard deviation of the Gaussian white noise is 1, since we do not know the real antenna's Signal-to-Noise Ratio.
- The sensory range, the communication range, and the rejection range are 200 meters, 100 meters, and 100 meters respectively.

The example results of the simulation are the following figures: figure 9 and figure 10. Figure 10 shows the signal strength against distance to visualize the relationship between signal strength and distance. Asides from the effect of the White Gaussian Noise and the Fading, it shows that it has a logarithmic relationship. Figure 9 shows four simulation results that the four robots are randomly placed and the average signal strength are measured accordingly. The simulation result in figure 9 shows that the measured average signal strength are measured differently with distance. It also shows that the robots around the communication range has signal strength around -60db, and the robots within the sensory range have signal strength of more than -70db, whereas the signal strength between two robots outside of the sensory range is measured less than -70db.

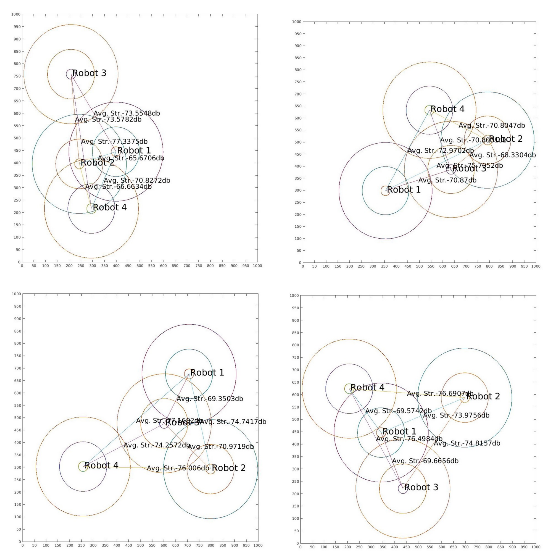

Fig. 12. Four sample simulations

To have better understanding of DOA pmuisc function, we implement angle_ gui.m file to show the simple version of the MUSIC algorithm. Since every robot has four antennas, the receiving signal will be a $1 * 4$ matrix of four signal strength from these antennas. We obtain DOA by applying

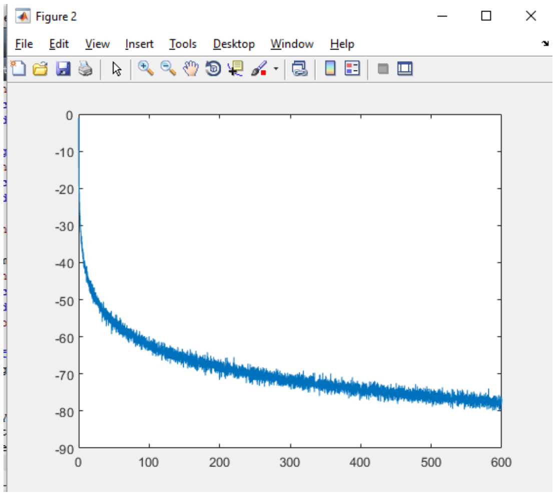

Fig. 13. Power vs. Distance

pmuisc function to the signal matrix.

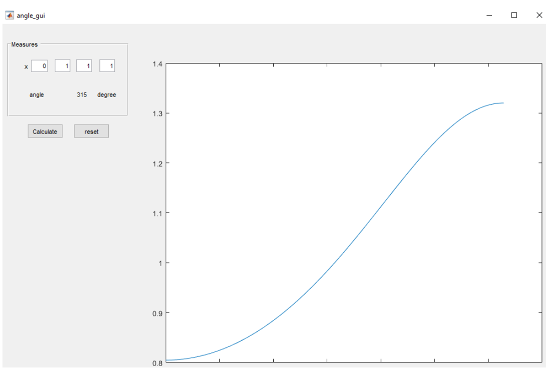

Fig. 14. Four sample simulations

When robots are gathering together within their communication range, we can evaluate the coverage area of the robot network system. The ideal maximum range is when each robot's center is located on the edge of other robot's communication range with the first three leading robots forms triangle group like the following graph.

The area of ideal case is 1.6058e+05 square meters over 1000*1000 square meters moving area. However, the simulation coverage area is always smaller than ideal area. The following graph is one of the example of simulation. Eight robots are gathering together and the right graph is their topology graph. We calculate the area of simulation area by the number of random points located in coverage area over total number of points in moving area times the moving area. To get accurate coverage area, we apply 1000 million random points. The result is 1.5883e+05 square meters. So the coverage difference between ideal and simulation is 1.09 %.

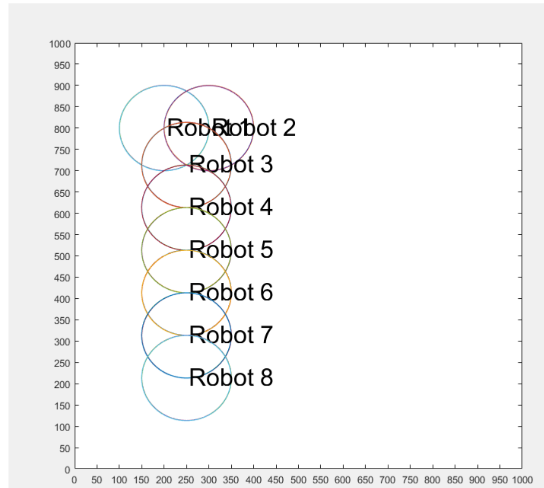

Fig. 15. Ideal coverage

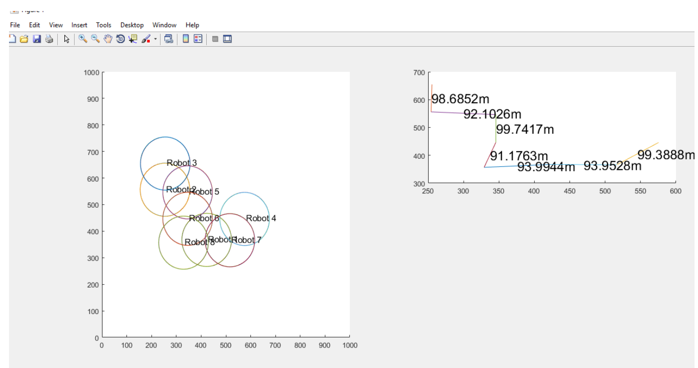

Fig. 16. Simulation sample

V. Conclusion

According to our simulation result, we can see that due to the small distance between four antennas in one robots, we can only see the three range circle for each robot instead of 12, which make sense since this indicates that the distance of four antennas will not effect our distance measurement much.

In terms of power vs. distance result, we can see that when distance is greater than about 380-600 meters, the signal strength will be less than -75db, which is the medium quality of signal. As a result, we can conclude that in our case, the largest range that can be acceptable is approximately 450 meters, and we will get high quality signal when it is greater than -55db, which means robot can get good quality about ninety percent within 50 meters of a transmitter.

We will also have a better understanding why the noise is a big challenge in our project, since received signal with noise gives us a signal strength with big tolerance, for example, it's about 220 meters tolerance when calculating medium quality range, which will cause a big difference when evaluating the location.

The future plan is to be more proficient using MUSIC algorithm and enhance our methodology of distance calculating.

As we can see, the current simulation indicates we will have a big tolerance of distance.

REFERENCES

[1] Wikipedia. Roomba — Wikipedia, the free encyclopedia. http://en.wikipedia.org/w/index.php?title=Roomba&oldid=712743018, 2016. [Online; accessed 08-April-2016].

[2] Wikipedia. Multiple signal classification — wikipedia, the free encyclopedia, 2015. [Online; accessed 17-December-2015].

[3] Channel parameter estimation for scatter cluster model using modified music algorithm : Figure 1.

[4] Magy Elsayed. Wireless communications.

[5] Wikipedia. Path loss — wikipedia, the free encyclopedia, 2015. [Online; accessed 17-December-2015].

[6] Wikipedia. Rayleigh fading — wikipedia, the free encyclopedia, 2015. [Online; accessed 17-December-2015].

[7] Wikipedia. Normal distribution — wikipedia, the free encyclopedia, 2015. [Online; accessed 17-December-2015].

[8] Simulation and analysis of white noise in matlab, 2013.

[9] Daniel B Faria et al. Modeling signal attenuation in ieee 802.11 wireless lans-vol. 1. *Computer Science Department, Stanford University*, 1, 2005.

[10] Wikipedia. Simultaneous localization and mapping — wikipedia, the free encyclopedia, 2015. [Online; accessed 17-December-2015].

[11] J.J. Leonard and H.F. Durrant-Whyte. Mobile robot localization by tracking geometric beacons. *Robotics and Automation, IEEE Transactions on*, 7(3):376–382, Jun 1991.