GRADUATE SCHOOL OF SCIENCE AND ENGINEERING

COMPARISON AND ANALYSIS OF VARIOUS INDOOR POSITIONING SYSTEMS TECHNIQUES

GRADUATE THESIS

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"I, DERYA DEMİRKOL, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis."

DERYA DEMİRKOL

ABSTRACT

COMPARISON AND ANALYSIS OF VARIOUS INDOOR POSITIONING SYSTEMS TECHNIQUES

DERYA DEMİRKOL

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Indoor Positioning has been a research subject in order to facilitate people life easier. Different type of methods has been implemented and tested by the years.

The Global Positioning System (GPS) is a satellite based navigation system. This technique is using outdoor environment to navigate people or buildings. In indoor positioning, GPS signals are usually too weak to provide accurate positioning estimate. Other technique need to investigate to get better result of accuracy. Ultrasonic Positioning Systems, RFID, Computer Vision System, RF, Wireless Indoor Positioning System has been used. Recent year, Wireless Indoor Positioning Technique is most popular technique. It is easier to set up every indoor environment by using Access Points (AP) and costs are very low comparing to other techniques. Also Wireless technique does not need any extra component or effort.

In this thesis, Indoor Positioning techniques were investigated. Different algorithms were implemented to estimate location in indoor areas and accuracy comparison has been made by using Wireless technology.

Keywords: Indoor Positioning Systems, Triangulation, Maximum Likelihood, Fuzzy Logic, Localization

ÖZET

ÇEŞİTLİ KAPALI MEKAN KONUMLANDIRMA SİSTEM TEKNİKLERİNİN ANALİZİ VE KARŞILAŞTIRILMASI

DERYA DEMİRKOL

Bilgisayar Mühendisliği, Yüksek Lisans

Danışman: Yard. Doç. Dr. Tamer DAĞ

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Mayıs, 2016

Kapalı mekan konumlandırma sistemleri, insanların hayatını kolaylaştırmak için araştırma konusu olmuştur. Seneler içinde ,çeşitli methodlar uygulanmış ve test edilmiştir.

Kürsel Konumlandırma Sistemi (KKS) uydu konumlandırması kullanılarak gerçekleştirilen navigasyon tekniğidir. Bu teknik dış mekanlarda insanların veya binaların konumlarının bulunmasında kullanılmaktadır. İç mekan konumlandırılmasında KSS sinyalleri çok zayıf kaldığından doğru konumlandırma yapamamaktadır. Kullanılan diğer teknikler üzerinde çalışmalar yaparak daha doğru konumlandırma tahmini yapılmaya çalışmaktadır. Ultrasonik Konumlandırma Sistemleri, RFID, Bilgisayar Görsellik Sistemi, RF, Kablosuz Kapalı Konumlandırma Sistemleri kullanılmıştır.

Son yıllarda Kablosuz Kapalı Konumlamdırma Tekniği en popüler tekniklerden biri olmuştur. Her türlü kapalı ortama modem kullanılarak kolaylıkla kurulabilmesi, onu diğer tekniklerden daha az masraflı olmasını sağlamıştır. Ayrıca bu teknik sinyal kullanarak ileştişim sağladığından fazladan bileşen veya çabaya gerek duymamaktadır.

Bu tezde, Kapalı Konumlandırma teknikleri araştırlmıştır. Farklı algoritmalar uygulanarak kapalı ortamlarda konum tahmini yapılmaya çalışılmış ve bu algoritmalar arasında hassasiyet karşılaştırılması yapılmıştır.

Anahtar Kelimeler: Kapalı Konumlandırma Sistemleri, Üçgenleme, Maksimum Olabilirlik, Bulanık Mantık, Konumlandırma

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Foremost, I indebted to thank my supervisor, Asst. Prof. Tamer Dağ and Asst. Prof. Taner Arsan, for the continuous support of my M.S. study and research, for their patience, motivation, enthusiasm, expertise and immense knowledge.

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List of Abbreviations

IPS	Indoor Positioning System
LBS	Location Based Service
PDA	Personal Digital Assistant
RSSI	Received Signal Strength Indication
GPS	Global Positioning System
LOS	Line of Sight
UWB	Ultra Wide Band
RF	Radio Frequency
WLAN	Wireless Local Area Network
AP	Access Point
RLTS	Real Time Locating Systems
RFID	Radio Frequency Identification
TOA	Time of Arrival
TOF	Time of Flight
AOA	Angle of Arrival
TDOA	Time Difference of Arrival
MLE	Maximum Likelihood Algorithm
MMSE	Minimum Mean Square Error
FLIPS	Fuzzy Logic Indoor Positioning System

CHAPTER 1

Introduction

1.1 Background and Motivation

Nowadays, Location based services (LBSs) are very important for people's life. People need to know things (people, buildings, objects etc.) physically location. [1]

Indoor location awareness is important for such fields as ambient intelligence, assisted daily life, behavior analysis, social interaction studies, and myriads of other context-aware applications. [2] In new report of IDTechEx Research has exposed that Indoor Positioning Systems (IPS) and real time locating systems usage are increasing rapidly with years. Research shows that IPS technologies will be highly important in people's life. According to IDTechEx,

> "The subjects are converging with Apple, Samsung, Google, Nokia, Microsoft, Hewlett Packard and IBM clashing for the tens of billions of dollars of business that is emerging. Emergency services, healthcare, retailing, manufacturing, logistics, and many other industries will be transformed by what is becoming possible" Figure 1.1 [3].

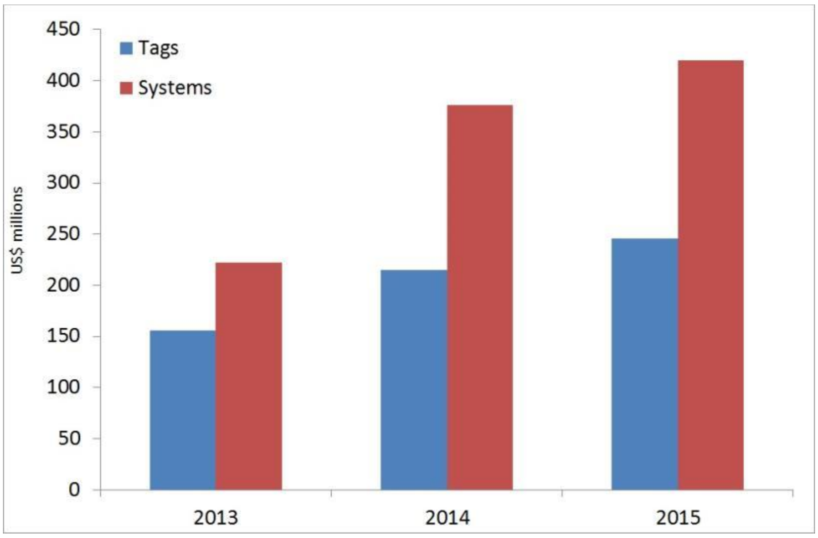


Figure 1.1 Forecast of global RLTS market by value $US millions [3]

Also IDTechEx claims that $10 billion addressable market waits for RLTS.

"Whereas IPS is only now starting to be widely deployed commercially, Hewlett Packard is servicing and RLTS order for $543 million from the US veterans' hospital group with IBM the unsuccessful bidder. This order was 100 times the size of previous record for RLTS. Indeed, IDTechEx forecasts $4.8 billion in RTLS sales worldwide in 2024". Figure 1.2 [4]

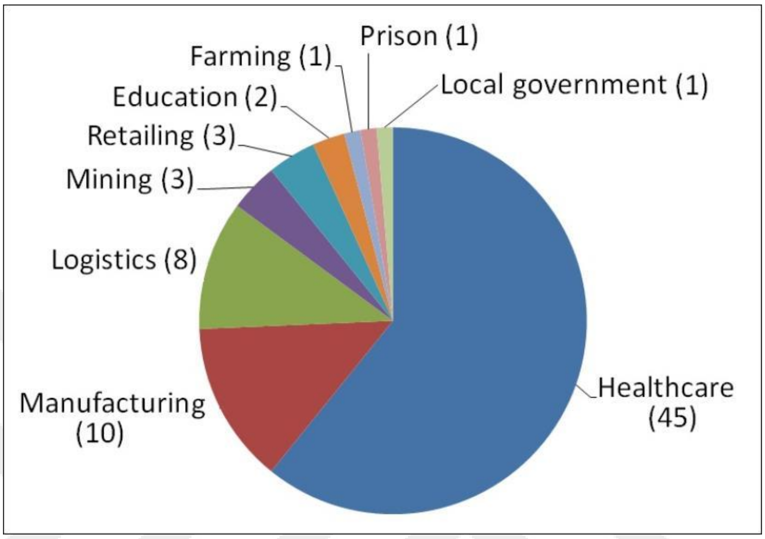


Figure 1.2 Survey of 74 case studies of RLTS by application [4]

Research are shown us [3, 4] there are lots of example that those indoor positioning systems that can be used in daily life. For example, people want to navigate places in public buildings such as hospitals, libraries, shopping malls. Those buildings can be complicated to your way. It would be really helpful to show people how to go their destination through a system. In shopping mall while people stroll through shops, a system estimate people location which they are close store and send advertisement to mobile phone about brand [Figure 1.3]. In Figure 1.3, X, Y, Z is representing people and line is showing which shop they are closes. Let X is closes to Shop 1; IPS system will estimate X location and system will send advertisement about Shop 1. Also X can easily find where Shop 4 is.

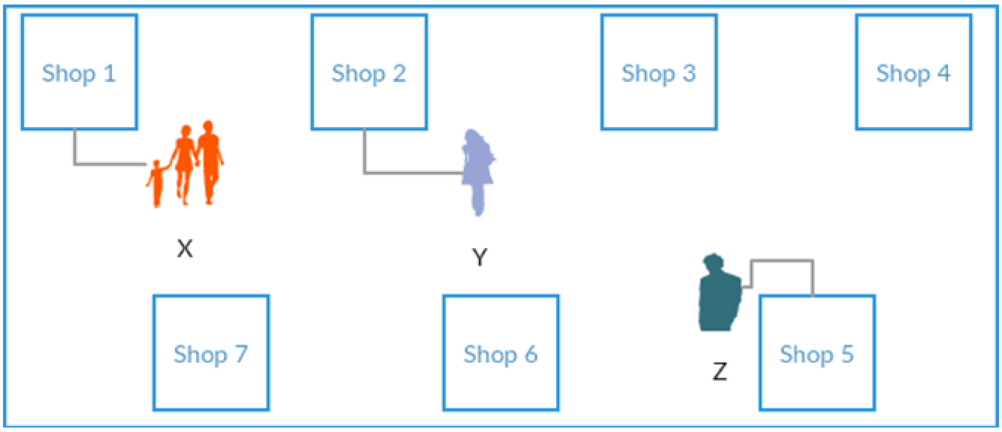


Figure 1.3 IPS model in Shopping Mall

In order to estimate people location, many techniques have been investigated. GPS is most widely-used tracking technology in the world. GPS technology is using received signal strengths from multiple satellites and uses triangulation algorithm to find location of object [Figure 1.4]. At least three satellites required for implementing triangulation algorithm. In next chapters we are going to explore triangulation method. Object locations can be determined within 1-5 meters with GPS technique. However High Sensitive GPS technique has been implemented to estimate location in indoor environments. GPS is working with line-of-sight (LOS). In indoor environments, there is no direct line from the satellites. Also buildings reflections, diffractions and scatterings are decreasing accuracy of estimations. [5]

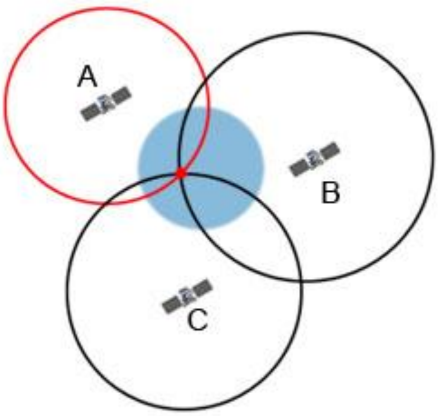


Figure 1.4 GPS Working Principle [6]

In this thesis, we are using RSSI measurement in indoor positioning. We are implemented some Indoor Positioning methods Triangulation Method, Maximum Likelihood Method, Fuzzy Logic Method, Multiple Linear Regression, we are going to compare their accuracy based on estimation.

1.2 Existing Indoor Positioning Systems

In this section, Existing Indoor Positioning System briefly introduced.

1.2.1 Infrared Positioning Systems

Active badges are the first indoor positioning systems developed by AT&T Cambridge. Every person wears miniature beacon that emit RF tag. Each location in a building has IR sensor which detect these transmissions. A central database collecting data from IR sensors, since each user wears RF tag, location of user can be determined. This technique can be used with short range communications. Moreover infrared technique needed LOS between transmitter and receiver. Since indoor environment has multiple obstacles such as walls, windows, people and so on. Thus, this technique has low accuracy. [5, 8]

1.2.2 Ultrasonic Positioning Systems

1.2.2.1 Active Bats

AT&T Cambridge developed ultrasonic tracking technology named Active Bats; it's getting better accuracy Active Badges. Basic principle is that triangulation algorithm. In Bat systems, user wears small badges which emit an ultrasonic pulse from the receiver. System is measuring time-of-flight pulse from receiver to known point of ceiling.

Also speed of sound in air is known and distance between Bats to each receiver can be calculated. System has enough information to calculate 3D positioning of Bat. [9] Figure 1.5. System will estimate location approximately 3 cm. [9]

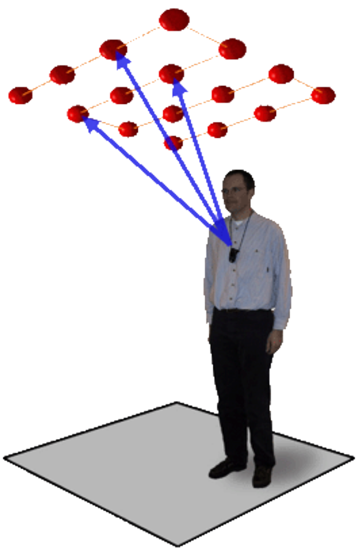


Figure 1.5 Active Bat System [9]

Problem is Active Bat System is that during implementation lots of receivers are required. Also receivers' placement of ceiling needed sensitive alignment. Thus, active bat positioning systems are hard to implement. [5]

1.2.2.2 Crickets

The Cricket technology developed with MIT's Project Oxygen. Crickets Figure [1.6] uses combination of RF and ultrasound technologies to estimate location. In a cricket unit there are both receiver and transmitter application. Devices called *listener*, carried by mobile users, receives RF signals from beacons (transmitters), estimate distance for corresponding beacon by RF (speed of light), ultrasound (speed of sound). The listeners run algorithms that which is best correlation [11].

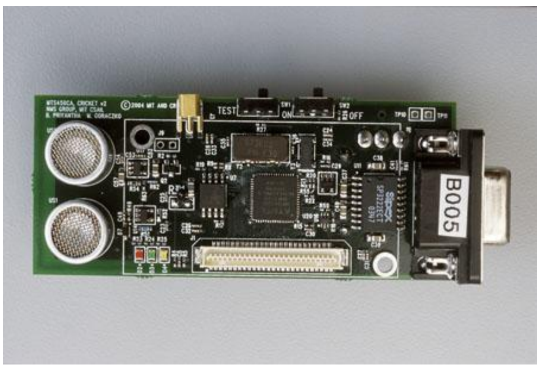


Figure 1.6 Cricket Unit Sensor [11]

According to [5], accuracy of 3D positioning is 1-2 cm in a 10 m3 environment. However, this system is required additional equipment and sensitive transmitter localization. It will be hard and can be high cost to implement when people want to use this method in shopping mall.

1.2.3 RSSI Positioning Systems

1.2.3.1 Radio Frequency Identification Technology

RFID technology is an automatic identification technology that uses radio signals to track, estimate objects like peoples, devices, and vehicle. Object has RFID tag which is identified with RFID reader. These tags are unique ID numbers, and it can be consist of location information of RFID tag.

RFID tags divided into two categories: active and passive. Passive tags do not have battery, so it's smaller and cheaper compared to active tags. When passive tags read by reader, the tags have enough power so tags able to transmit its reply. Passive tags can be used like a traditional barcode technology. However, reading range is limited. [12]. On the other hand, active tags has its own battery and it has more range than passive tags. But this is increase price and size of tag.

RFID technology has lower cost than Ultrasonic Positioning Systems. It is more common technology in IPS systems. Since active tags have more range, it is using more commonly. In LANDMARC [12] and SpotON [13] technology RFID and RSSI technology are used together to get higher accuracy. This is example of integrated IPS systems.

1.2.3.2 Ultra Wide Band (UWB) Technology

Ultra-wide Band technology (UWB) is using very short radio pulses and high bandwidth (> 500 MHz) while transmitting data. The difference between normal radio and UWB is in Figure [1.11] and Figure [1.12]. [15]

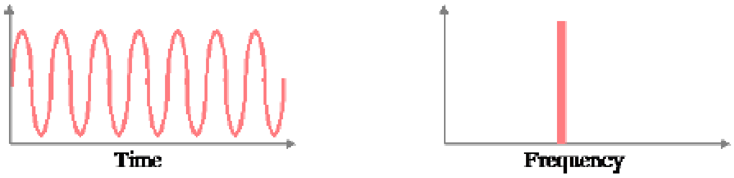


Figure 1.7 Time and Frequency of conventional radio [15]

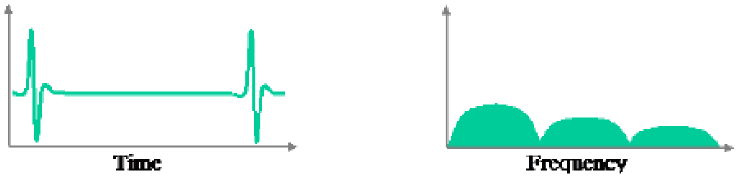


Figure 1.8 Time and Frequency of UWB radio [15]

Time of Arrival (TOA) and Time of Flight methods can be used. Time synchronization create good accuracy (>20 cm). [17] Also, large bandwidth has benefit that UWB signal is going to less effective with obstacles than conventional radio signal. [18]

1.2.3.3 RADAR Technology

RADAR is RF-based indoor positioning tracking system developed in Microsoft Research. This system is using received signal strength information for collecting data from multiple receivers. It is using triangulation method to estimate user location. RADAR can estimate user location within 3 meters. [19] But this accuracy depends on to buildings structures, indoor's region and indoor's obstacles.

1.2.3.4 Wi-Fi Technology

In this thesis we are going to use Wi-Fi technology and implement this technology to our methods. Wi-Fi (IEEE 802.11 standard family) is the most popular technology to communicate all around the world. Wi-Fi operates different bands including 2.4 GHz ISB band with 11, 54 or 108 Mbps and has coverage range 50 to 100 meters. [17] Wi-Fi is named in marketing area Wireless Local Area Network (WLAN). Most of device in the world has WLAN adapter such as computers, mobile phones, PDAs and so on. Moreover every buildings such as universities, hospitals, shopping malls, libraries has WLAN infrastructure. Since this technology is placed in our daily life, it can be used estimating location indoor environment. In WLAN, access points (APs) is a station that transmits and receives data. Each access point can serve multiple users; while user move beyond access point range they are automatically handed over next one. [20] In indoor environment there could be multiple APs depending on size of area. Each AP in different location, they are receiving RSS values from target devices. By applying positioning techniques, location of target device can be estimated.

1.3 Position Estimate Techniques

There are lots of positioning techniques that estimation target's location. In this section, we are going to examine most widely using techniques in indoor environment.

1.3.1 Received Signal Strength Indication

RSSI is a value that indicating of the strength when propagated radio wave is received. It is usually measured with dBm. (1dBm = 1.3 mill watt). The closer a receiver is to transmitter, signal will be stronger, attenuates as it propagates through the air and the attenuation is proportional to the distance.

In order to find relationship between RSSI and distance, transmitter (AP) is remained at fixed-known point and we are collecting RSSI while slowly moving away from transmitter. We are going to examine this content in Chapter 2.

1.3.2 Time of Arrival (TOA)

Time of Arrival is measures round-trip time between transmitter and receiver of signals. The round-trip time basically measures total time through signal travel between source and destination. The Euclidean distance between two devices (transmitter and receiver) can be derived by the multiplication of travel time wave speed.

TOA requires very accurate and synchronized clocks for transmitter and receiver. The measurement accuracy is high important while determining accuracy of location. The speed of radio propagation through air is$3\ x\ 10^{8}$.

In 1 micro second error in TOA measurement will lead to 300 meters error in estimation location. This is really hard to implement in real indoor environment since it is impacting accuracy in high level.

1.3.3 Angle of Arrival (AOA)

The Angle of Arrival (AOA) method is finding PDAs position by direction of receiving signal from transmitters Figure1.9. To measure received angle, the Base Stations (APs in indoor environments) of system applying AOA are equipment with different direction aware antenna which usually composed of an array of elements that are able to divide their directivity lobes equivalently among different directions. [21]

In order to improve accuracy more antennas should be used and this method requires LOS (line-of-sight). However it would be costly and time consuming to apply more antennas in system.

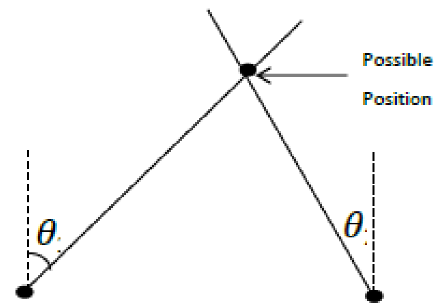


Figure 1.9 Angle of Arrival

1.3.4 Time Difference of Arrival (TDOA)

The Time Difference of Arrival is similar with Time of Arrival. This method is using time difference for signal propagation between receiver and transmitter. To estimate location, there should be at least three receivers are required. Receiver is keeping time when signal is arrive and send information to location engine in order to calculate difference in arrival time. Like in TOA method, synchronization of transmitters and receiver are highly important for accuracy.

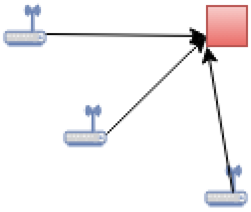


Figure 1.10 Time Difference of Arrival

CHAPTER 2

Received Signal Strength Indicator

Radio signals on wireless communication system hence system performance, depends on distance between transmitter and receiver. In order to estimate location in indoor environment, it is important to find distance between receiver and transmitter via RSSI values. To get better performance wireless system requires LOS between transmitter and receiver. However, there are lots of obstacles in indoor environment such as walls, floors, building structures, people movement and so on. There might be reflections, diffraction and scattering effects.

2.1 Basic Mechanisms of Propagation

Reflection, diffraction and scattering are impacts on signal propagation. In this part we are going to explain these concepts briefly.

2.1.1 Reflection

Reflection occurs when electromagnetic wave falls on object. When a radio wave falls on another medium having different electrical properties, part of radio wave is going to transmitted, other part is reflected. Reflected wave is related with coefficient p. The value of p can be changed when properties of different fields. In indoor environment, signals can be reflected by walls, windows, furniture and so on.

2.1.2 Diffraction

Diffraction allows waves to propagates different obstacles like curved earth surface or tall buildings. However received signal strength is decreased when user moves deeper into obstacles areas. This situation explained with Huygens' Principle [30]; all points of wave front can act like new source of new wavelet.

Diffraction is caused by the propagation of secondary wavelets into a shadowed region. The field strength of a diffracted wave in the shadowed region is the vector sum of electric field components of all secondary wavelets in the space around the obstacle.

2.1.3 Scattering

Scattering occurs when wave travel large dimension to small dimension compared to wavelength. The radio wave meet through surface, the reflected energy is spread out in all directions due to scattering. This provides extra energy at receiver.

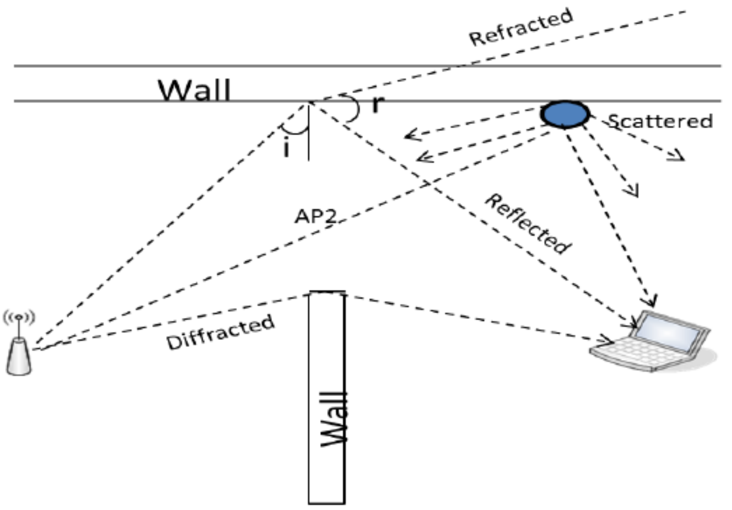


Figure 2.1 Reflections, Diffraction, and Scattering. [8]

2.2 RSSI Distance Relationship

We are going to examine how to measure distance between transmitter and receiver by using RSSI values.

2.2.1 Free Space Path Loss Model

When transmitter and receiver are in LOS range in free space environment (ideal environment), distance can be found:

$$PL(d) = -10log\left[\frac{G_t G_r \lambda^2}{(4\pi)^2 d^2}\right] \tag{2.1}$$

G_t, G_r are ratio gains from transmitter and receiver antennas. λ is wavelength in meters and d is distance in meter.

2.2.2 Log Distance Path Loss Model

Log-distance model RSS is decreasing with distance. The path loss in dBm is;

$$RSSI = -(10nlog10d + A) \tag{2.2}$$

n is signal propagation constant, also named propagation exponent, d is distance from sender; A is received signal strength at one meter. In this thesis n value is accepted *2.18.*

2.2.3 Log Normal Shadowing Model

In log distance model we do not consider the shadowing effect. Log normal shadowing effect formula is;

$$RSSI = -(10nlog10d + A) + X_\sigma \tag{2.3}$$

X_σ is zero-mean Gaussian random variable with standard deviation σ. These variables should be at dB.

2.3 RSSI Measurement

In order to understand RSSI behavior in indoor environment, we measured RSSI values with certain distance 1meter up to 6 meter. Experiment-1 is in Kadir Has University FABLAB Laboratory Corridor. Area is closed environment but there are 7 tables and some electronic devices in it. Like in Figure 2.2 and Figure 2.3, there are obstacles in measurement area.

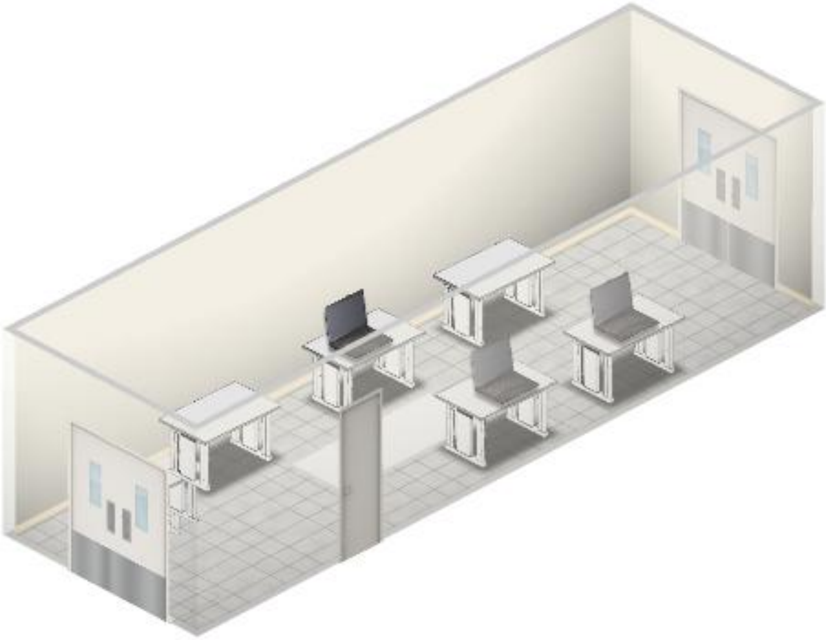


Figure 2.2 KHU FABLAB Corridor, Measurement Area 3D Visualization

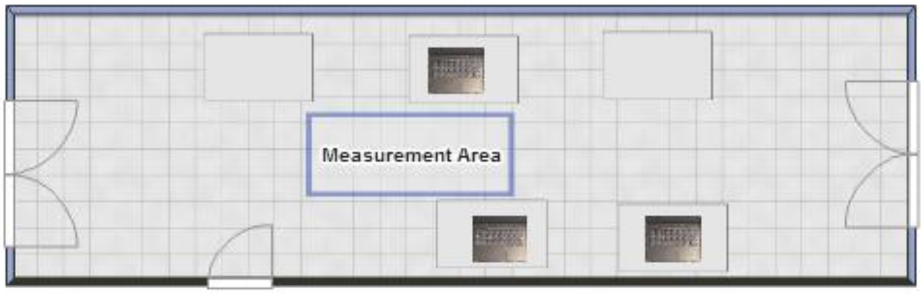


Figure 2.3 KHU FABLAB Corridor, Measurement Area 2D Visualization

We measured RSSI values through a line in a rectangular area, we used two different access point. Results are;

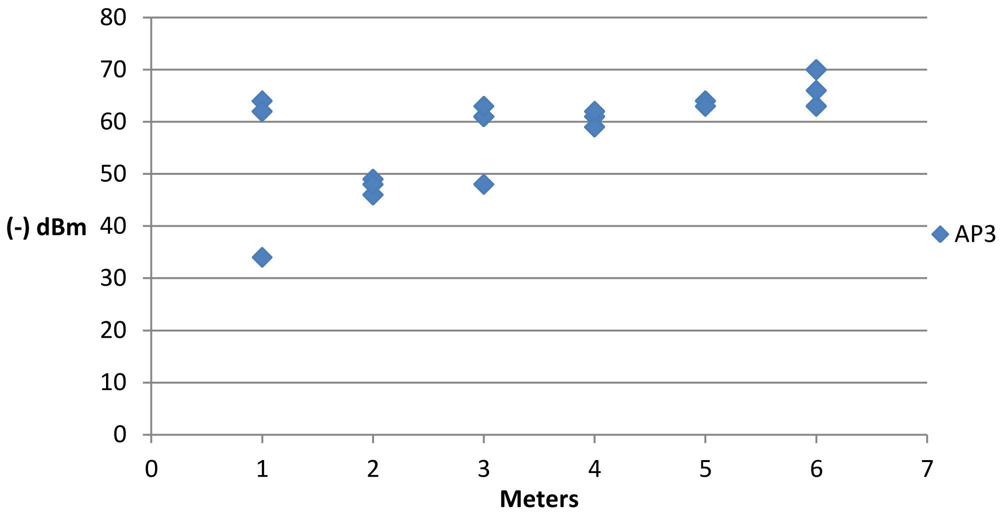


Figure 2.4 Access Point No1 results at experiment-1

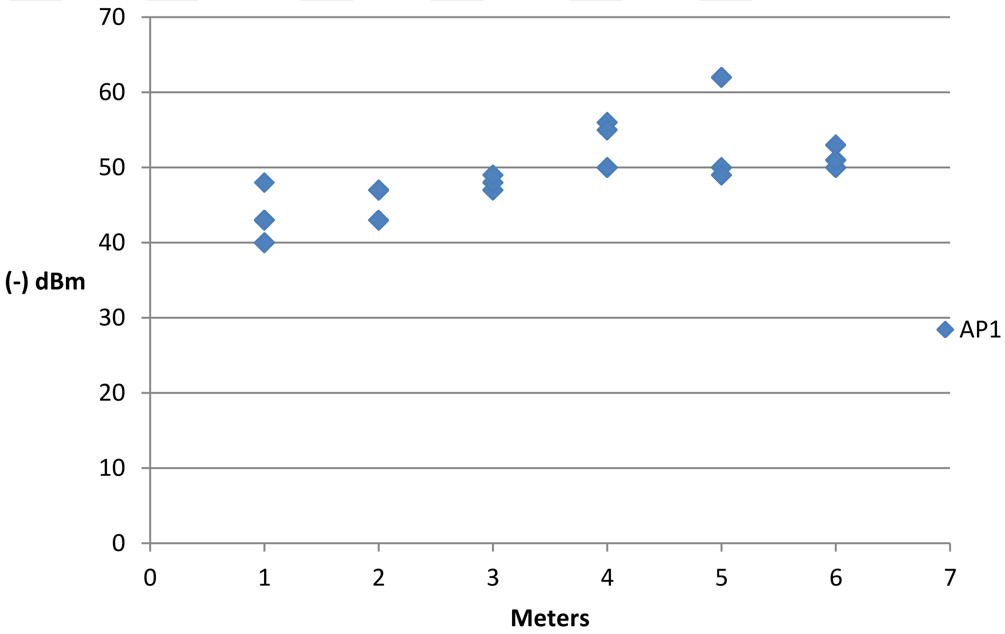


Figure 2.5 Access Point No2 results at experiment-1

On experiment-2 on RSSI values, we measured access point RSSI values at 1 meter within 10 minutes. Experiment is KHU FABLAB corridor on the top of table, Figure 2.6. We changed only distance (one meter) of measurement area and keep measurement at ten minutes. Results are in Figure 2.7 and Figure 2.8. In figures, 5664 samples are collected within 100 msec during 10 minutes.

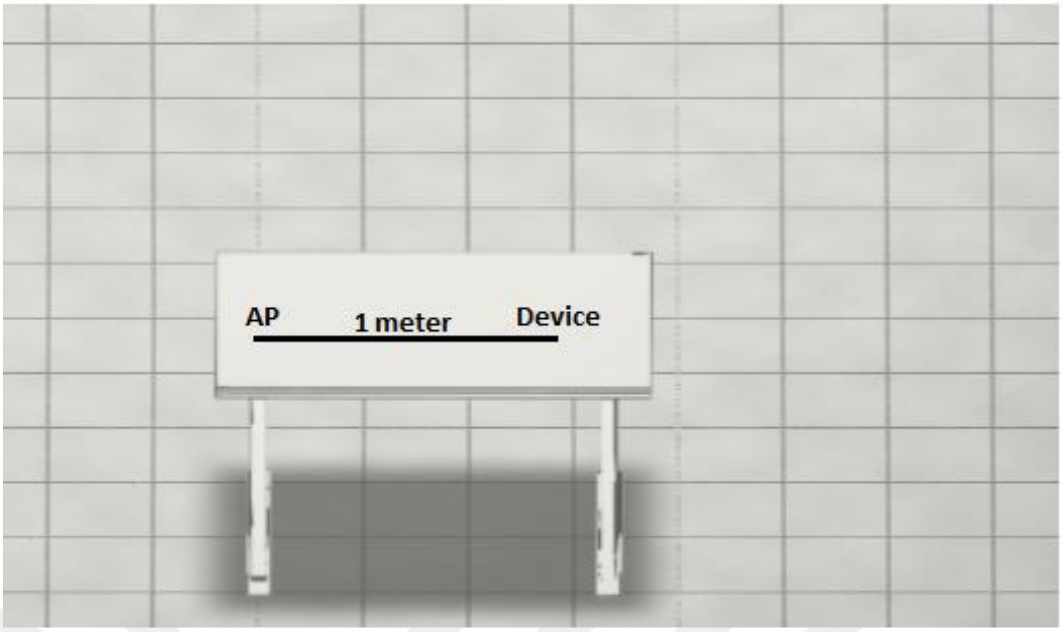


Figure 2.6 RSSI measurements at experiment-2

In Figure 2.7 Average RSSI value is: -46.23 dBm, standard deviation is: 2.04.

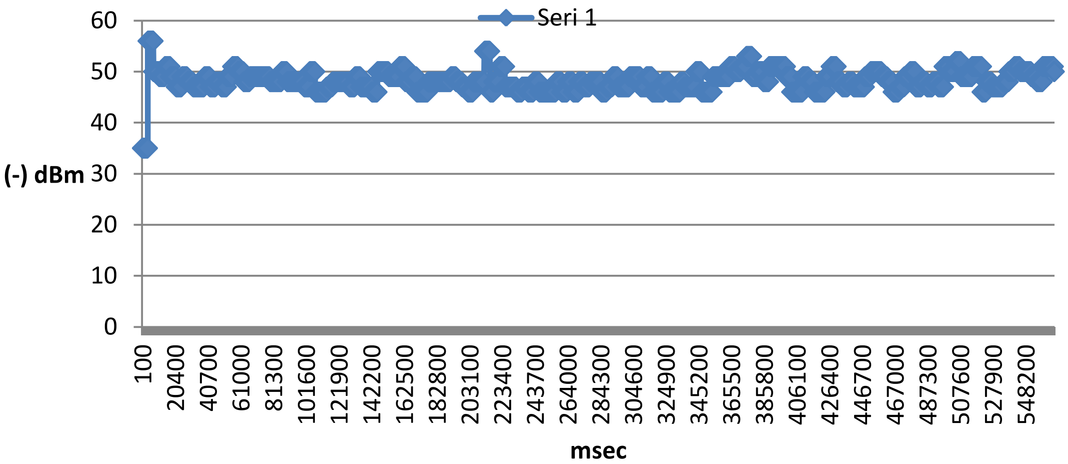


Figure 2.7 Access Point No1 results at experiment-2

In Figure 2.8; Average RSSI value is: -63.41 dBm, standard deviation is: 3.50.

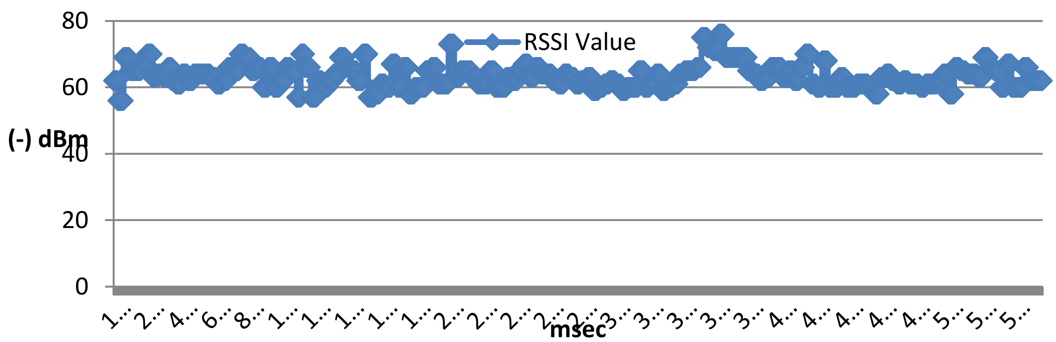


Figure 2.8 Access Point No2 results at experiment-2

According to radio propagation model the signal strength value should be decreased exponential with respect to distance. Experiment-1 shows that there is not any pattern between distance and RSSI values. RSSI values interference of reflection, diffraction, and scattering, obstacles like walls, equipment, and structure of building even people movement. There is difficult to find LOS between transmitter and receiver in indoor environment.

Results on experiment-2 shows that even same environment without any obstacles between transmitter and receiver, access point behavior can be different. Access Point-1 average RSSI measured at one meter 48.23 dBm; on the other hand Access Point-2 average RSSI measured 68.41 dBm.

CHAPTER 3

Experimental Area

In chapter 2, experiments show that indoor environment difficult to get accurate result. RSSI values are affected with multiple reasons. Obstacles, building structure, people movement and so on. In same environment, we measured different RSSI values with different access point. There are a lot of affect on RSSI values. In order to compare algorithm results successfully, created synthetic data is required.

3.1 Synthetic Data Set

Synthetic data is used with 6mx6m, 12mx12m, 24mx24m measurement areas. There are two type of data; data with noise and data with no noise. Data with no noise is line-of-sight data. There is no any loss in RSSI values. Data-with-noise type of data that prototype of obstacles between transmitter and receiver. Incrementally increased with values; 0.5 dBm, 1 dBm, 1.5 dBm, 2 dBm, 2.5dBm, 3 dBm, 3.5 dBm, 4 dBm, 4.5 dBm, 5 dBm.

In each measurement area, four access points are used at the corner of test environment. $AP1, AP2, AP3$ and $AP4$. Access points' RSSI values in one meter are accepted *-50 dBm*, *-52 dBm*, *-54 dBm*, *-50 dBm* respectively. Path loss exponent is accepted *2.18*.

In each dataset has X and Y coordinates, Euclidian distance (d) between receiver and transmitter (3.1), path loss exponent (n), and estimated RSSI value. In LOS environment RSSI can be obtain equation (2.2) is used. On the other hand, noise data environment equation (2.3) is using for each feature.

$$d_i = -10^{\frac{RSSI_i + A}{10n}} \tag{3.1}$$

3.2 Measurement Area with Synthetic Dataset

In this part, measurement areas are introduced with features node in graphically. There are 11 synthetic data model with different signal lost has been used in algorithms. Synthetic data models are available on CD with thesis I have delivered.

In experimental dataset each features have; x and y coordinates, distance between target and node points (d) and $RSSI$ vector.

3.2.1 6m x 6m Measurement Area

For testing performance of proposed systems, 256 data (features) are created within an interval of 0.4 meter in area of 6 square meters (m^2) Figure 3.1. Each feature has $RSSI$ vector.

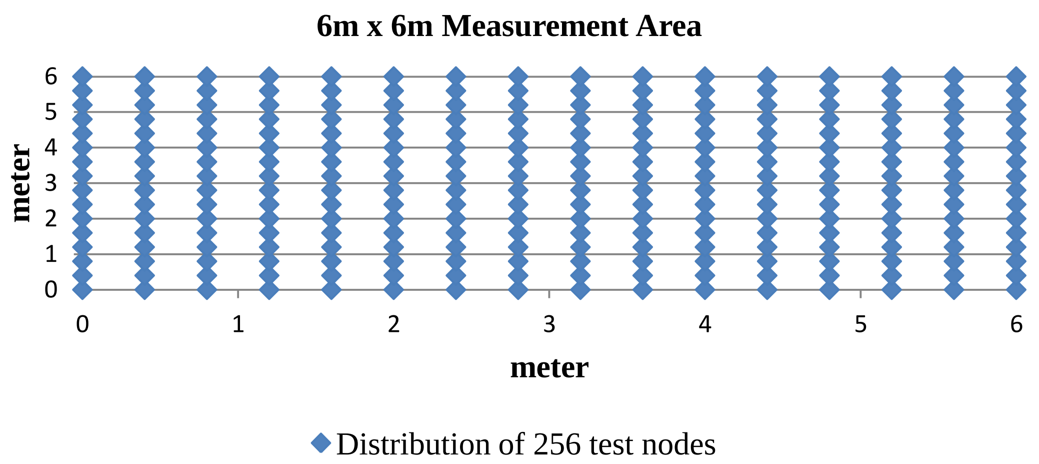


Figure 3.1 6mx6m Measurement Area

3.2.2 12mx12m Measurement Area

For testing performance of proposed systems, 625 data (features) are created within an interval of 0.5 meter in area of 12 square meters (m^2) (Figure 3.2)

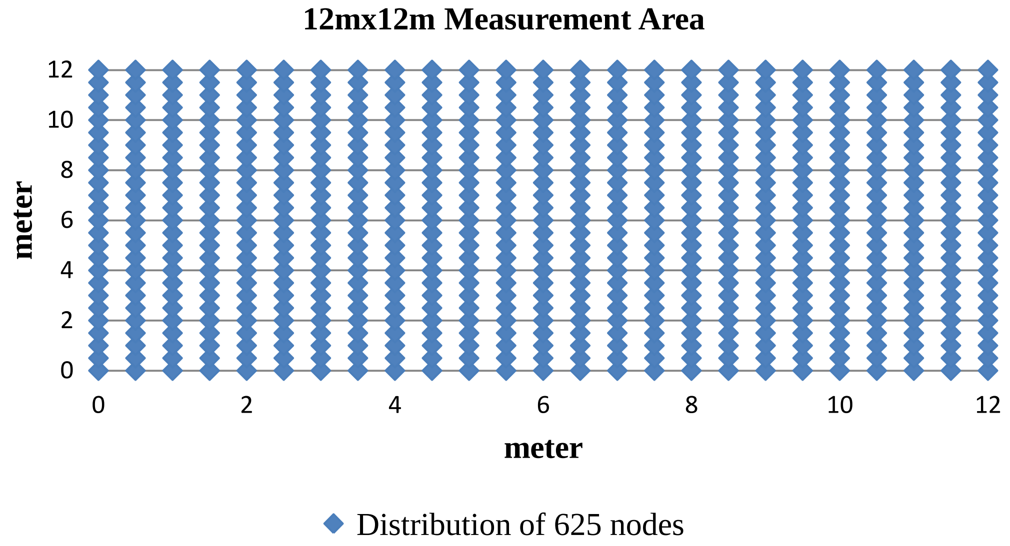


Figure 3.2 12mx12m Measurement Area

3.2.3 24mx24m Measurement Area

For testing performance of proposed systems, 2397 data (features) are created within an interval of 0.5 meter in area of 24 square meters (m^2) (Figure 3.3)

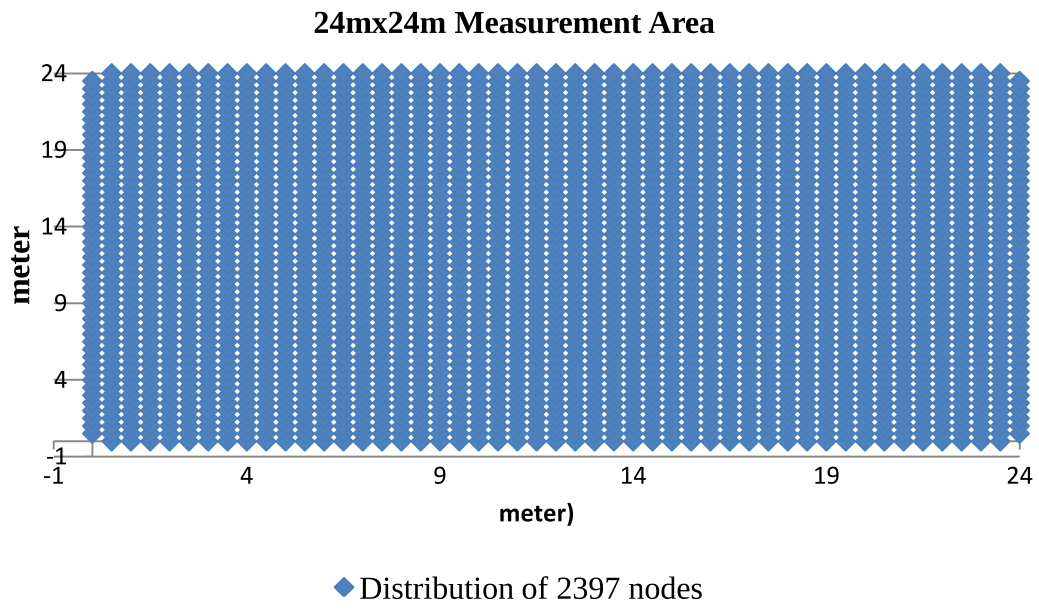


Figure 3.3 24mx24m Measurement Area

3.3 Real Data Measurement

In order to compare algorithms with each other, real RSSI data were used. Kadir Has University's canteen was chosen as a measurement area. Indoor environment are effected with person movement thus we choose holiday in order to avoid students' effect on our environment. 6 square meter and 12 square meter areas were created. In 6 square meter area, 255 features and for 12 square meter are 444 features were used. Cell phone gathered RSSI values from each features inside of measurement area. During experiment, another cell phone (agent) is placed at the middle of measurement area and measured RSSI values from same node. In 6 square meter area agent coordinate is (3, 3) and for 12 square meter area agent coordinate is (6, 6). Agent provides to find "A" value from 4 different access points. Path Loss exponent (n) are calculation with Brute Force technique for each RSSI values that measured.

Brute Force algorithm is used to find optimum N values. Basically algorithm finds path loss exponent value for each access point. Algorithm find exponent until estimated distance and real distance is equal to each other for each RSSI values. Let assume there are N measurement point. Path Loss exponent for access point is;

$$n_{avg} = \sum_{i=0}^{N} n_i \tag{3.1}$$

In 6mx6m environment, A values respectively; -50.41, -49.09, -46.03, -47.65. Path Loss exponent is *2.97* for each access points.

In 12mx2m environment, A values respectively; -42.28, -35.45, -32.72, -35.89. Path Loss exponent values respectively *2.97*, *3.63*, *3.40*, *4.52*

CHAPTER 4

Triangulation

Basic principle is using geometric properties of triangles to complete object location. There are two types of triangulation method; lateration and angulations. Lateration is using distance measurement, angulations is using primarily angle or bearing measurements. [21]

4.1 Lateration

Lateration or Trilateraion is most well known estimation location in indoor positioning. Lateration is required three known positioned APs. We are collecting RSSI values from receivers. Measured RSSI values are converting into distance measurement by using path loss model. The path loss model shows the expected path loss in signal strength at a given distance (At one meter, dBm). Then known three distances from known APs are using Euclidean distance in order to estimate unknown object location Figure 4.1 [15].

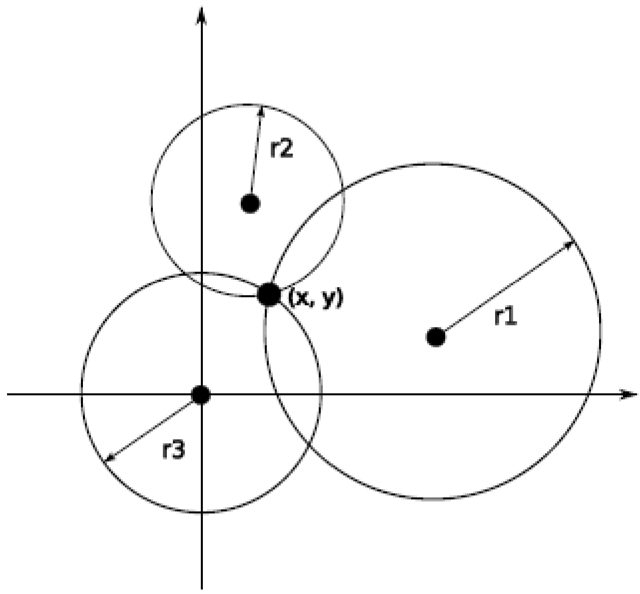


Figure 4.1 Lateration Method[15]

The distance d_i is estimated from RSSI values are used to compute centered in the three reverences anchor nodes. Ideally, the target should be intersection of the circles like in Figure 4.1.

From General Euclidean distance, radius can be find as

$$r_1 = \sqrt{(x_1 - x)^{2} + (y_1 - y)^{2}}$$
$$r_2 = \sqrt{(x_2 - x)^{2} + (y_2 - y)^{2}}$$
$$r_3 = \sqrt{(x_3 - x)^{2} + (y_3 - y)^{2}}$$

(4.1)

After we re-arrange basic equation, we have matrix form;

$$\begin{bmatrix} (r_1)^{2} - (r_2)^{2} + (x_2{}^2 + y_2{}^2 - x_1{}^2 - y_2{}^2) \\ (r_1)^{2} - (r_3)^{2} + (x_3{}^2 + y_3{}^2 - x_1{}^2 - y_2{}^2) \end{bmatrix} = \begin{bmatrix} 2(x_2 - x_1) & 2(y_2 - y_1) \\ 2(x_3 - x_1) & 2(y_3 - y_1) \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}$$

$$\bar{A} = \bar{B} * x$$

(4.2)

Target location can be estimated after matrix equation is solved in (4.2)

$$\begin{bmatrix} x \\ y \end{bmatrix} = (\bar{A}^T A)^{-1} * (\bar{A}^T B)$$

(4.3)

4.2 Angulations

Angulations are similar to Lateration, except instead of distance this method is using angle to determine position of object. This method is using AOA measurement so; it is required extra device to measure angles. Basically, the angle measurements at two APs and known AP locations are required. Then simple trigonometry can be applied to estimate distance. [15]

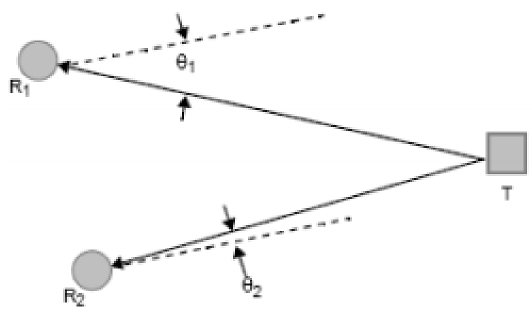


Figure 4.2 Angulations' Method (AOA principle) [15]

4.3 Test Bed

Triangulation algorithm requires 3 access points; $AP1, AP2$ and $AP3$. In equation [4.1]; $r_1, r_{2,} r_3$ are representing $AP1, AP2, AP3$'s distance from measurement point. In order to find distance from measurement point, we are going to use Log-distance path loss model that we mentioned in chapter 2. Estimated distances in each feature were measured using equation (3.1).

4.4 Experimental Result

In chapter 3, synthetic data is created as triangulation method input. 6mx6m, 12mx12m and 24mx24m measurement areas are used. Coordinate of access points respectively: (0, 0), (6, 0), (6, 6).

For each experiment, equation (2.2), (3.1) and (4.3) are applied.

4.4.1 6m x 6m Measurement Area

Circle figures represent access point placement. There are 256 test nodes, however we ignore nodes where it is access point coordinates. 253 data features were used within an interval of 0.4 meter in an area of 6 square meters (m^2).

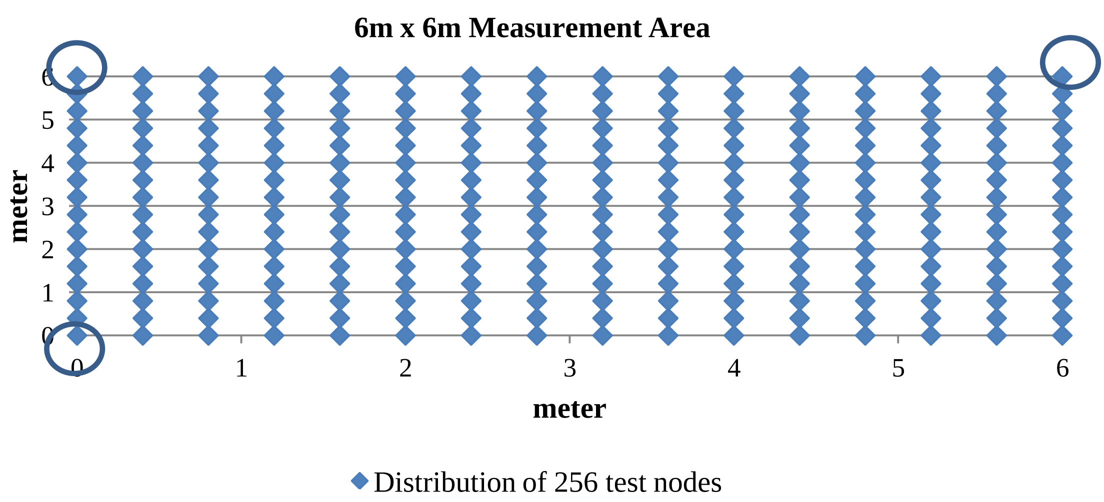
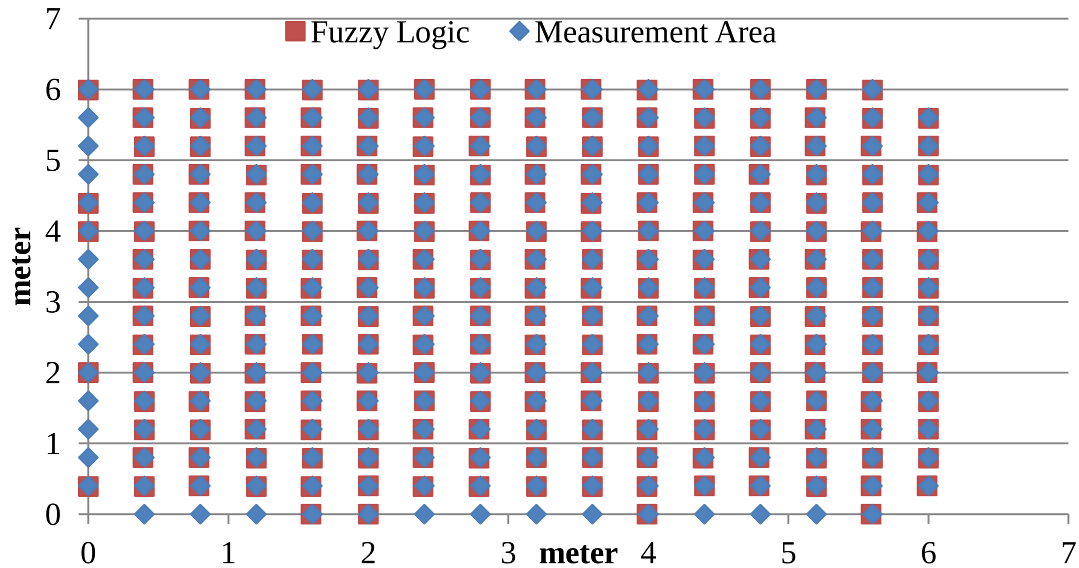


Figure 4.3 6mx6m Measurement Area – Access Point Placement

4.4.1.1 6mx6m Area (LOS Environment)

There are not any obstacles between transmitter and receiver in LOS environment. This model is representing when there is any signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 0.0 meter, minimum error is -0.01 meter, maximum error is 0.01 meter and standard deviation is 0.00 meter. (Figure 4.4)

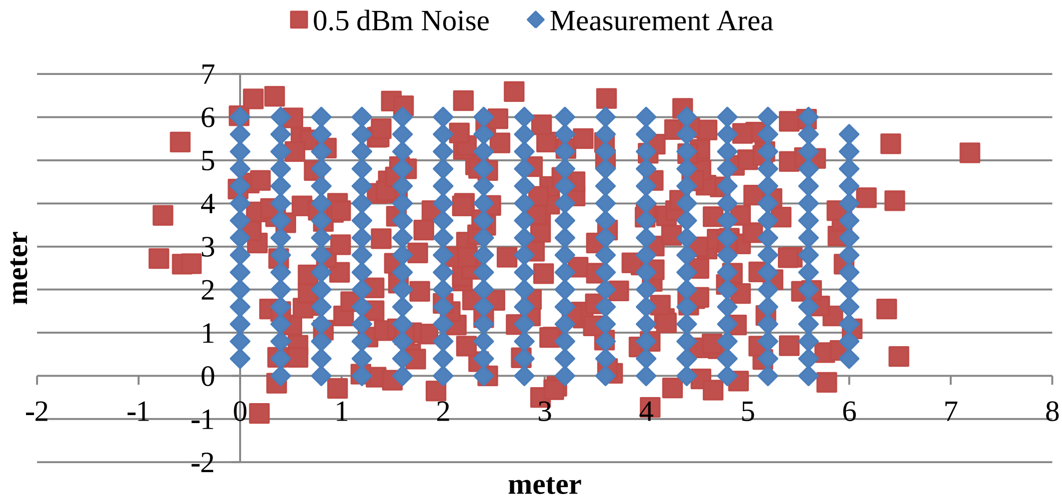


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	0.00	0.00	0.01	0.00

Figure 4.4 Experiment on LOS Environment (6mx6m)

4.4.1.2 6mx6m Area (0.5 dBm Noise)

This model is representing when there is 0.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 0.42 meter, minimum error is 0.02 meter, maximum error is 1.82 meter, and standard deviation is 0.33 meter. (Figure 4.5)

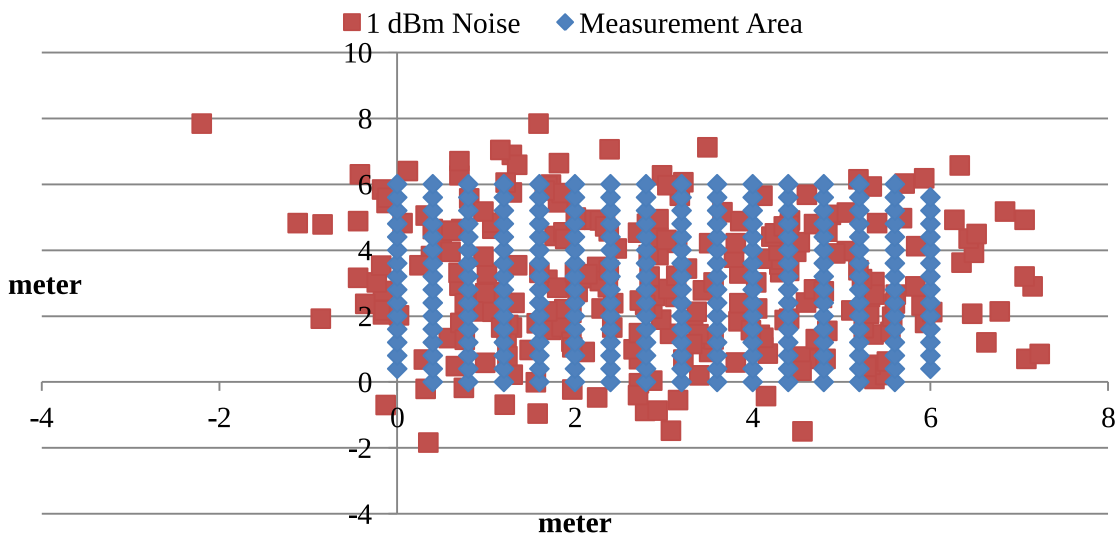


N Value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	0.42	0.02	1.82	0.33

Figure 4.5 Experiment on 0.5 Noise Environment (6mx6m)

4.4.1.3 6mx6m Area (1 dBm Noise)

This model is representing when there is 1 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 0.86 meter, minimum error is 0.03 meter, maximum error is 4.01 meter, and standard deviation is 0.61 meter. (Figure 4.6)



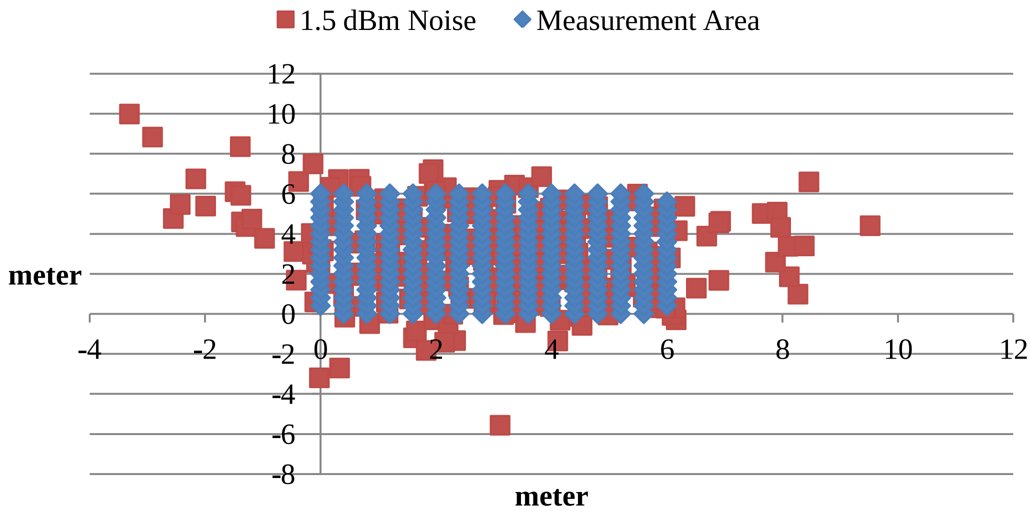
N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	0.86	0.03	4.01	0.61

Figure 4.6 Experiment on 1 Noise Environment (6mx6m)

4.4.1.4 6mx6m Area (1.5 dBm Noise)

This model is representing when there is 1.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.

Average is 1.35 meter, minimum error is 0.03 meter, maximum error is 7.01 meter, and standard deviation is 1.1 meter. (Figure 4.7)



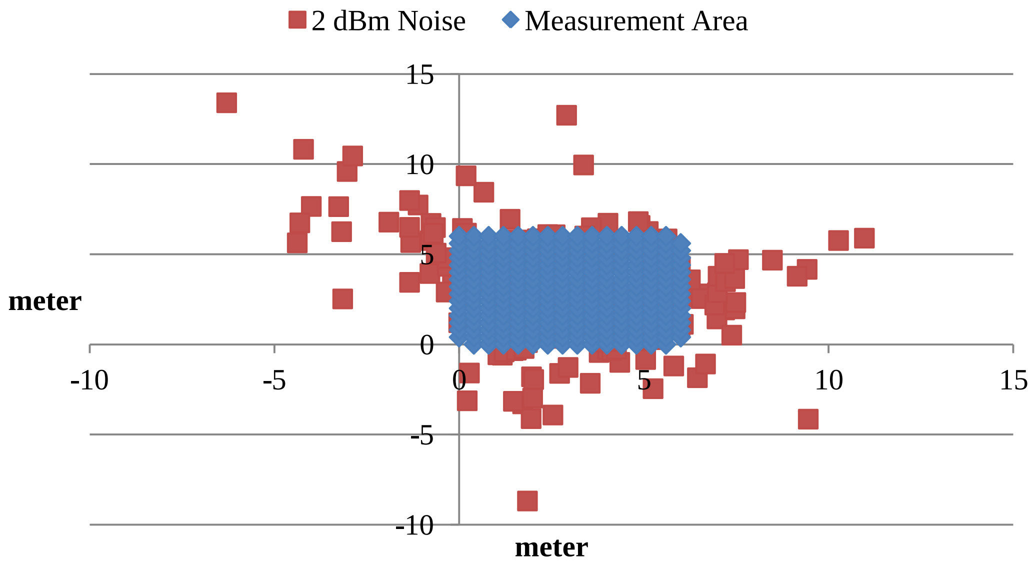
N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	1.35	0.03	7.14	1.1

Figure 4.7 Experiment on 1.5 Noise Environment (6mx6m)

4.4.1.5 6mx6m Area (2 dBm Noise)

This model is representing when there is 2 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.

Average is 1.93 meter, minimum error is 0.04 meter, maximum error is 10.66 meter, and standard deviation is 1.79 meter. (Figure 4.8)

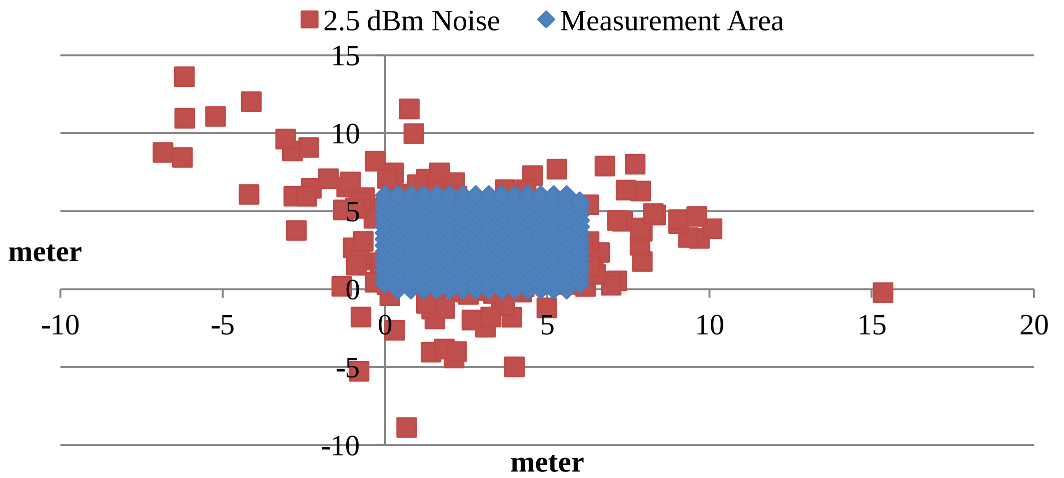


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	1.93	0.04	10.66	1.79

Figure 4.8 Experiment on 2 Noise Environment (6mx6m)

4.4.1.6 6mx6m Area (2.5 dBm Noise)

This model is representing when there is 2.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 2.31 meter, minimum error is 0.04 meter, maximum error is 9.36 meter, and standard deviation is 1.93 meter. (Figure 4.9)

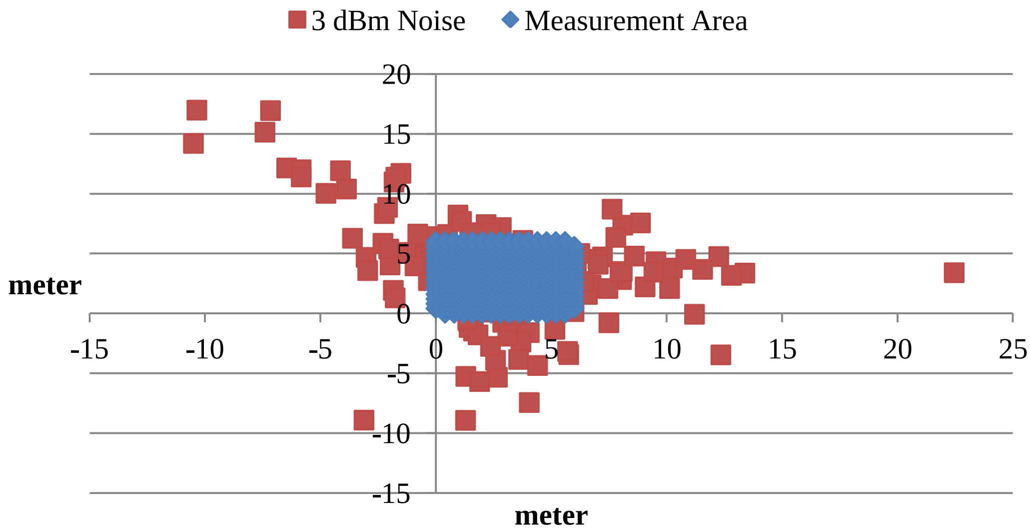


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	2.31	0.04	9.86	1.93

Figure 4.9 Experiment on 2.5 Noise Environment (6mx6m)

4.4.1.7 6mx6m Area (3 dBm Noise)

This model is representing when there is 3 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 2.94 meter, minimum error is 0.02 meter, maximum error is 18.31meter, and standard deviation is 2.91 meter. (Figure 4.10)

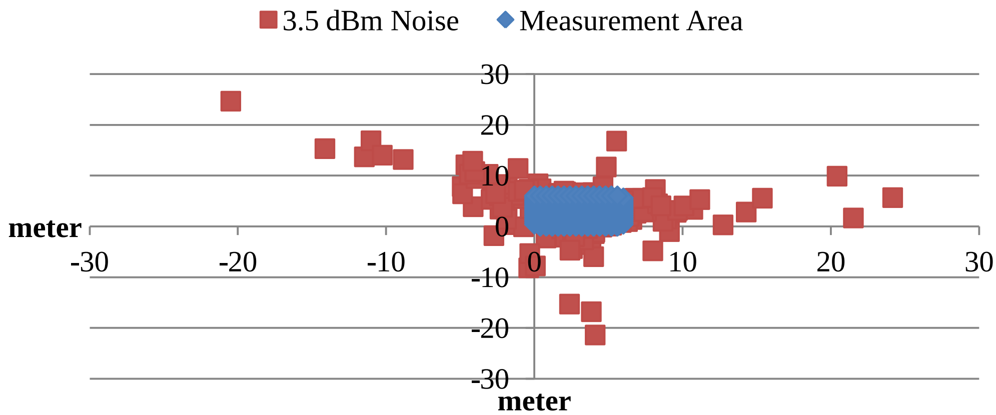


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	2.94	0.02	18.31	2.91

Figure 4.10 Experiment on 3 Noise Environment (6mx6m)

4.4.1.8 6mx6m Area (3.5 dBm Noise)

This model is representing when there is 3.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 3.65 meter, minimum error is 0.04 meter, maximum error is 30.50 meter, and standard deviation is 4.19 meter. (Figure 4.11)



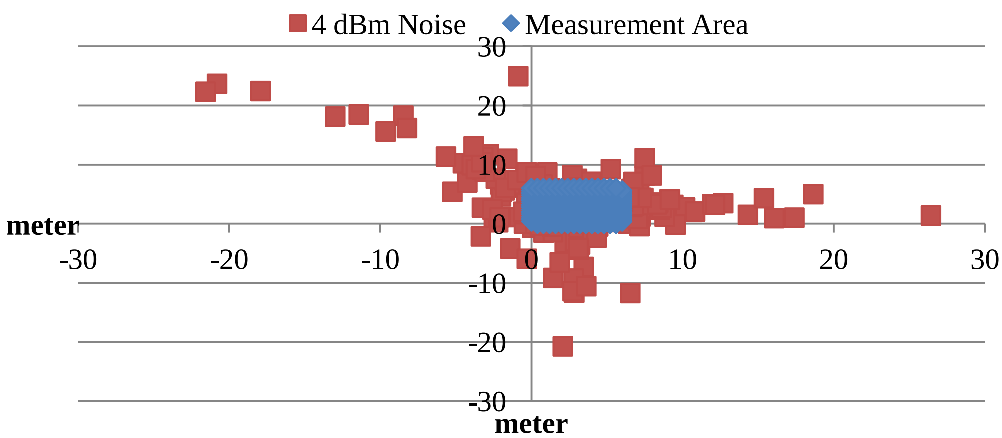
N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	3.65	0.04	30.50	4.19

Figure 4.11 Experiment on 3.5 Noise Environment (6mx6m)

4.4.1.9 6mx6m Area (4 dBm Noise)

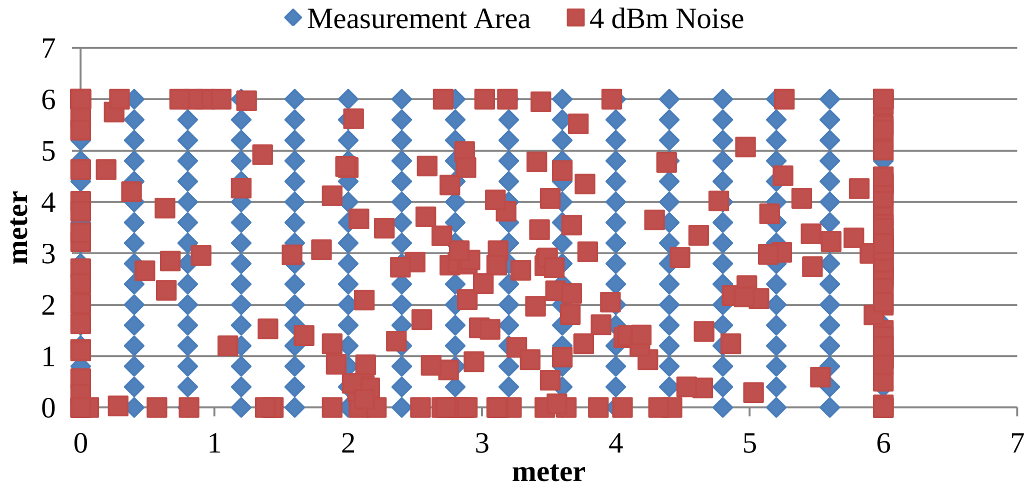
This model is representing when there is 4 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 4.30 meter, minimum error is 0.04 meter, maximum error is 28.38 meter, and standard deviation is 4.56 meter. (Figure 4.12)

In Figure 4.13, we restricted estimated location with measurement area. 177 nodes were out of area. Average is 2.05 meter, minimum error is 0.06, maximum error is 6.72 meter and standard deviation is 1.24 meter.



N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	4.30	0.04	28.38	4.56

Figure 4.12 Experiment on 4 Noise Environment (6mx6m)

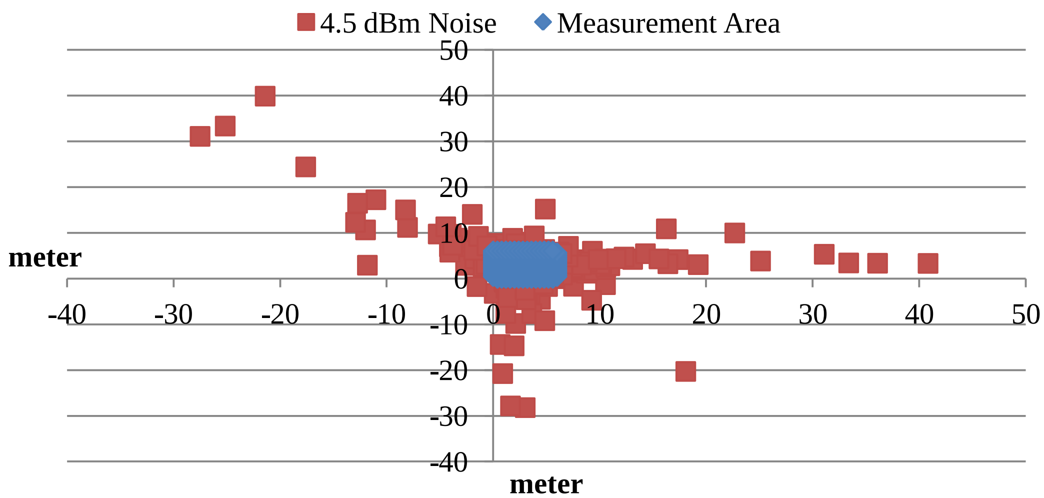


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	2.05	0.00	6.72	1.24

Figure 4.13 Experiment on 4 Noise Environment (6mx6m) - Recuirement

4.4.1.10 6mx6m Area (4.5 dBm Noise)

This model is representing when there is 4.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 5.54 meter, minimum error is 0.33 meter, maximum error is 42.07 meter, and standard deviation is 7.05 meter. (Figure 4.14)

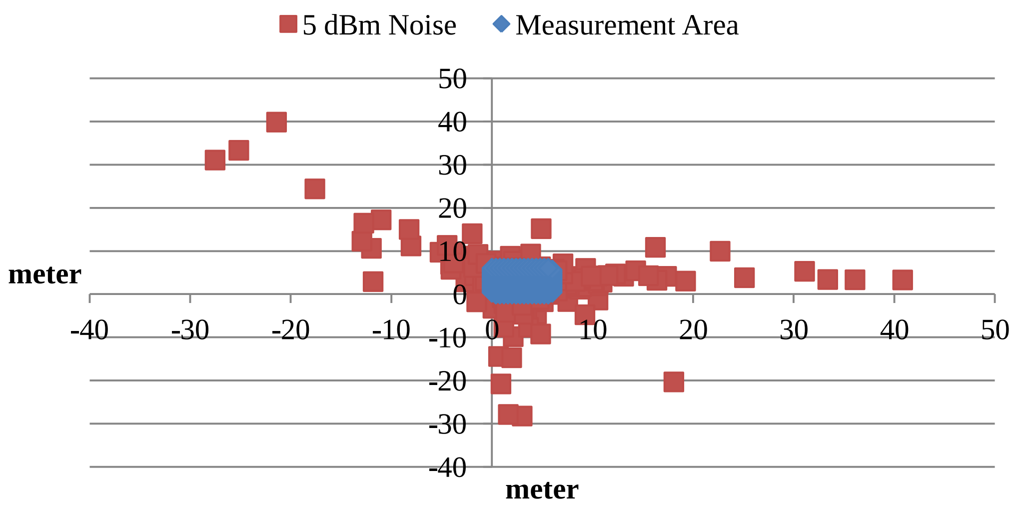


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	5.54	0.33	42.07	7.05

Figure 4.14 Experiment on 4.5 Noise Environment (6mx6m)

4.4.1.11 6mx6m Area (5 dBm Noise)

This model is representing when there is 5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 6.32 meter, minimum error is 0.14 meter, maximum error is 62.40 meter, and standard deviation is 7.26 meter. (Figure 4.15)

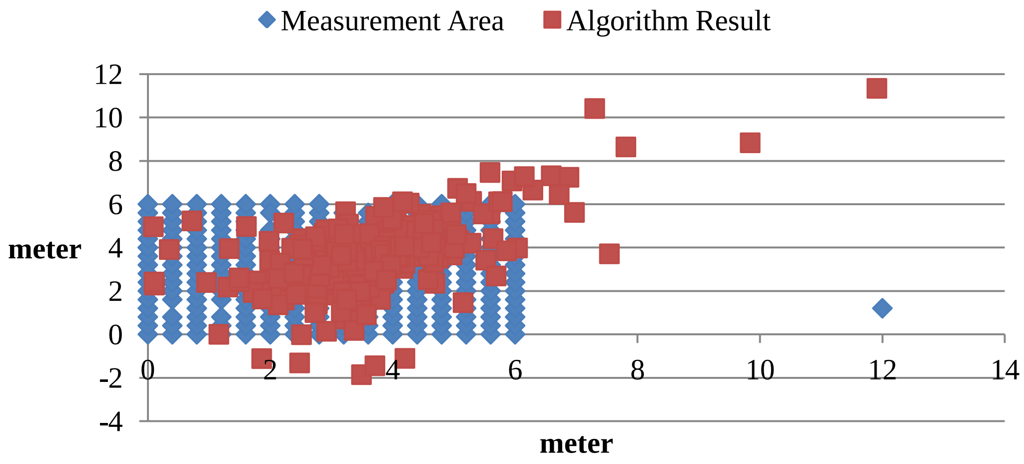


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	6.32	0.14	62.40	7.26

Figure 4.15 Experiment on 5 Noise Environment (6mx6m)

4.4.1.12 Experiment with Real Data

In chapter 3, environment with real data is described. $AP1, AP2$ *and* $AP3$ is used during experiment. Average is 2.32 meter, minimum error is 0.2 meter, maximum error is 10.13 meter, and standard deviation is 1.35 meter. (Figure 4.16)



Average Error	Minimum Error	Maximum Error	Standard Deviation
2.32	0.2	10.13	1.35

Figure 4.16 Experiment with Real Data (6mx6m)

4.4.2 12mx 12m Measurement Area

Circle figures represent access point placement. There are 625 test nodes, however we ignore nodes where it is access point coordinates. 623 data features were used within an interval of 0.5 meter in an area of 12 square meters (m^2) Figure 4.17.

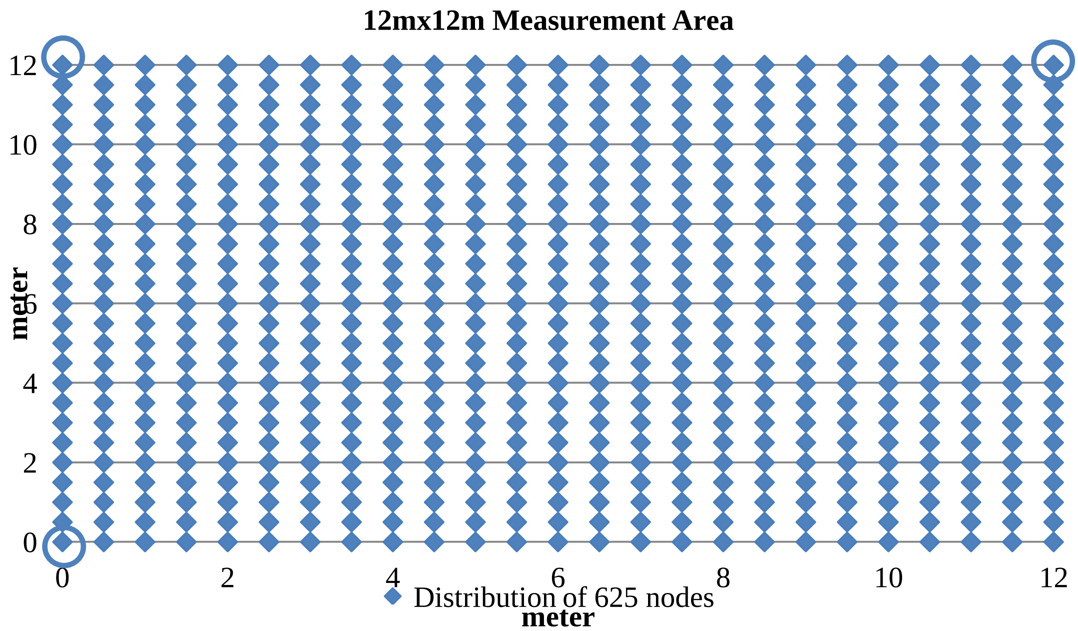
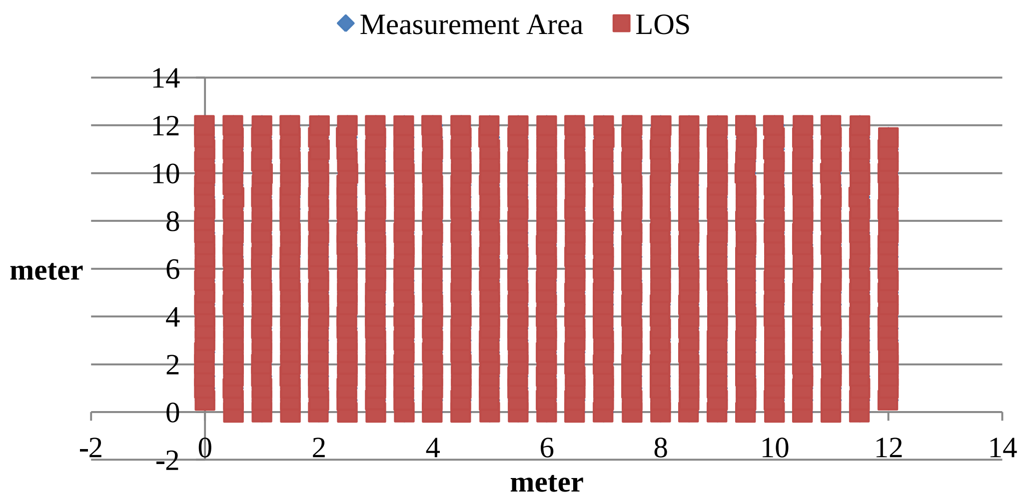


Figure 4.17 12mx12m Measurement Area-Access Point Placement

4.4.2.1 12mx12m Area (LOS)

There are not any obstacles between transmitter and receiver in LOS environment. This model is representing when there is any signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.

Average is 0.0 meter, minimum error is 0.00 meter, maximum error is 0.02 meter and standard deviation is 0.00 meter. (Figure 4.18)



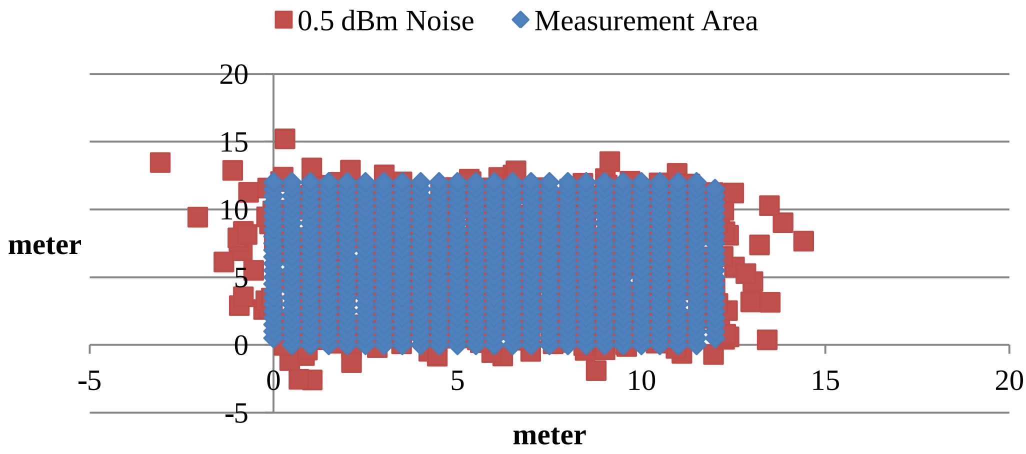
N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	0,00	0.00	0,02	0,00

Figure 4.18 Experiment on LOS Environment (12mx12m)

4.4.2.2 12mx12m Area (0.5 dBm Noise)

This model is representing when there is 0.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.

Average is 0.83 meter, minimum error is 0.03 meter, maximum error is 4.54 meter and standard deviation is 0.63 meter. (Figure 4.19)

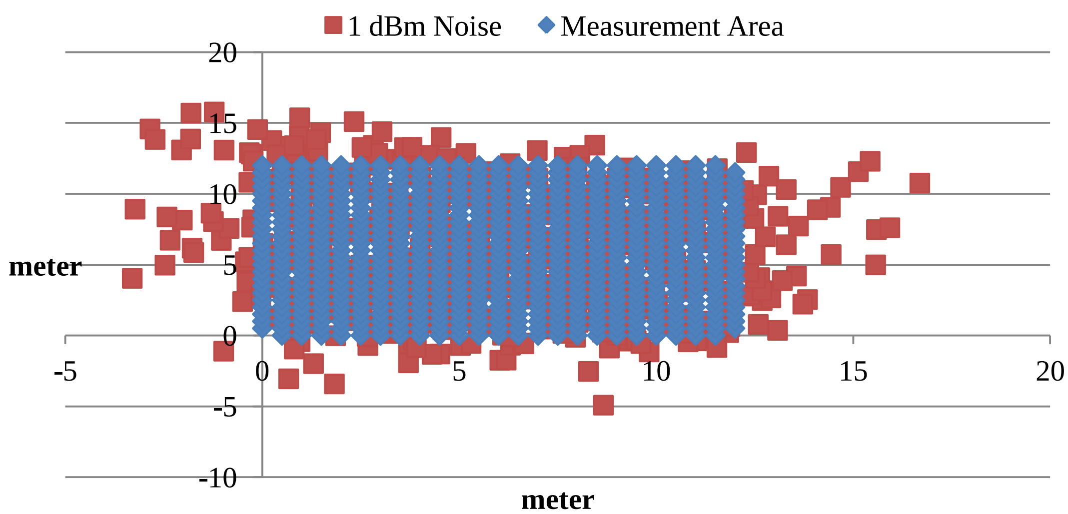


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	0.83	0.03	4.54	0.63

Figure 4.19 Experiment on 0.5 dBm Noise Environment (12mx12m)

4.4.2.3 12mx12m Area (1 dBm Noise)

This model is representing when there is 1 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 1.72 meter, minimum error is 0.05 meter, maximum error is 8.08 meter and standard deviation is 1.23 meter. (Figure 4.20)



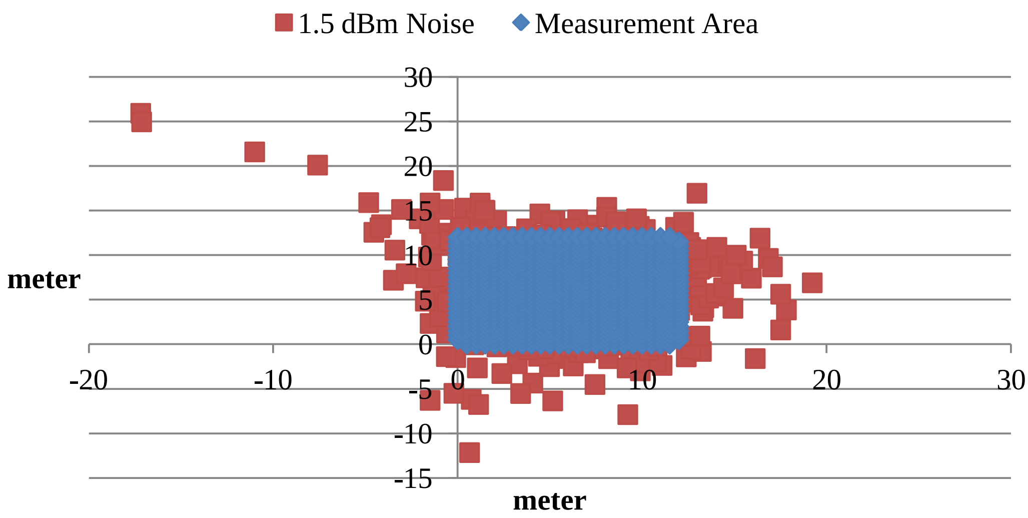
N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	1.72	0.05	8.08	1.23

Figure 4.20 Experiment on 1 dBm Noise Environment (12mx12m)

4.4.2.4 12mx12m Area 1.5 dBm

This model is representing when there is 1.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.

Average is 2.59 meter, minimum error is 0.02 meter, maximum error is 24.46 meter and standard deviation is 2.26 meter. (Figure 4.21)



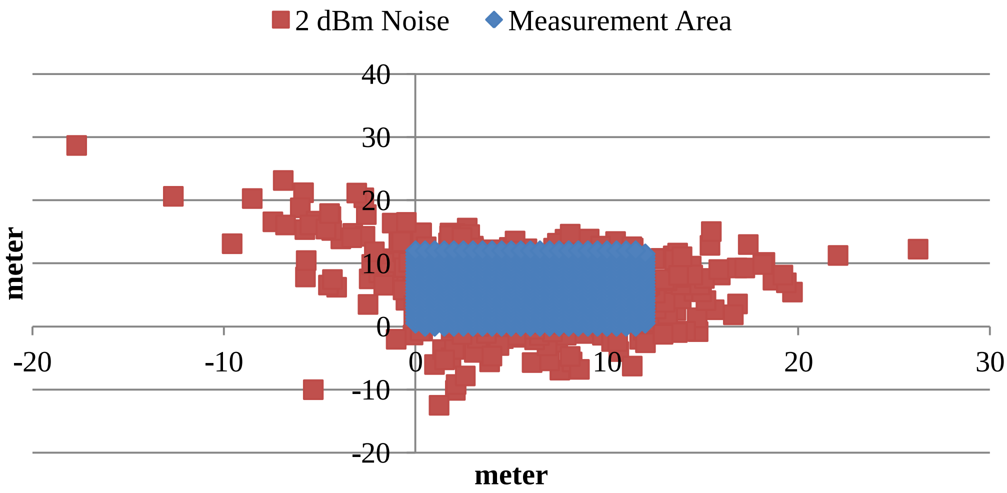
N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	2.59	0.02	24.46	2.26

Figure 4.21 Experiment on 1.5 dBm Noise Environment (12mx12m)

4.4.2.5 12mx12m Area 2dBm

This model is representing when there is 2 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.

Average is 3.60 meter, minimum error is 0.08 meter, maximum error is 27.14 meter and standard deviation is 2.94 meter. (Figure 4.22)

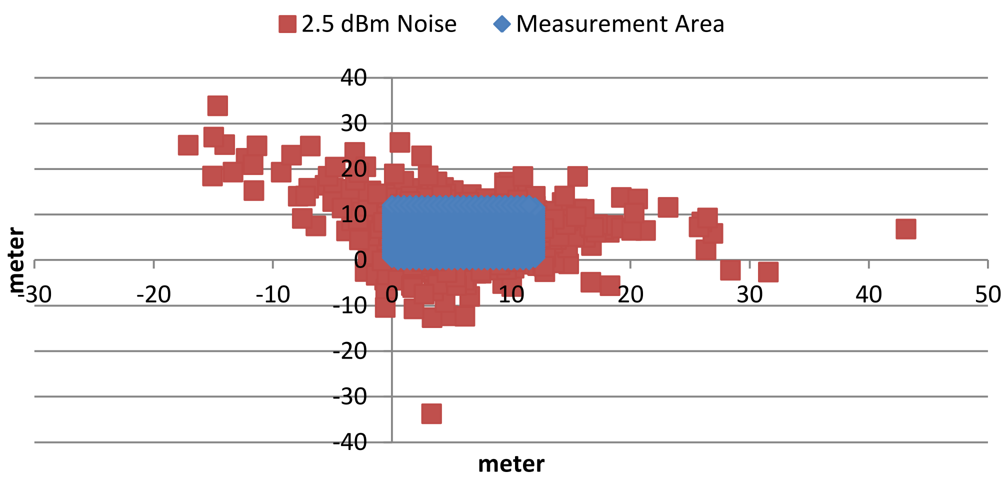


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	3.60	0.08	27.14	2.94

Figure 4.22 Experiment on 2 dBm Noise Environment (12mx12m)

4.4.2.6 12mx12m Area 2.5 dBm

This model is representing when there is 2.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 4.64 meter, minimum error is 0.04 meter, maximum error is 36.81 meter and standard deviation is 4.34 meter. (Figure 4.23)



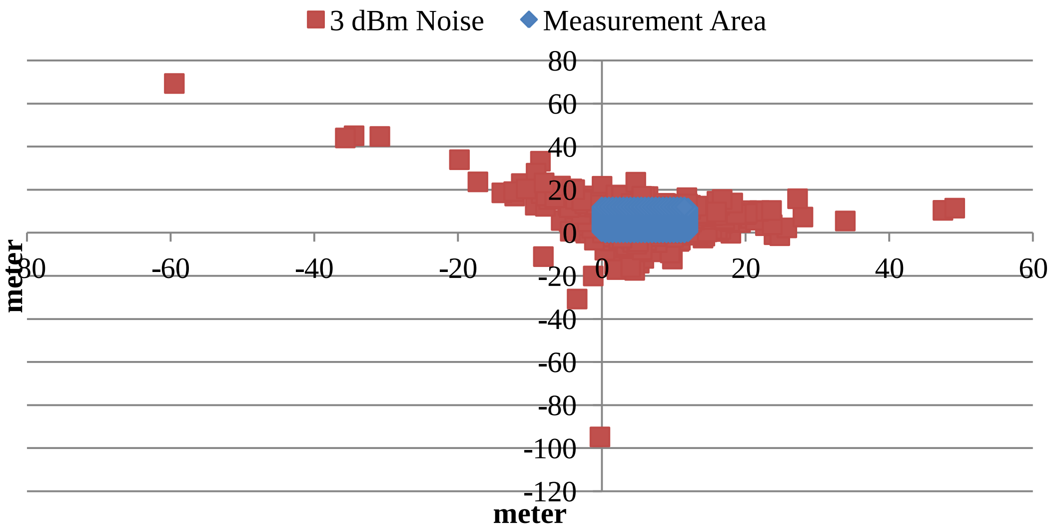
N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	4.64	0.04	36.81	4.34

Figure 4.23 Experiment on 2.5 dBm Noise Environment (12mx12m)

4.4.2.7 12mx12m Area 3 dBm

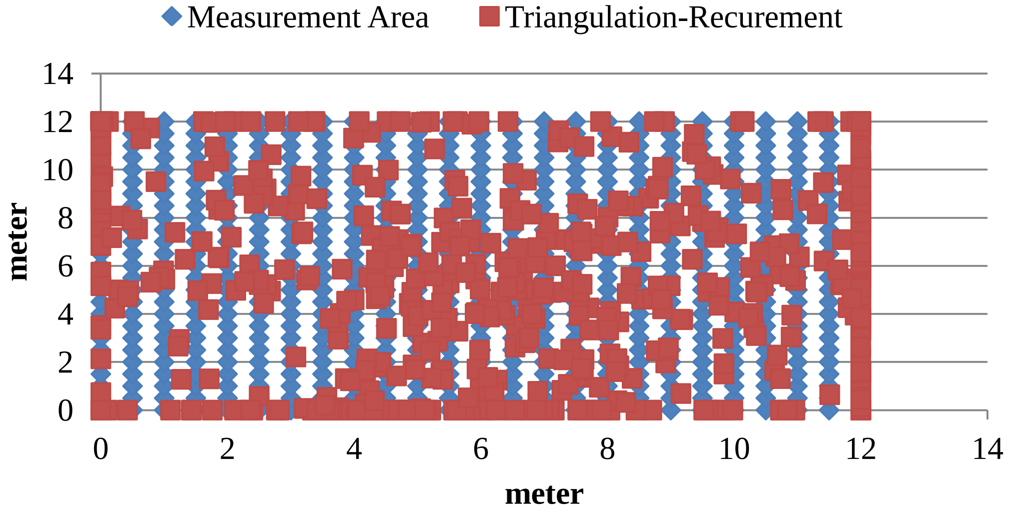
This model is representing when there is 3 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 5.99 meter, minimum error is 0.05 meter, maximum error is 95.27 meter and standard deviation is 7.55 meter. (Figure 4.24)

In Figure 4.25, we restricted estimated location with measurement area. 344 nodes were out of area. Average is 3.55 meter, minimum error is 0.00, maximum error is 11.88 meter and standard deviation is 2.45 meter.



N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	5.99	0.05	95.27	7.55

Figure 4.24 Experiment on 3 dBm Noise Environment (12mx12m)



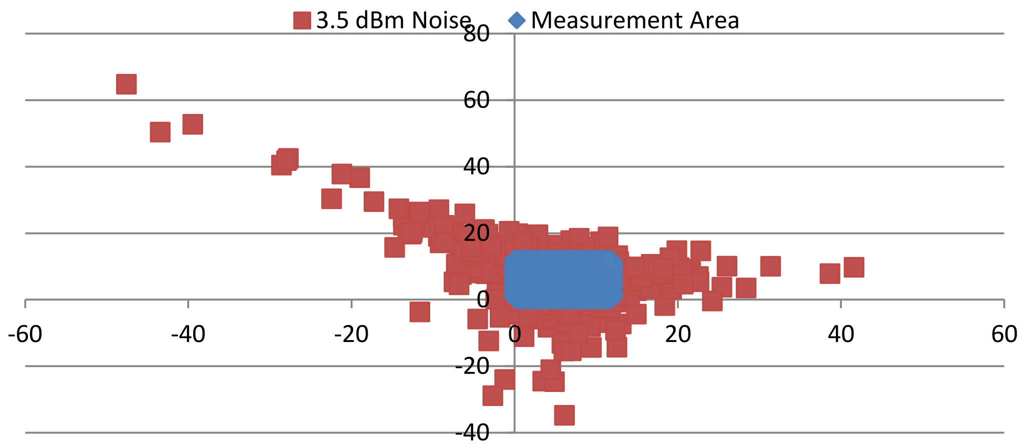
N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	3.55	0.00	11.88	2.45

Figure 4.25 Experiment on 3 dBm Noise Environment (12mx12m)

4.4.2.8 12mx12m Area 3.5 dBm

This model is representing when there is 3.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.

Average is 6.87 meter, minimum error is 0.10 meter, maximum error is 74.84 meter and standard deviation is 7.60 meter. (Figure 4.26)



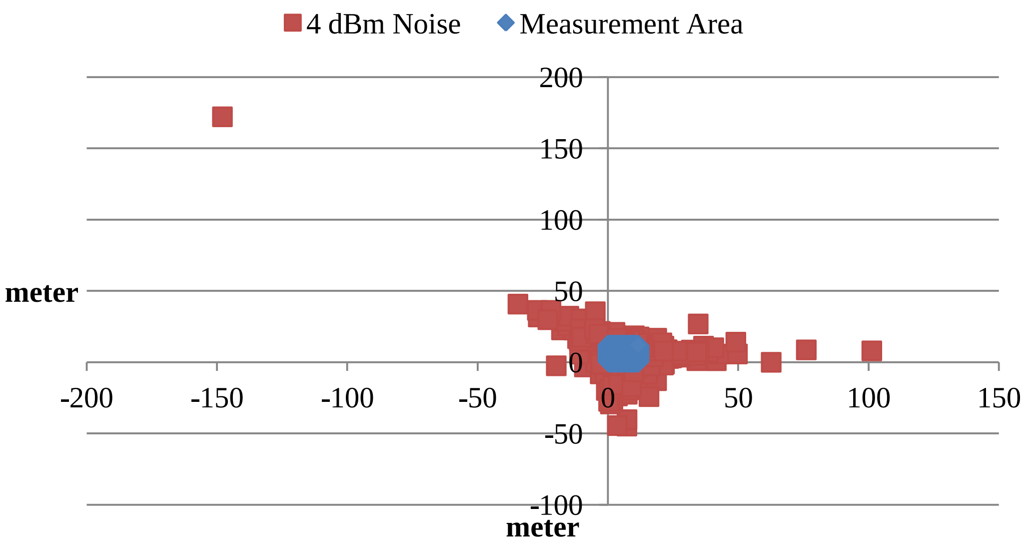
N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	6.87	0.10	74.84	7.60

Figure 4.26 Experiment on 3.5 dBm Noise Environment (12mx12m)

4.4.2.9 12mx12m Area 4 dBm

This model is representing when there is 4 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.

Average is 8.98 meter, minimum error is 0.07 meter, maximum error is 218.34 meter and standard deviation is 12.49 meter. (Figure 4.27)



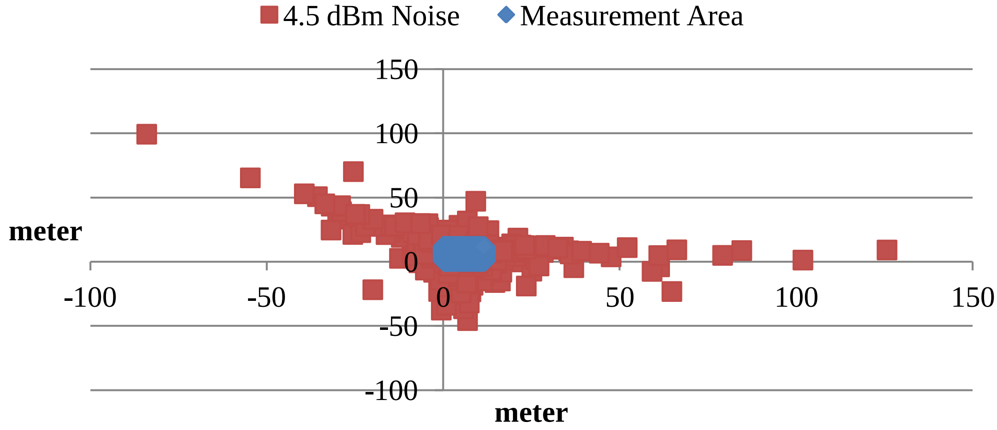
N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	8.98	0.07	218.34	12.49

Figure 4.27 Experiment on 4 dBm Noise Environment (12mx12m)

4.4.2.10 12mx12m Area 4.5 dBm

This model is representing when there is 4.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.

Average is 10.71 meter, minimum error is 0.07 meter, maximum error is 123.22 meter and standard deviation is 13.94 meter. (Figure 4.28)

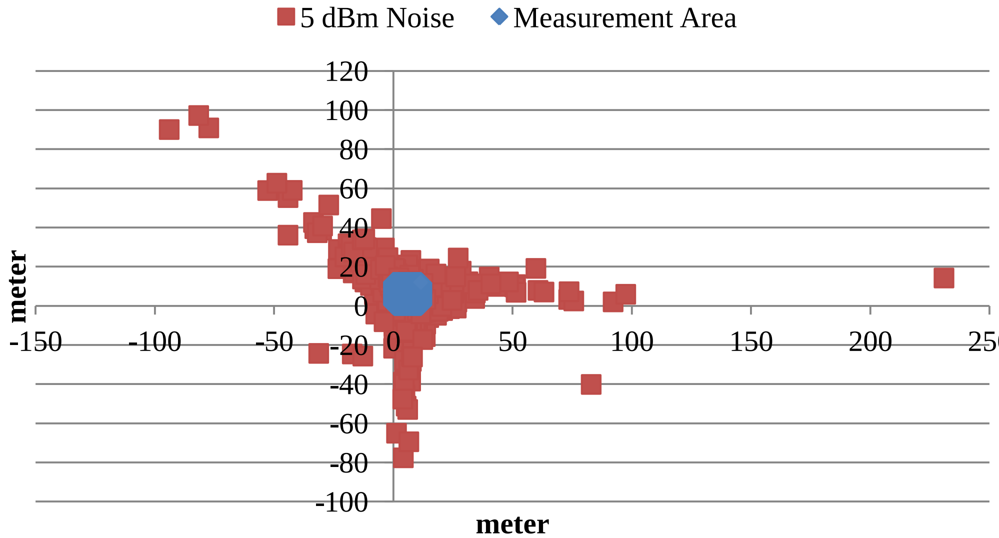


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	10.71	0.07	123.22	13.94

Figure 4.28 Experiment on 4.5 dBm Noise Environment (12mx12m)

4.4.2.11 12mx12m Area 5 dBm

This model is representing when there is 5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 12.42 meter, minimum error is 0.16 meter, maximum error is 219.42 meter and standard deviation is 18.03 meter. (Figure 4.29)

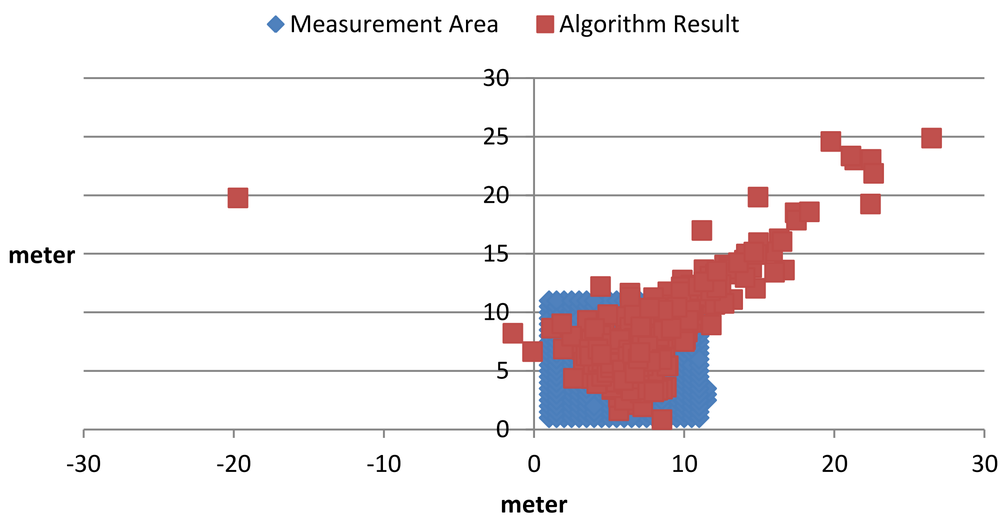


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	12.42	0.16	219.42	18.03

Figure 4.29 Experiment on 5 dBm Noise Environment (12mx12m)

4.4.2.12 Experiment with Real Data

In chapter 3, environment with real data is described. $AP1, AP2 \ and \ AP3$ is used during experiment. Average is 4.23 meter, minimum error is 0.41 meter, maximum error is 25.39 meter, and standard deviation is 3.21 meter. (Figure 4.30)



Average Error	Minimum Error	Maximum Error	Standard Deviation
4.23	0.41	25.39	3.21

Figure 4.30 Experiment on Real Data (12mx12m)

4.4.3 24m x 24m Measurement Area

Circle figures represent access point placement. There are 2397 nodes, however we ignore nodes where it is access point coordinates. 2394 data features were used within an interval of 0.5 meter in an area of 24 square meters (m^2). (Figure 4.31)

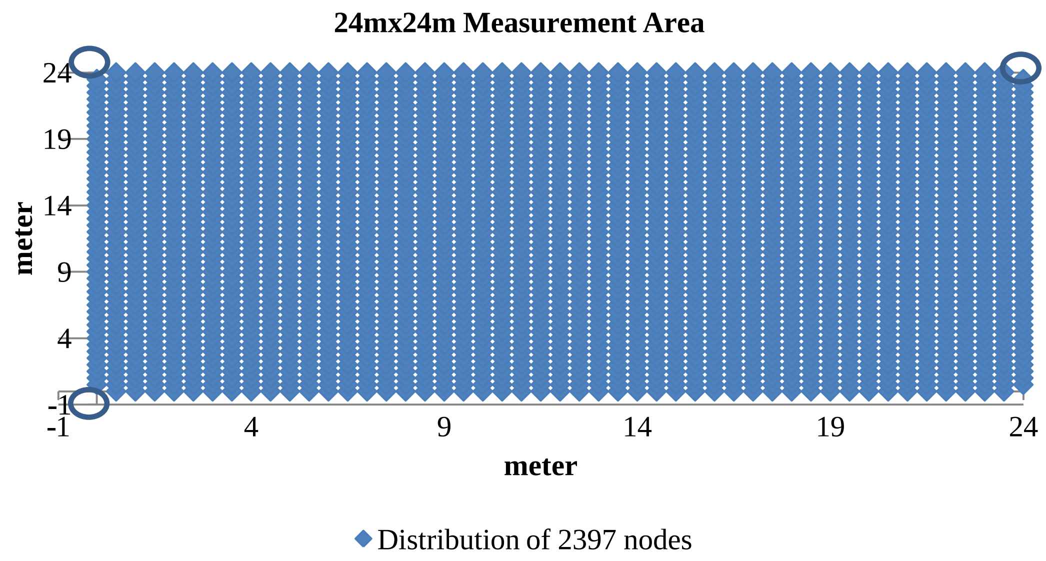
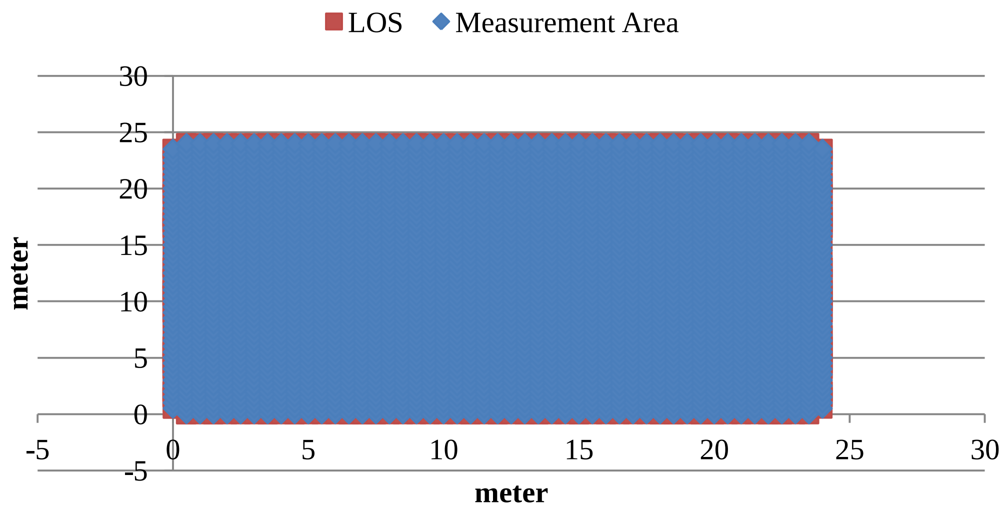


Figure 4.31 24mx24m Measurement Area-Access Point Placement

4.4.3.1 24m x 24m (LOS)

There are not any obstacles between transmitter and receiver in LOS environment. This model is representing when there is any signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 0.0 meter, minimum error is 0.0 meter, maximum error is 0.0 meter and standard deviation is 0.0 meter. (Figure 4.32)



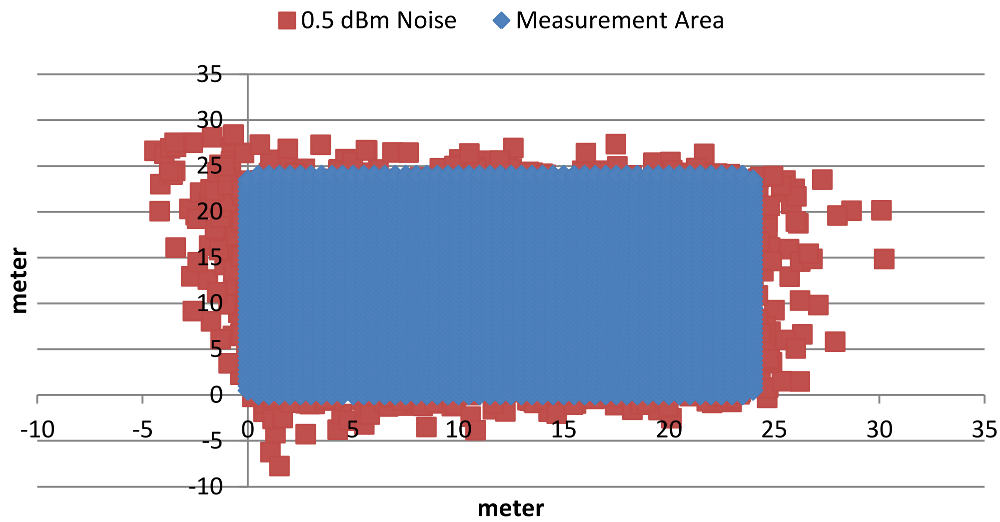
N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	0.0	0.0	0.0	0.0

Figure 4.32 Experiment on LOS Environment (24mx24m)

4.4.3.2 24m x 24m (0.5 dBm Noise)

This model is representing when there is 0.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.

Average is 1.65 meter, minimum error is 0.02 meter, maximum error is 8.88 meter and standard deviation is 1.20 meter. (Figure 4.33)



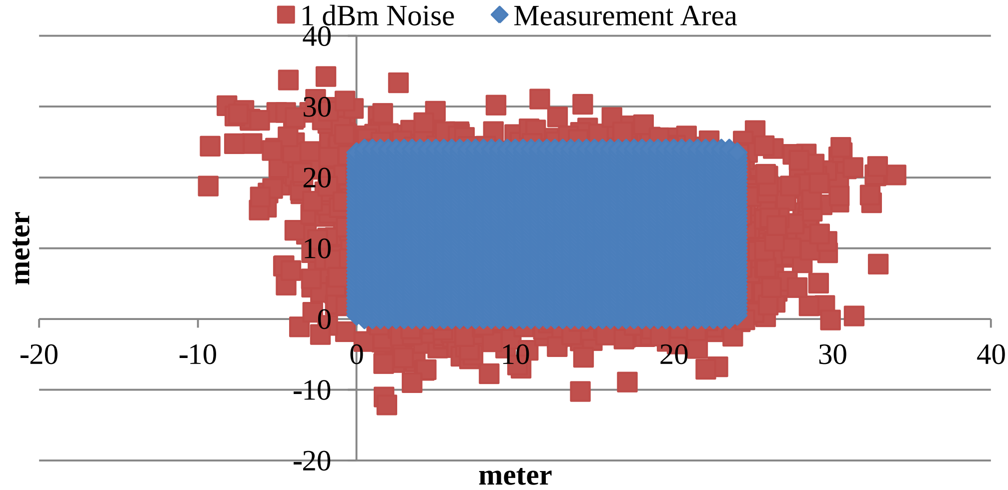
N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	1,65	0,02	8,88	1,20

Figure 4.33 Experiment on 0.5 dBm Noise Environment (24mx24m)

4.4.3.3 24m x 24m (1 dBm Noise)

This model is representing when there is 1 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.

Average is 3.84 meter, minimum error is 0.05 meter, maximum error is 30.94 meter and standard deviation is 3.76 meter. (Figure 4.34)

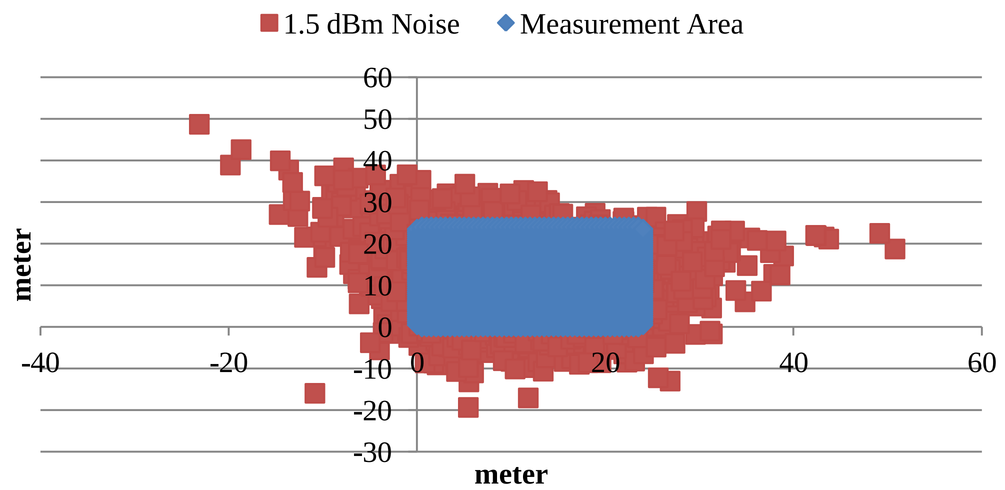


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	3.84	0.05	30.94	3.76

Figure 4.34 Experiment on 1 dBm Noise Environment (24mx24m)

4.4.3.4 24m x 24m (1.5 dBm Noise)

This model is representing when there is 1.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 5.53 meter, minimum error is 0.08 meter, maximum error is 37.36 meter and standard deviation is 4.81 meter. (Figure 4.35)

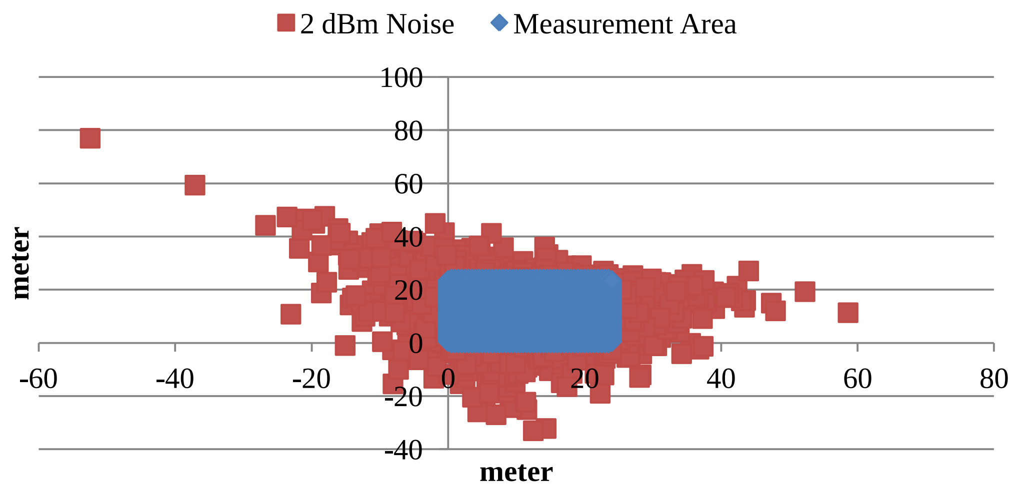


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	5.53	0.08	37.36	4.81

Figure 4.35 Experiment on 1.5 dBm Noise Environment (24mx24m)

4.4.3.5 24m x 24m (2 dBm Noise)

This model is representing when there is 2 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.
Average is 5.53 meter, minimum error is 0.08 meter, maximum error is 37.36 meter and standard deviation is 4.81 meter. (Figure 4.36)

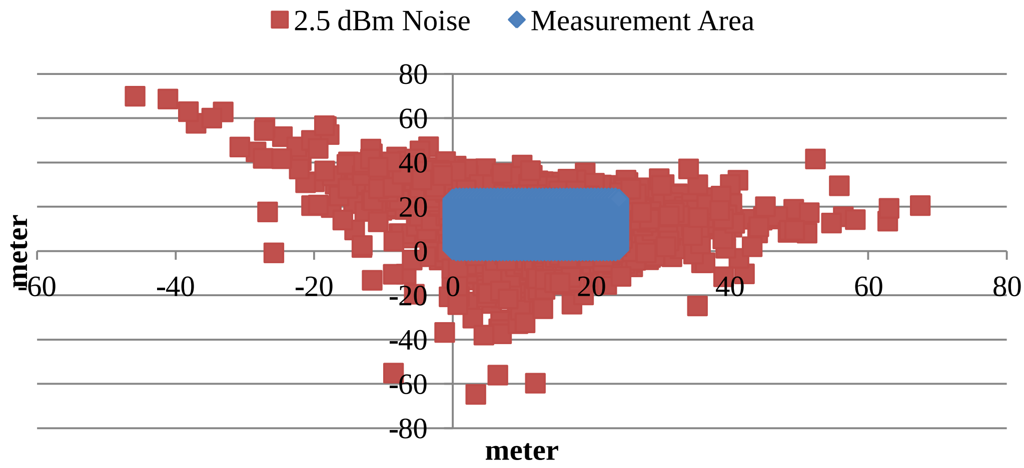


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	7.40	0.06	81.68	6.45

Figure 4.36 Experiment on 2 dBm Noise Environment (24mx24m)

4.4.3.6 24m x 24m (2.5 dBm Noise)

This model is representing when there is 2.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.
Average is 9.59 meter, minimum error is 0.15 meter, maximum error is 83.69 meter and standard deviation is 8.54 meter. (Figure 4.37)

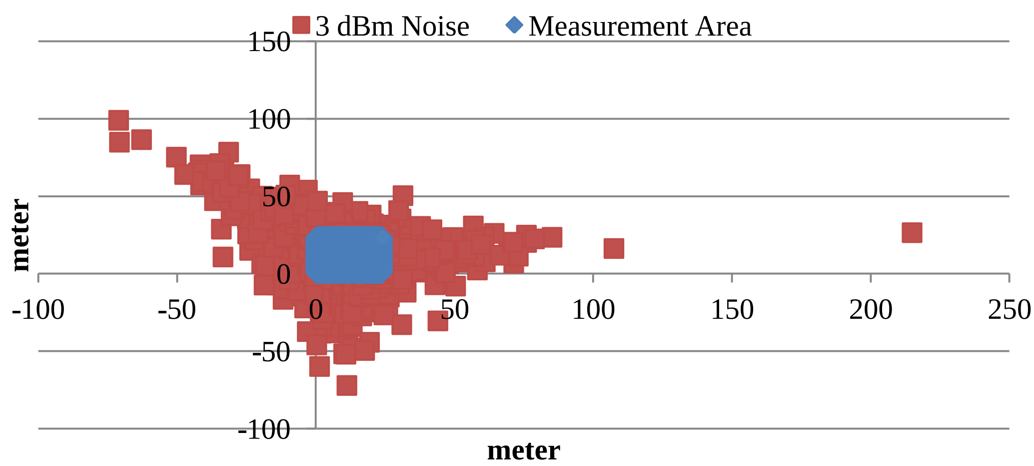


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	9.59	0.15	83.69	8.54

Figure 4.37 Experiment on 2.5 dBm Noise Environment (24mx24m)

4.4.3.7 24m x 24m (3 dBm Noise)

This model is representing when there is 3 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 12.12 meter, minimum error is 0.16 meter, maximum error is 191.46 meter and standard deviation is 12.09 meter. (Figure 4.38)

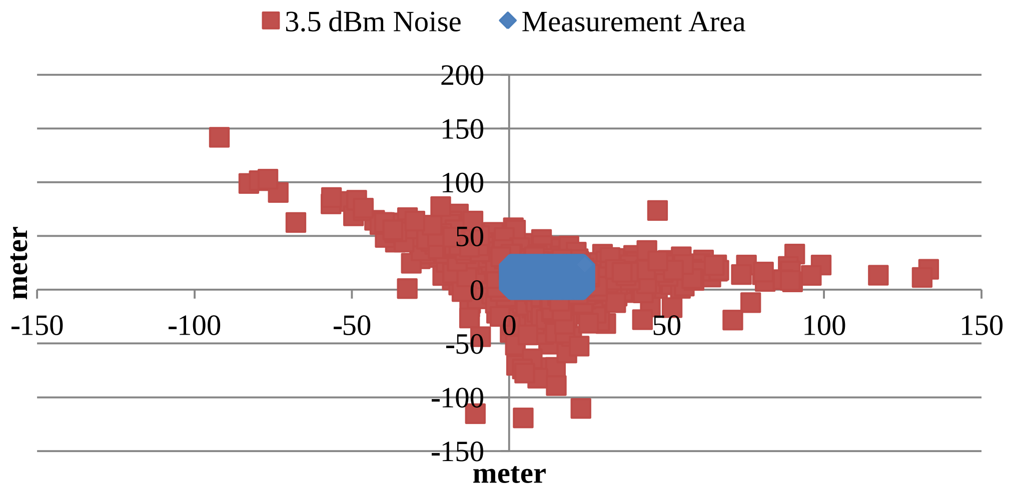


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	12.12	0.16	191.46	12.09

Figure 4.38 Experiment on 3 dBm Noise Environment (24mx24m)

4.4.3.8 24m x 24m (3.5 dBm Noise)

This model is representing when there is 3.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 14.25 meter, minimum error is 0.07 meter, maximum error is 157.42 meter and standard deviation is 15.03 meter. (Figure 4.39)

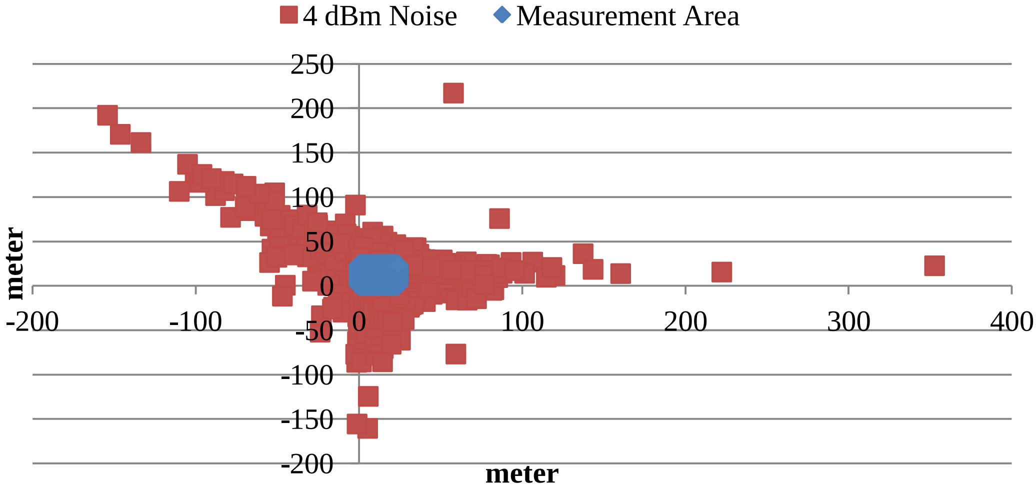


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	14.25	0.07	157.52	15.03

Figure 4.39 Experiment on 3.5 dBm Noise Environment (24mx24m)

4.5.3.9 24m x 24m (4 dBm Noise)

This model is representing when there is 4 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 18.25 meter, minimum error is 0.18 meter, maximum error is 331.20 meter and standard deviation is 22.40 meter. (Figure 4.40)

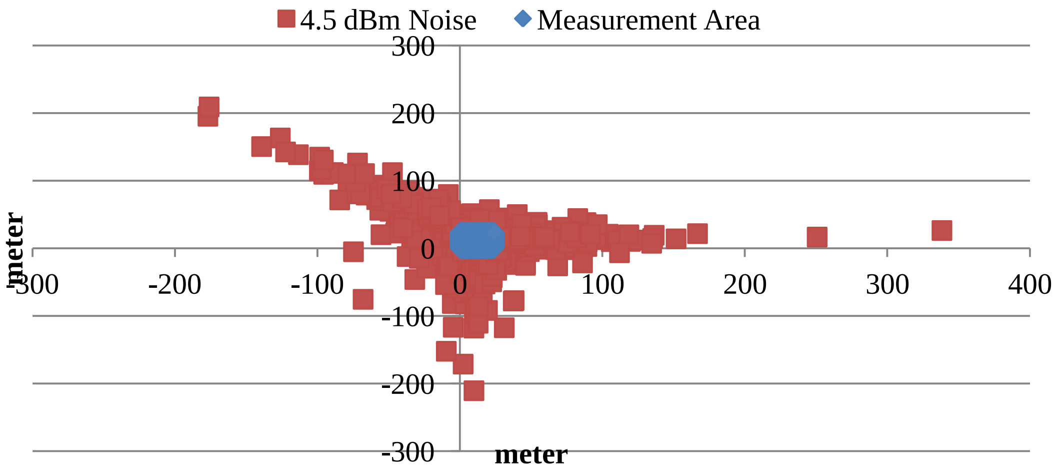


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	18.55	0.18	331.20	22.40

Figure 4.40 Experiment on 4 dBm Noise Environment (24mx24m)

4.4.3.10 24m x 24m (4.5 dBm Noise)

This model is representing when there is 4.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 21.24 meter, minimum error is 0.22 meter, maximum error is 316.41 meter and standard deviation is 25.35 meter. (Figure 4.41)

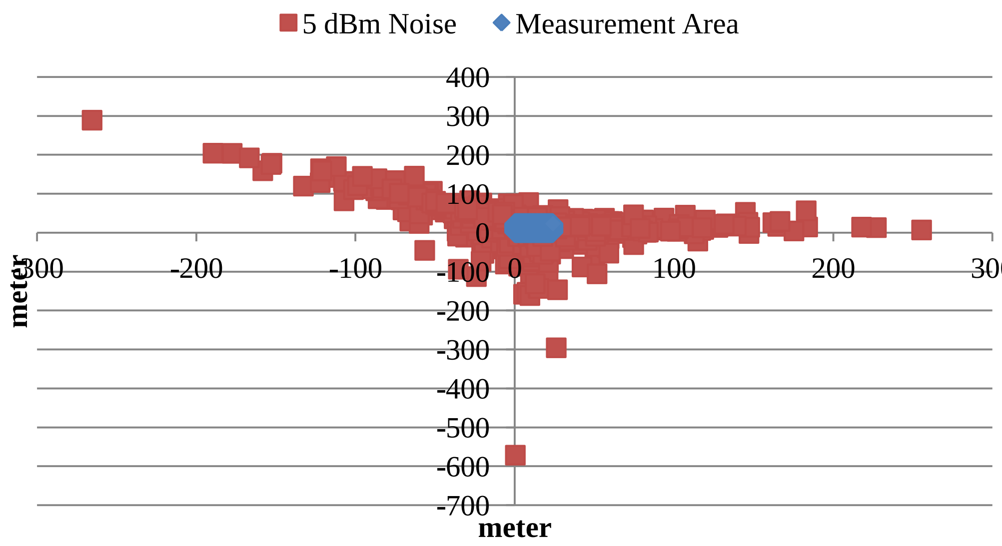


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	21.24	0.22	316.41	25.35

Figure 4.41 Experiment on 4.5 dBm Noise Environment (24mx24m)

4.4.3.11 24m x 24m (5 dBm Noise)

This model is representing when there is 5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 24.76 meter, minimum error is 0.20 meter, maximum error is 578.28 meter and standard deviation is 33.34 meter. (Figure 4.42)



N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	24.76	0.20	578.28	33.34

Figure 4.42 Experiment on 5 dBm Noise Environment (24mx24m)

4.4.4 Experiment Results Summary Table

Table 4.1 is shown all measurement area result in a summary table. 4* is representing restricted area experiment. Summary table is clearly shown us, in triangulation algorithm, while expanding measurement area and increasing noise, errors are getting increased.

Best accuracies are measured in LOS environment in 3 different experiment areas. However LOS environment is not a good example of indoor environment, so algorithm gave best accuracy in 6 square meter area with 0.5 dBm noisy environment. Also experiment show that when we restrict area, accuracy increased with 109%.

Table 4.1 Triangulation Experiment Result Summary Table

TRIANGULATION														
	6mx6m					12mx12m					24mx24m			
dBm	avg	min	max	std		avg	min	max	std		avg	min	max	std
0	0	-0.01	0	0	0	0	0	0.02	0	0	0	0	0.02	0
0.5	0.42	0.02	1.82	0.33	0.5	0.83	0.03	4.54	0.63	0.5	1.65	0.02	8.88	1.2
1	0.86	0.03	4.01	0.61	1	1.72	0.05	8.08	1.23	1	3.84	0.05	30.94	3.76
1.5	1.35	0.03	7.14	1.1	1.5	2.59	0.02	24.46	2.26	1.5	5.53	0.08	37.36	4.81
2	1.93	0.04	10.66	1.79	2	3.6	0.08	27.14	2.94	2	7.4	0.06	81.68	6.45
2.5	2.31	0.04	9.36	1.93	2.5	4.64	0.04	36.81	4.34	2.5	9.59	0.15	83.69	8.54
3	2.94	0.02	18.31	2.91	3	5.99	0.05	95.27	7.55	3	12.12	0.16	191.46	12.09
3.5	3.65	0.04	30.5	4.19	3.5	6.87	0.1	74.84	7.6	3.5	14.25	0.07	157.52	15.03
4	4.3	0.04	28.38	4.56	4	8.98	0.07	218.34	12.49	4	18.55	0.18	331.2	22.4
4*	2.05	0	6.72	1.24	4.5	10.71	0.07	123.22	13.94	4.5	21.24	0.22	316.41	25.35
4.5	5.54	0.33	42.07	7.05	5	12.42	0.16	219.42	18	5	24.76	0.2	578.28	33
5	6.32	0.14	62.4	7,22										
Real Data	2.32	0.2	10.33	1.35	Real Data	4.23	0.41	25.39	3.21					

CHAPTER 5

Maximum Likelihood

Maximum Likelihood (MLE) is lateration-based position estimation algorithm. It is required coordinate known APs. The main idea is calculate least mean square error (MSE) to estimate location of target device.

Firstly, we are finding distance between target point and anchor nodes. Then the estimated target node defines an error which is error that actual and estimated distance for target node. We consider $(x_1, y_1), (x_2, y_2), (x_3, y_3), \text{and}(x_4, y_4)$ are our AP locations. (X, Y) is the target node. Euclidean distance formula is using to find distance between anchor nodes and target node. (4.1)
d is shows Euclidean distance, s_i represent coordinate calculated from RSSI measurement, s_i' is shows real coordinate for target node. [23, 24]

$$(x_1 - X)^2 + (y_1 - Y)^2 = d_1^2 \ldots (x_n - X)^2 + (y_n - Y)^2 = d_n^2 \tag{5.1}$$

To solve equation and estimate location for(X, Y), we are subtracting (x_4, y_4) from other APs distance:

$$(x_1 - X)^2 - (x_4 - X)^2 + (y_1 - Y)^2 - (y_4 - Y)^2 = d_1^2 - d_4^2 \tag{5.2.a}$$

$$(x_2 - X)^2 - (x_4 - X)^2 + (y_2 - Y)^2 - (y_2 - Y)^2 = d_2^2 - d_4^2 \tag{5.2.b}$$

$$(x_3 - X)^2 - (x_3 - X)^2 + (y_3 - Y)^2 - (y_3 - Y)^2 = d_3^2 - d_4^2 \tag{5.2.c}$$

Re-arrange equation (4.2.b), (4.2.c) and (4.2.d) to get matrix depends on (X, Y) values;

$$2(x_{4-}\ x_1)x + 2(y_{4-}\ y_1)y\ = (d_1^2 - d_4^2) - (x_1^2 - x_4^2) - (y_1^2 - y_4^2)$$

(5.1.a)

$$2(x_{4-}\ x_2)x + 2(y_{4-}\ y_2)y\ = (d_2^2 - d_4^2) - (x_2^2 - x_4^2) - (y_2^2 - y_4^2)$$

(5.2.b)

$$2(x_{4-}\ x_3)x + 2(y_{4-}\ y_3)y\ = (d_3^2 - d_4^2) - (x_3^2 - x_4^2) - (y_3^2 - y_4^2)$$

(5.3.c)

Re-write equation with matrix form;

$$2 * \begin{bmatrix} x_4 - x_1 & y_4 - x_1 \\ x_4 - x_2 & y_4 - x_2 \\ x_4 - x_3 & y_4 - x_3 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} (d_1^2 - d_4^2) & (x_1^2 - x_4^2) & (y_1^2 - y_4^2) \\ (d_2^2 - d_4^2) & (x_2^2 - x_4^2) & (y_2^2 - y_4^2) \\ (d_3^2 - d_4^2) & (x_3^2 - x_4^2) & (y_3^2 - y_4^2) \end{bmatrix}$$

(5.4)

Since we have matrix form as follows;

$$A = \vec{x} * \vec{b}$$

(5.5)

We can solve equation by using basic formula from (5.5), where

$$A = \begin{bmatrix} 2(x_4 - x_1) & 2(y_4 - x_1) \\ 2(x_4 - x_2) & 2(y_4 - x_2) \\ 2(x_4 - x_3) & 2(y_4 - x_3) \end{bmatrix},\ x = \begin{bmatrix} x \\ y \end{bmatrix},$$

$$b = \begin{bmatrix} (d_1^2 - d_4^2) & (x_1^2 - x_4^2) & (y_1^2 - y_4^2) \\ (d_2^2 - d_4^2) & (x_2^2 - x_4^2) & (y_2^2 - y_4^2) \\ (d_3^2 - d_4^2) & (x_3^2 - x_4^2) & (y_3^2 - y_4^2) \end{bmatrix}$$

(5.6)

Equation (5.5) can be solved by using (5.7)

$$\vec{x} = A^{-1} * \vec{b}$$

(5.7)

In order to use [4.7] $n = m$ and A^{-1}, where n is number of anchor nodes, m is coordinates of target node. If $> m$, to estimate location we need to use minimum mean square error (MMSE) method. MMSE method is most suitable for indoor environment.

$$x = (A^T A)^{-1} * A^T * b \tag{5.8}$$

5.1 Test Bed

Maximum Likelihood algorithm requires 4 access points; $AP1, AP2 , AP3\ and\ AP4$. In equation [4.1]; d_1, d_2, d_3, d_4 are representing$AP1, AP2, AP3\ and\ AP4$'s distance from measurement point.

In order to find distance from measurement point, we are going to use Log-distance path loss model that we mentioned in chapter 2. Estimated distances in each feature were measured using equation (5.6).

5.2 Experimental Results

In chapter 3, synthetic data is created as triangulation method input. 6mx6m, 12mx12m and 24mx24m measurement areas are used. For each experiment, equation (2.2), (3.1) and (5.8) are applied.

5.2.1 6m x 6m Measurement Area

Coordinate of access points respectively: (0, 0), (6, 0), (6, 6) and (0, 6). Circle figures represent access point placement. There are 256 test nodes, however we ignore nodes where it is access point coordinates. 252 data features were used within an interval of 0.4 meter in an area of 6 square meters (m^2).

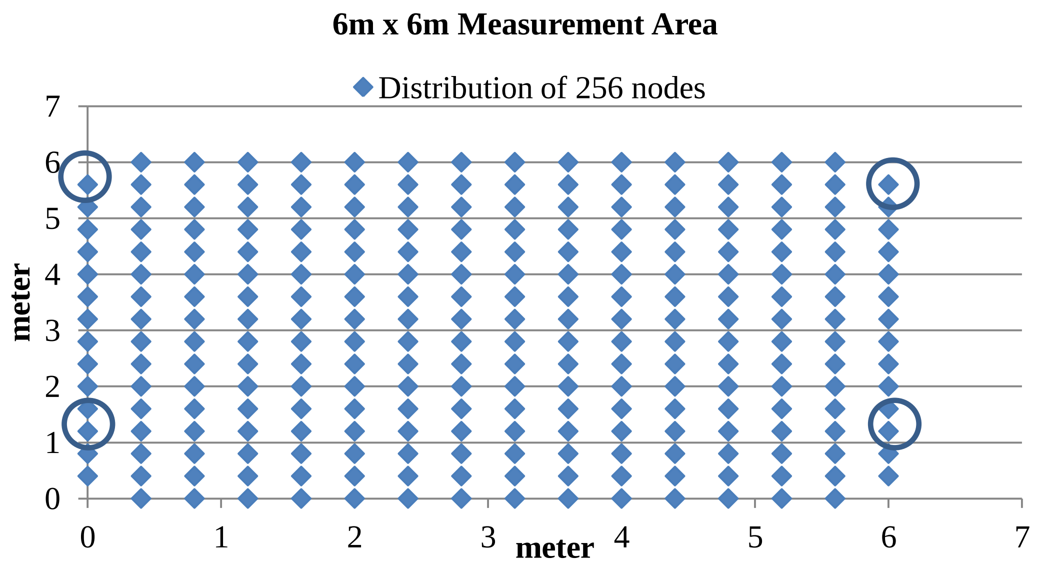
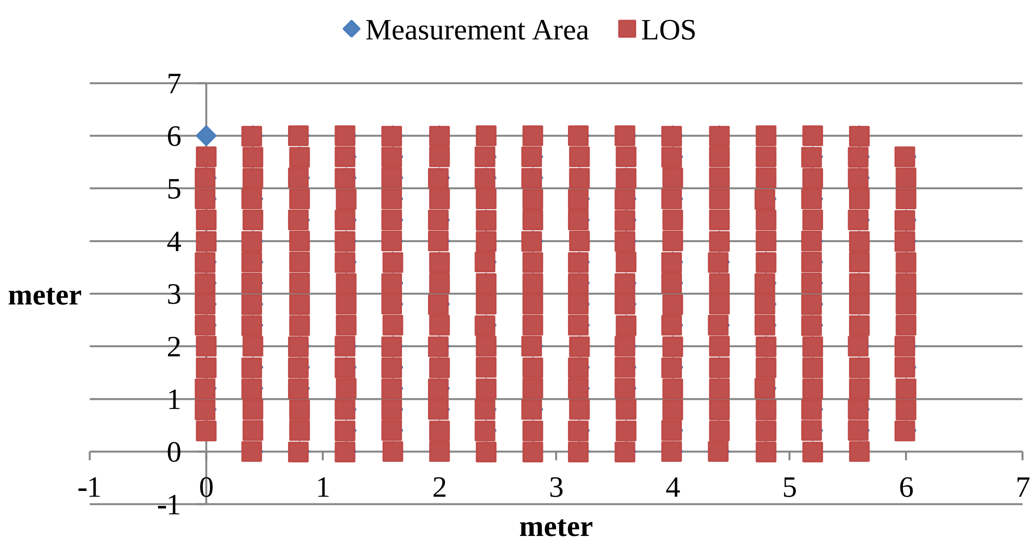


Figure 5.1 6mx6m Measurement Area-Access Point Placement

5.2.1.1 6mx6m Area (LOS)

There are not any obstacles between transmitter and receiver in LOS environment. This model is representing when there is any signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 0.01 meter, minimum error is 0.00 meter, maximum error is 0.01 meter and standard deviation is 0.01 meter. (Figure 5.2)

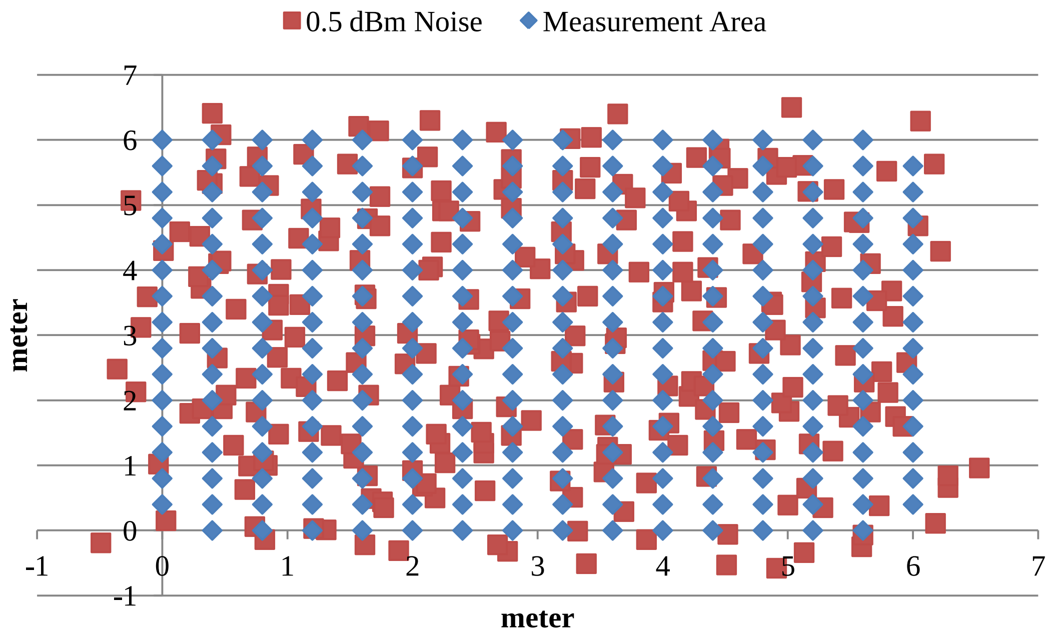


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	0.00	0.00	0.01	0.00

Figure 5.2 Experiment on LOS Environment (6mx6m)

5.2.1.2 6mx6m Area (0.5 dBm Noise)

This model is representing when there is 0.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 0.33 meter, minimum error is 0.03 meter, maximum error is 1.40 meter and standard deviation is 0.2 meter. (Figure 5.3)

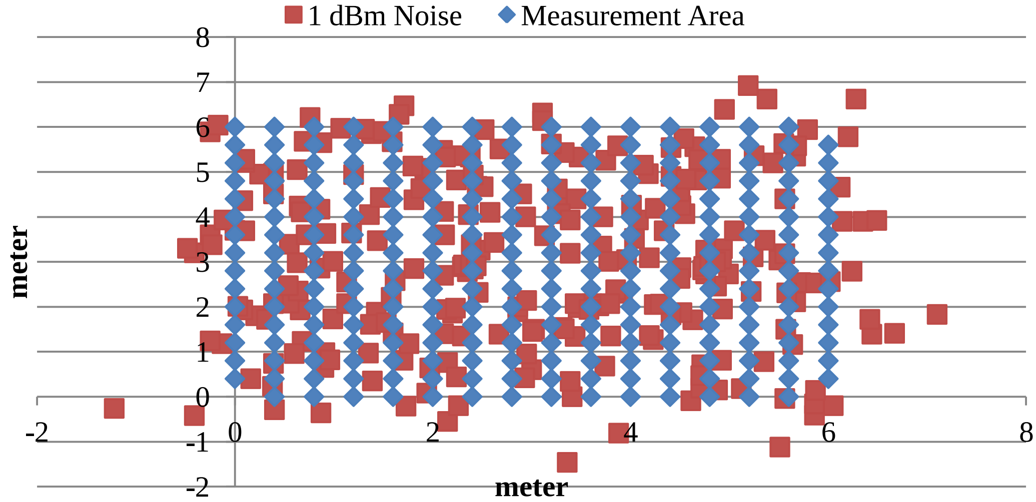


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	0.33	0.03	1.40	0.2

Figure 5.3 Experiment on 0.5 Noise Environment (6mx6m)

5.2.1.3 6mx6m Area (1 dBm Noise)

This model is representing when there is 1 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 0.55 meter, minimum error is 0.02 meter, maximum error is 2.14 meter and standard deviation is 0.38 meter. (Figure 5.4)

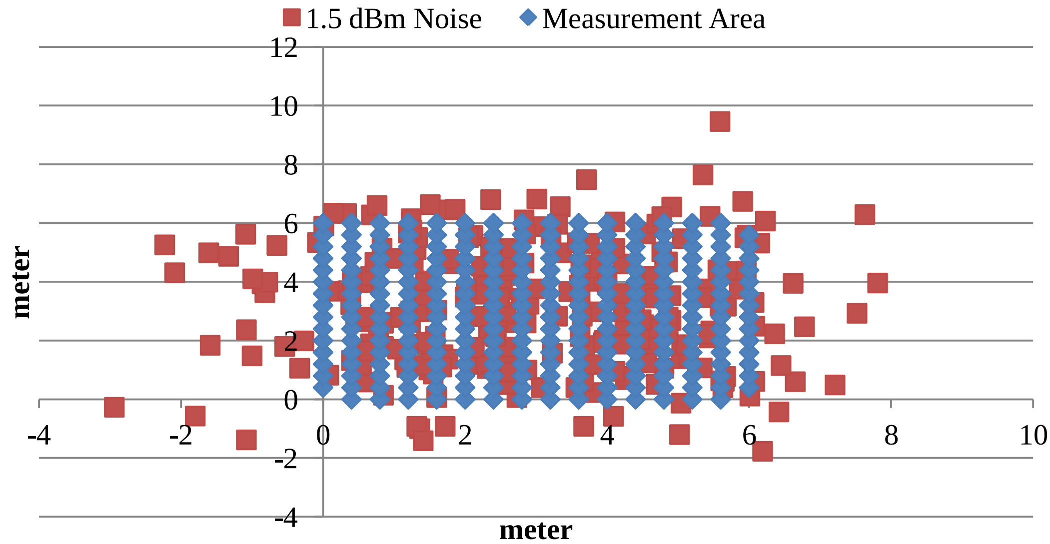


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	0.55	0.02	2.14	0.38

Figure 5.4 Experiment on 1 Noise Environment (6mx6m)

5.2.1.4 6mx6m Area (1.5 dBm Noise)

This model is representing when there is 1.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 1.03 meter, minimum error is 0.05 meter, maximum error is 4.49 meter and standard deviation is 0.66 meter. (Figure 5.5)



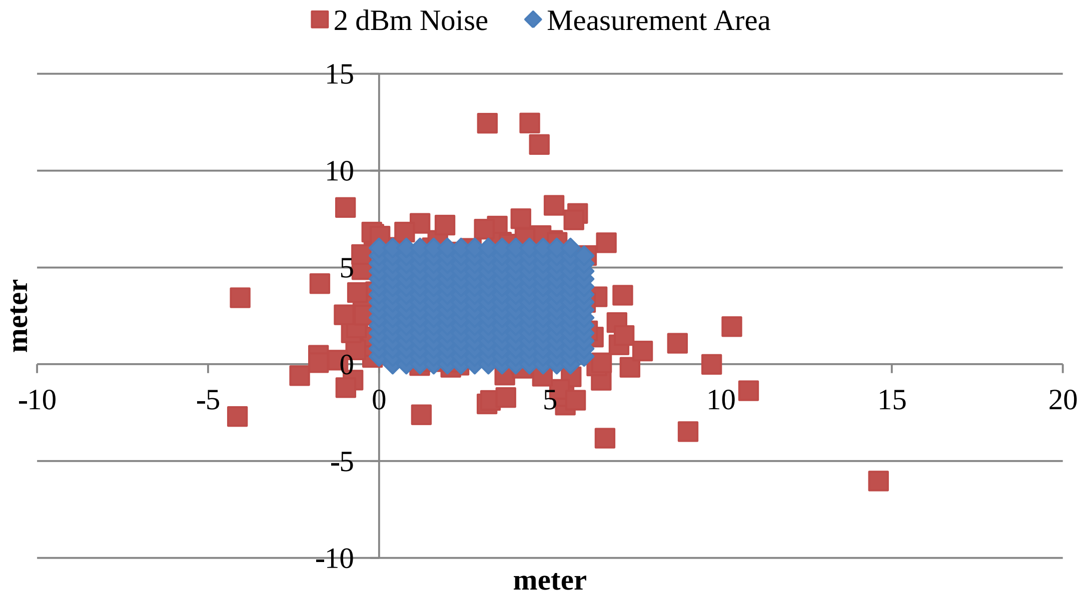
N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	1.03	0.05	4.49	0.66

Figure 5.5 Experiment on 1.5 Noise Environment (6mx6m)

5.2.1.5 6mx6m Area (2 dBm Noise)

This model is representing when there is 2 dBm signal loss in measurement area. Features’ real location is blue figure; estimated location’s are red figures.

Average is 1.55 meter, minimum error is 0.07 meter, maximum error is 12.433 meter and standard deviation is 1.39 meter. (Figure 5.6)



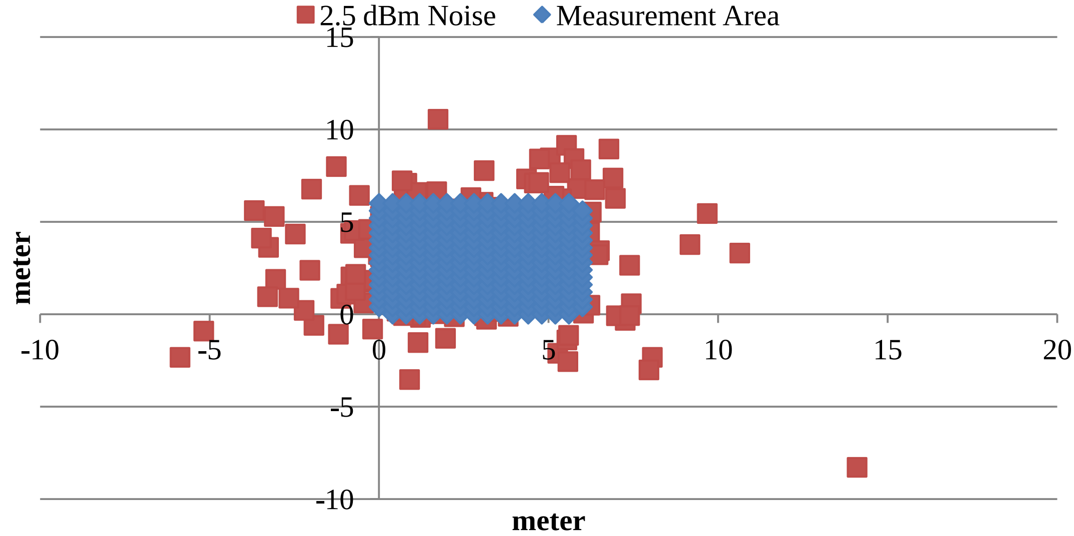
N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	1.55	0.07	12.33	1.39

Figure 5.6 Experiment on 2 Noise Environment (6mx6m)

5.2.1.6 6mx6m Area (2.5 dBm Noise)

This model is representing when there is 2.5 dBm signal loss in measurement area. Features’ real location is blue figure; estimated location’s are red figures.

Average is 1.73 meter, minimum error is 0.03 meter, maximum error is 13.06 meter and standard deviation is 1.39 meter. (Figure 5.7)

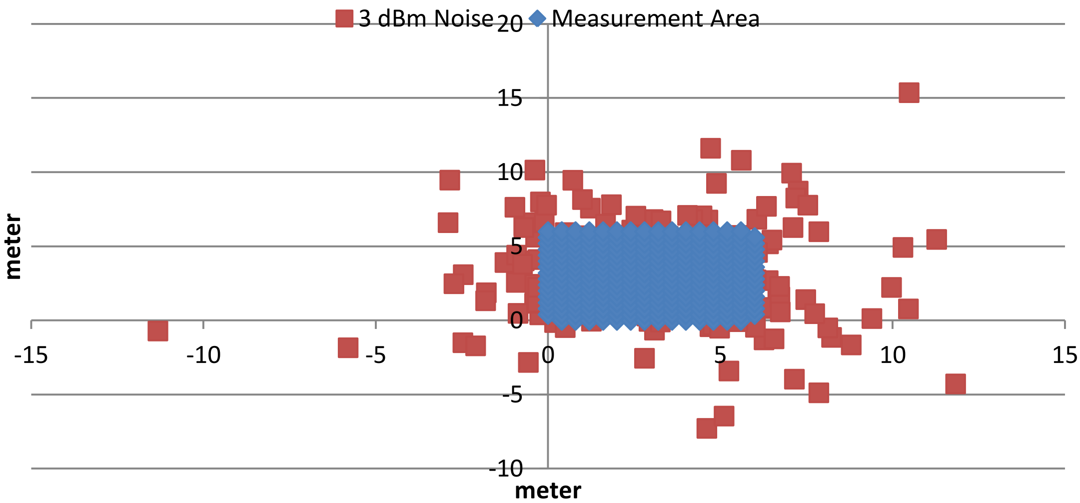


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	1.73	0.03	13.06	1.39

Figure 5.7 Experiment on 2.5 Noise Environment (6mx6m)

5.2.1.7 6mx6m Area (3 dBm Noise)

This model is representing when there is 3 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 2.26 meter, minimum error is 0.10 meter, maximum error is 12.73 meter and standard deviation is 1.83 meter. (Figure 5.8)



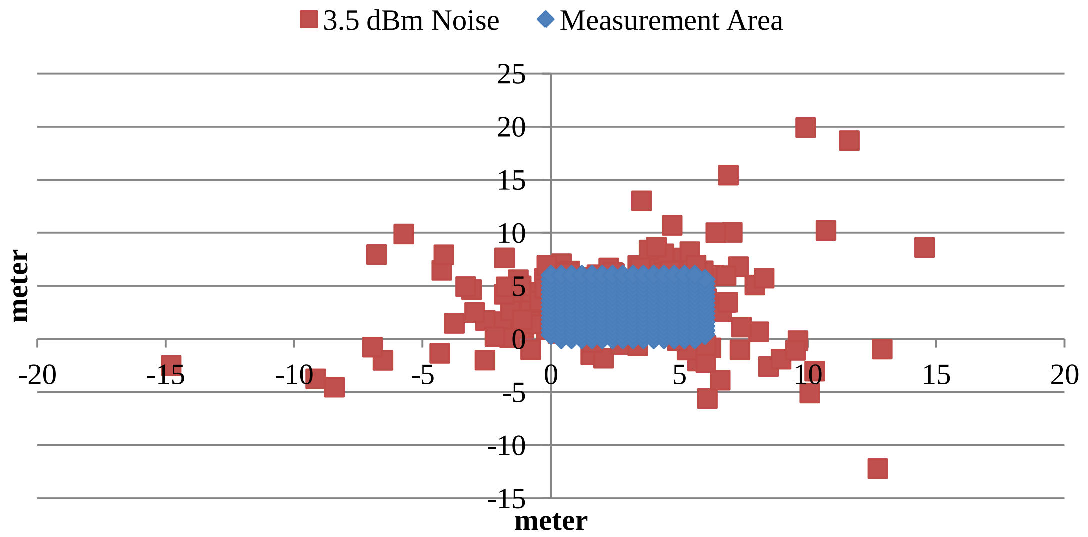
N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	2.26	0.10	12.73	1.83

Figure 5.8 Experiment on 3 Noise Environment (6mx6m)

5.5.1.8 6mx6m Area (3.5 dBm Noise)

This model is representing when there is 3.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.

Average is 2.80 meter, minimum error is 0.20 meter, maximum error is 17.41 meter and standard deviation is 2.76 meter. (Figure 5.9)



N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	2.80	0.20	17.41	2.76

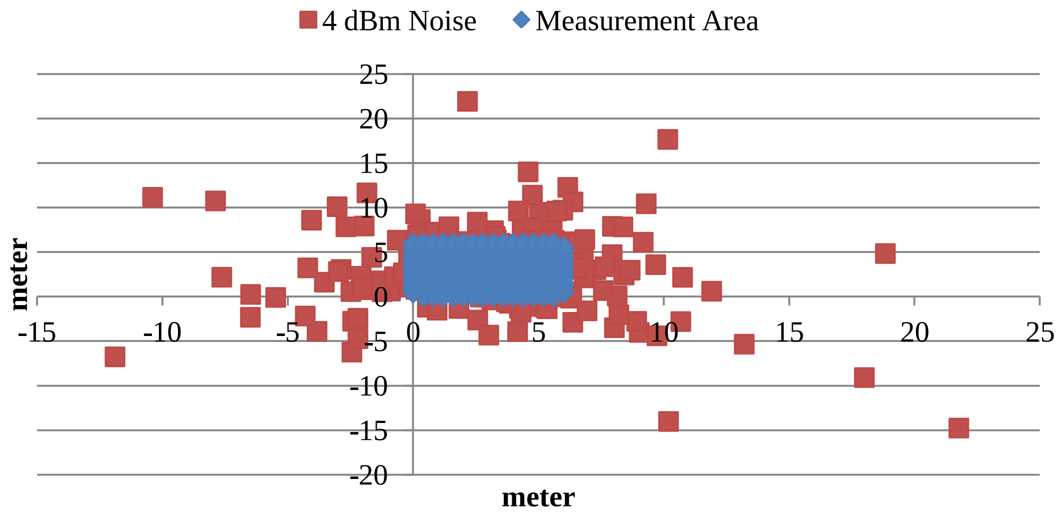
Figure 5.9 Experiment on 3.5 Noise Environment (6mx6m)

5.2.1.9 6mx6m Area (4 dBm Noise)

This model is representing when there is 4 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.

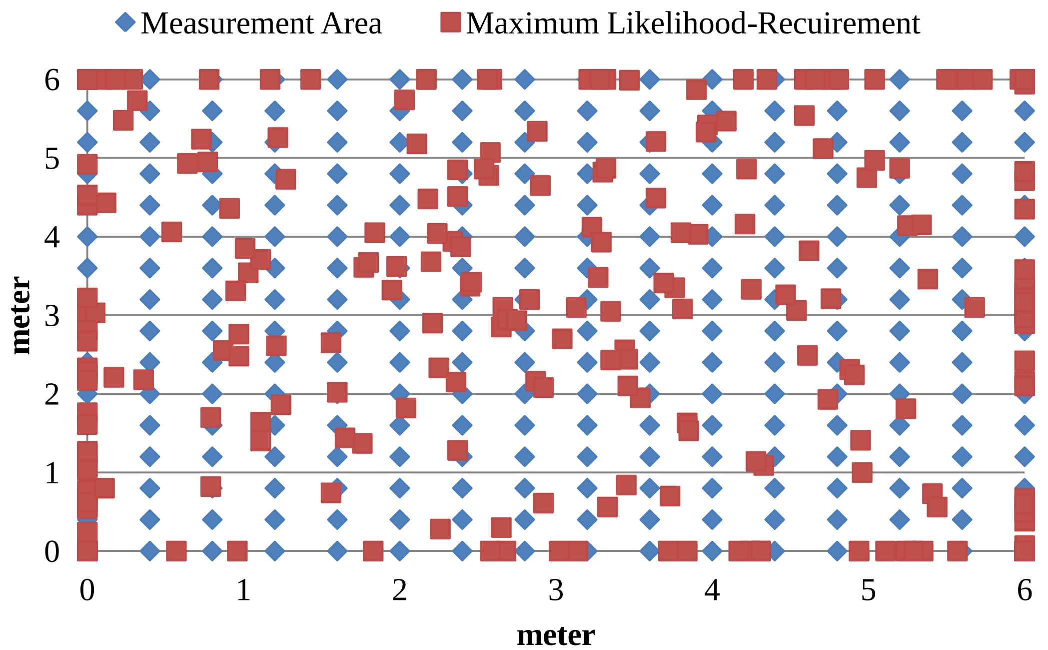
Average is 3.35 meter, minimum error is 0.06 meter, maximum error is 23.10 meter and standard deviation is 3.23 meter. (Figure 5.10)

In Figure 5.11, we restricted estimated location with measurement area. Average is 1.90 meter, minimum error is 0.06, maximum error is 5.73 meter and standard deviation is 1.10 meter.



N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	3.35	0.06	23.10	3.23

Figure 5.10 Experiment on 4 Noise Environment (6mx6m)



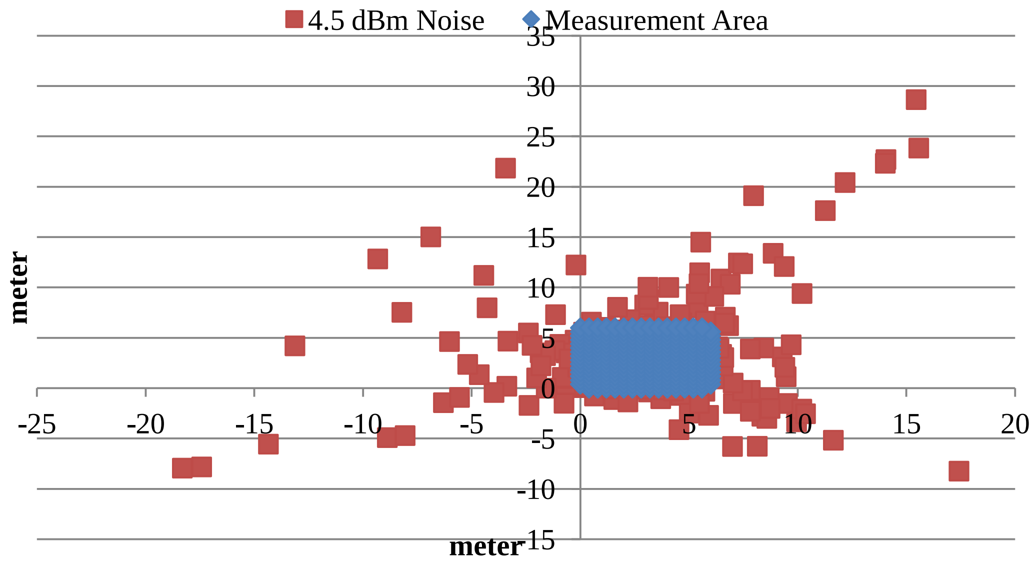
N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	1.90	0.06	5.73	1.10

Figure 5.11 Experiment on 4 Noise Environment (6mx6m) -Recuirement

5.2.10 6mx6m Area (4.5 dBm Noise)

This model is representing when there is 4.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.

Average is 4.10 meter, minimum error is 0.51 meter, maximum error is 26.30 meter and standard deviation is 4.32 meter. (Figure 5.12)



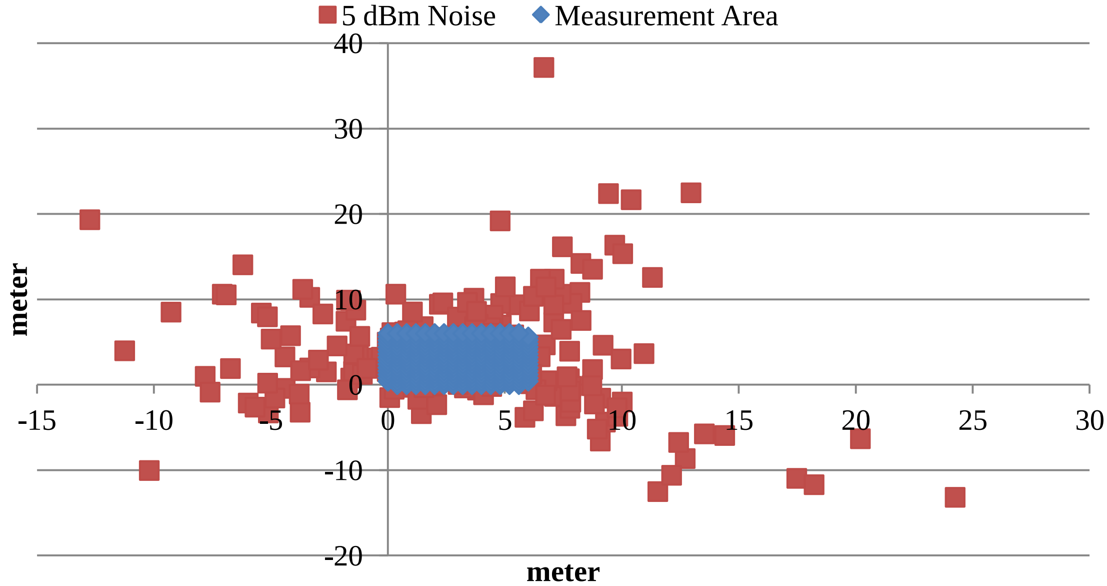
N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	4.10	0.51	26.30	4.32

Figure 5.12 Experiment on 4.5 Noise Environment (6mx6m)

5.2.1.11 6mx6m Area (5 dBm Noise)

This model is representing when there is 5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.

Average is 4.88 meter, minimum error is 0.43 meter, maximum error is 31.60 meter and standard deviation is 4.45 meter. (Figure 5.13)

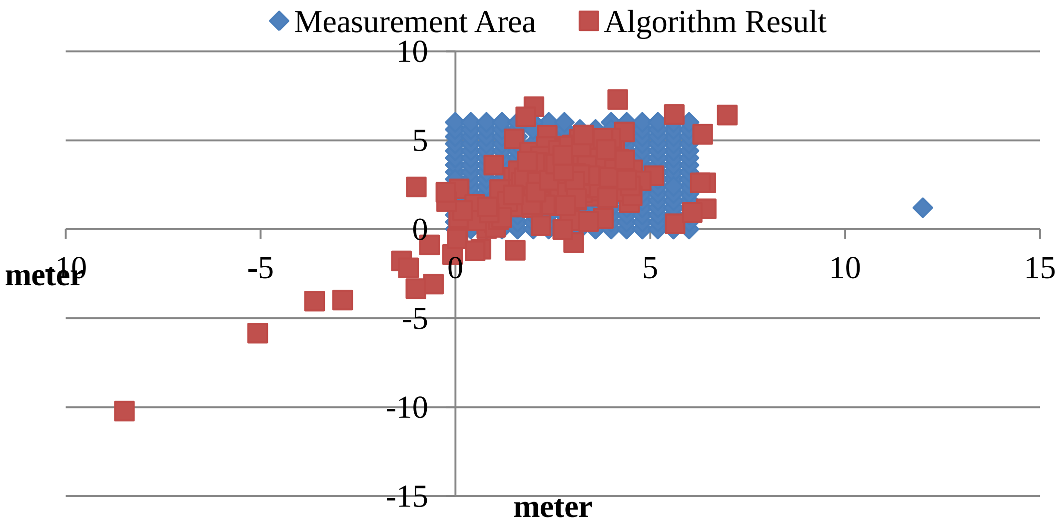


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	4.88	0.43	31.60	4.45

Figure 5.13 Experiment on 5 Noise Environment (6mx6m)

5.2.1.12 Experiment with Real Data

In chapter 3, environment with real data is described. $AP1, AP2$ *and* $AP3$ is used during experiment. Average is 2.15 meter, minimum error is 0.16 meter, maximum error is 16.16 meter, and standard deviation is 1.63 meter. (Figure 5.14)



Average Error	Minimum Error	Maximum Error	Standard Deviation
2.15	0.16	16.16	1.63

Figure 5.14 Experiment on Real Data (6mx6m)

5.2.2 12m x 12m Measurement Area

Circle figures represent access point placement. There are 625 test nodes, however we ignore nodes where it is access point coordinates. 621 data features were used within an interval of 0.5 meter in an area of 12 square meters (m^2). (Figure 5.15)

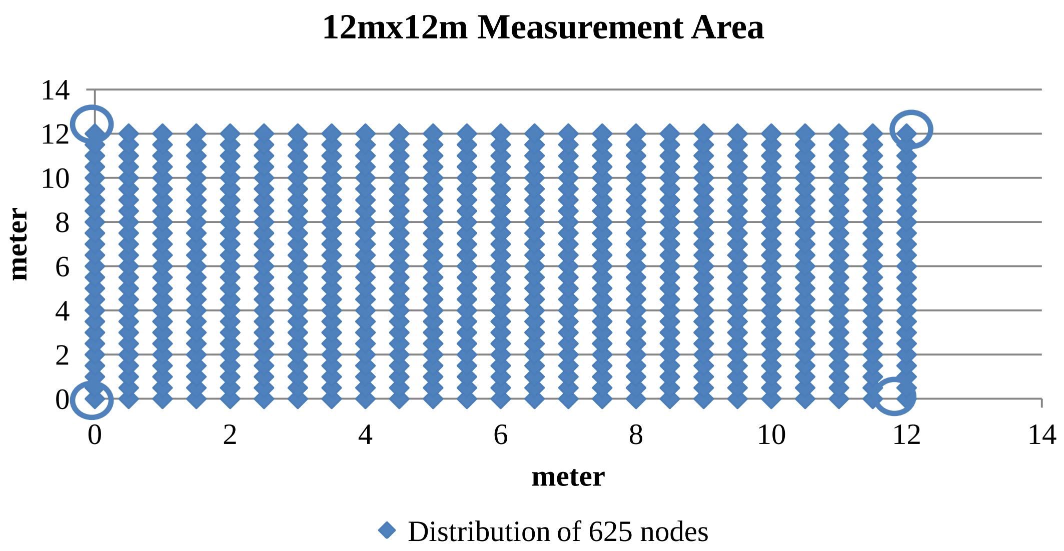
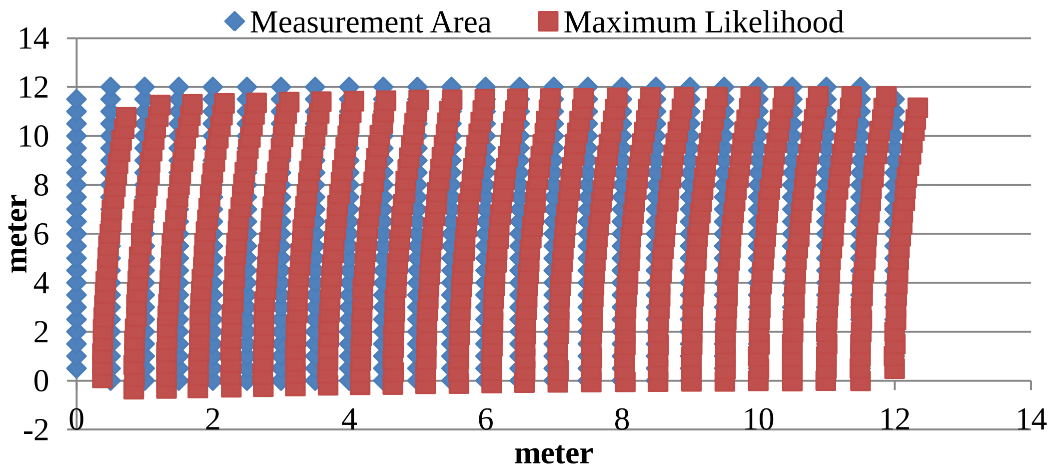


Figure 5.15 12mx12m Measurement Area -Access Point Placement

5.2.2.1 12m x 12m (LOS)

There are not any obstacles between transmitter and receiver in LOS environment. This model is representing when there is any signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.
Average is 0.36 meter, minimum error is 0.0 meter, maximum error is 1.03 meter and standard deviation is 0.23 meter. (Figure 5.16)

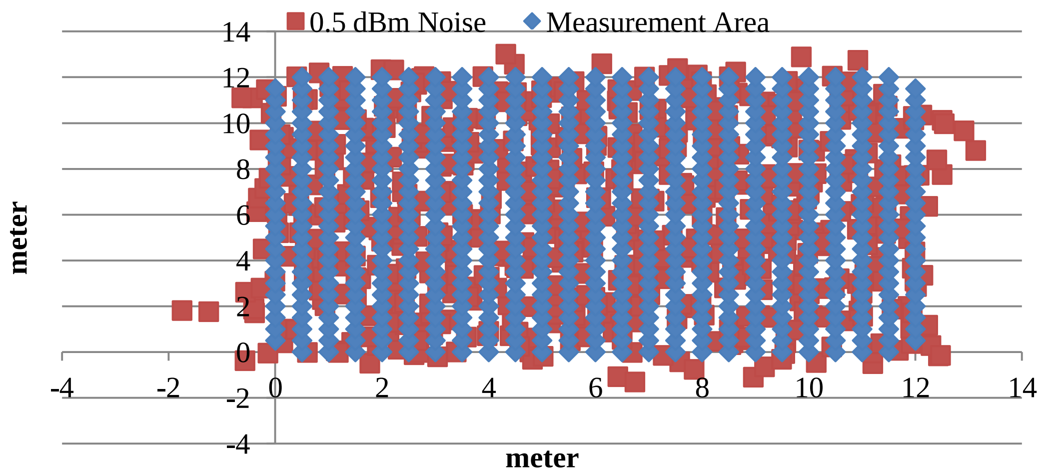


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	0.36	0.00	1.03	0.23

Figure 5.16 Experiment on LOS Environment (12mx12m)

5.2.2.2 12m x 12m (0.5 dBm Noise)

This model is representing when there is 0.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 0.64 meter, minimum error is 0.02 meter, maximum error is 2.54 meter and standard deviation is 0.38 meter. (Figure 5.17)

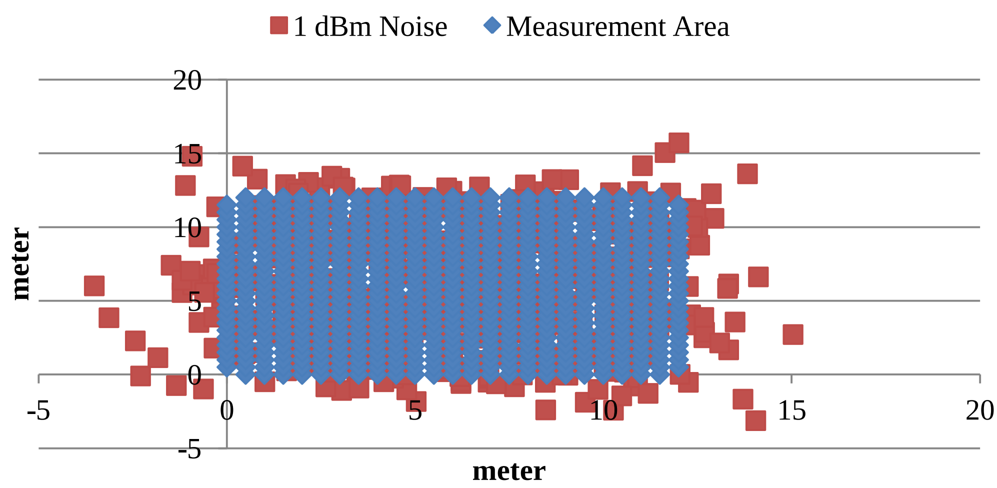


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	0.64	0.02	2.54	0.38

Figure 5.17 Experiment on 0.5 Noise Environment (12mx12m)

5.2.2.3 12m x 12m (1 dBm Noise)

This model is representing when there is 1 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.
Average is 1.31 meter, minimum error is 0.02 meter, maximum error is 5.06 meter and standard deviation is 0.76 meter. (Figure 5.18)

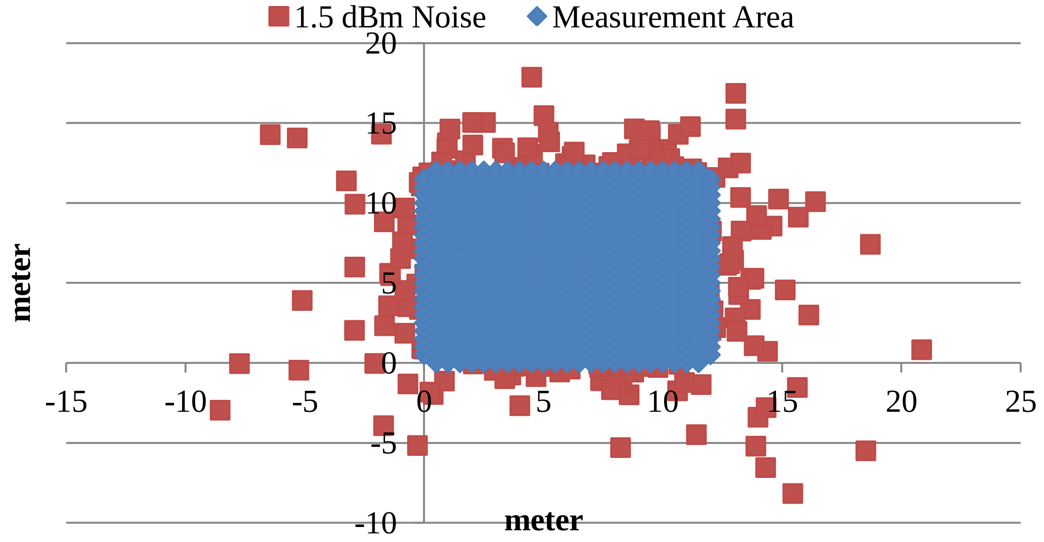


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	1.31	0.02	5.06	0.76

Figure 5.18 Experiment on 1 Noise Environment (12mx12m)

5.2.2.4 12m x 12m (1.5 dBm Noise)

This model is representing when there is 1.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.
Average is 2.05 meter, minimum error is 0.09 meter, maximum error is 10.72 meter and standard deviation is 1.47 meter. (Figure 5.19)

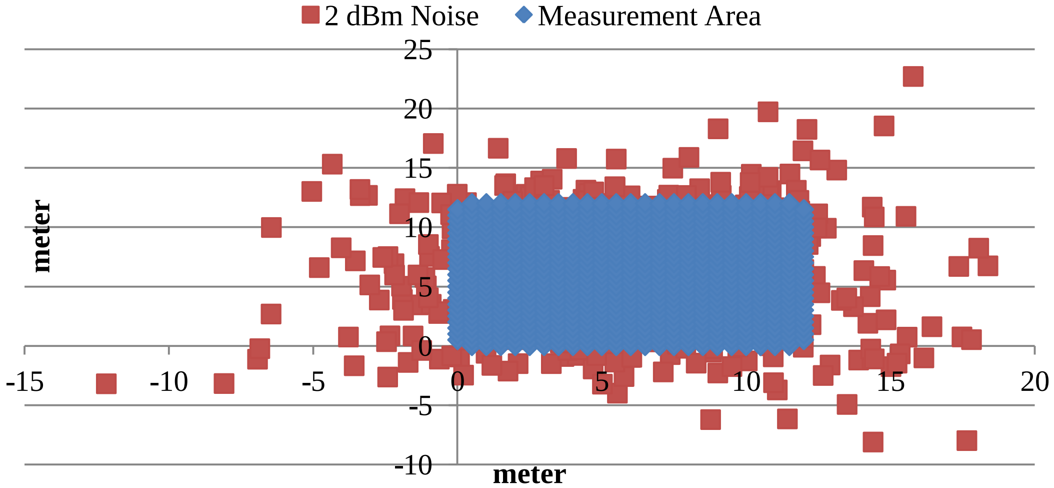


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	2.05	0.09	10.72	1.47

Figure 5.19 Experiment on 1.5 Noise Environment (12mx12m)

5.2.2.5 12m x 12m (2 dBm Noise)

This model is representing when there is 2 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 2.81 meter, minimum error is 0.06 meter, maximum error is 12.72 meter and standard deviation is 1.91 meter. (Figure 5.20)

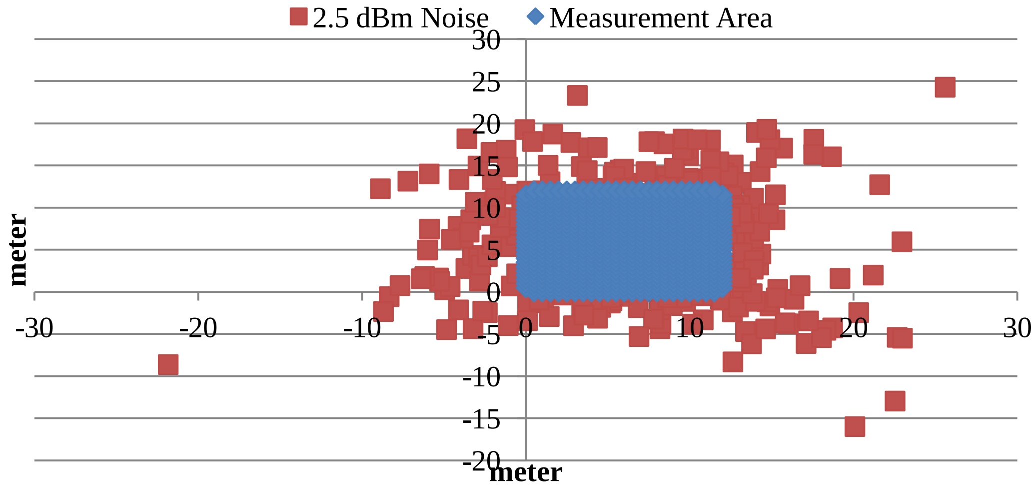


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	2.81	0.06	12.72	1.91

Figure 5.20 Experiment on 2 Noise Environment (12mx12m)

5.2.2.6 12m x 12m (2.5 dBm Noise)

This model is representing when there is 2.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 3.68 meter, minimum error is 0.15 meter, maximum error is 26.06 meter and standard deviation is 3.08 meter. (Figure 5.21)



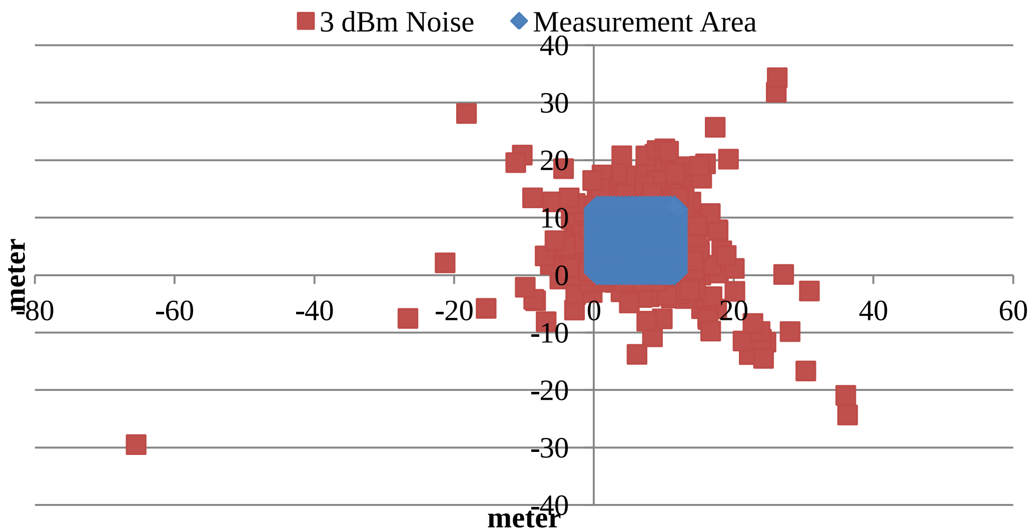
N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	3.68	0.15	26.06	3.08

Figure 5.21 Experiment on 2.5 Noise Environment (12mx12m)

5.2.2.7 12m x 12m (3 dBm Noise)

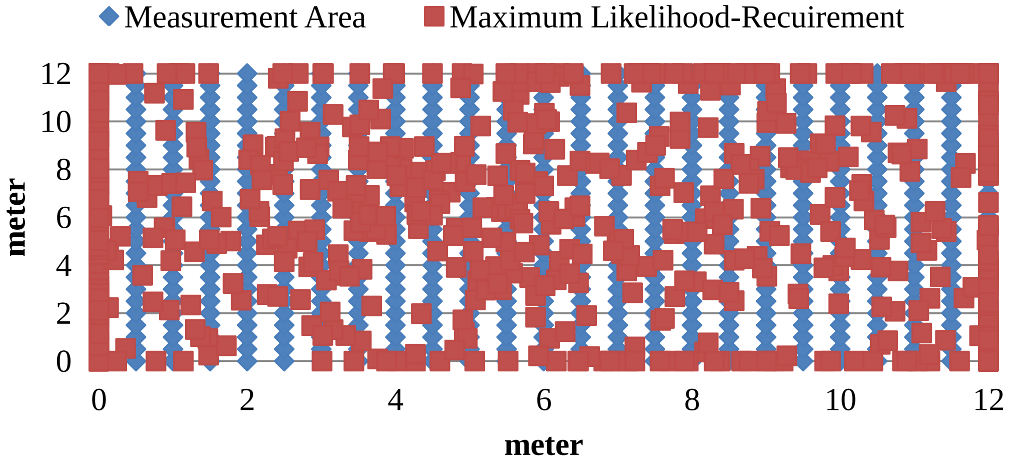
This model is representing when there is 3 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 4.73 meter, minimum error is 0.05 meter, maximum error is 72.97 meter and standard deviation is 5.40 meter. (Figure 5.22)

In Figure 5.23, we restricted estimated location with measurement area. 276 node was out of area. Average is 1.90 meter, minimum error is 0.06, maximum error is 5.73 meter and standard deviation is 1.10 meter.



N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	4.73	0.05	72.97	5.40

Figure 5.22 Experiment on 3 Noise Environment (12mx12m)

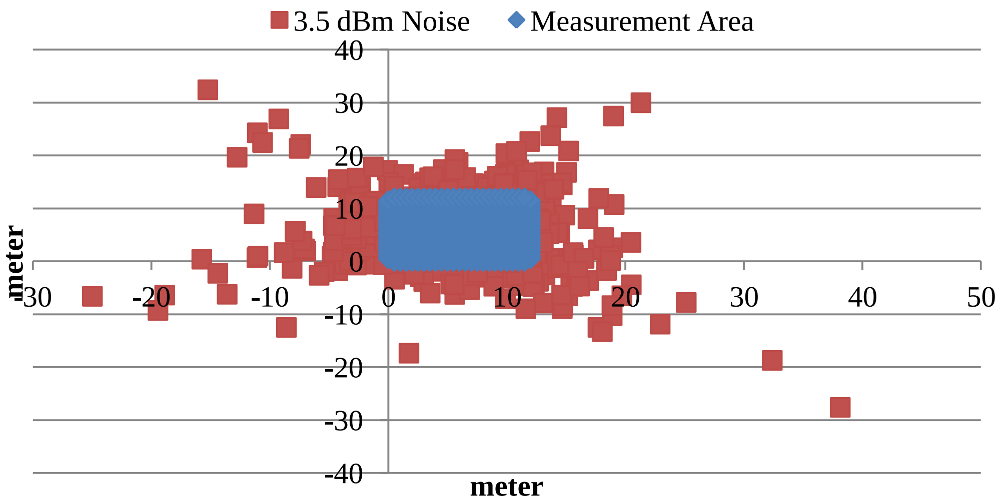


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	3.03	0.05	11.17	1.89

Figure 5.23 Experiment on 3 Noise Environment (12mx12m)- Recuirement

5.2.2.8 12m x 12m (3.5 dBm Noise)

This model is representing when there is 3.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 5.28 meter, minimum error is 0.25 meter, maximum error is 38.73 meter and standard deviation is 4.56 meter. (Figure 5.24)

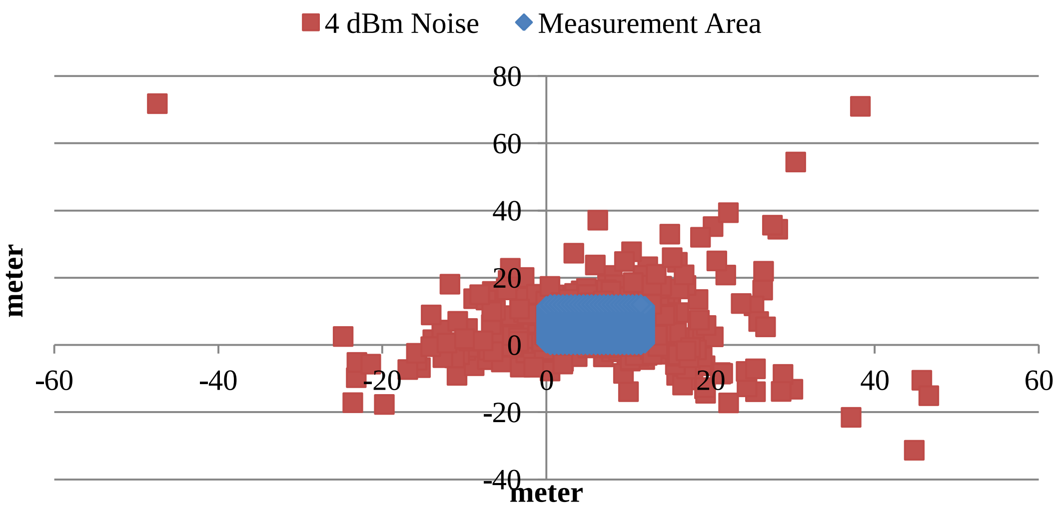


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	5.28	0.25	38.73	4.56

Figure 5.24 Experiment on 3.5 Noise Environment (12mx12m)

5.2.2.9 12m x 12m (4 dBm Noise)

This model is representing when there is 4 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.
Average is 7.40 meter, minimum error is 0.11 meter, maximum error is 76.71 meter and standard deviation is 7.67 meter. (Figure 5.25)

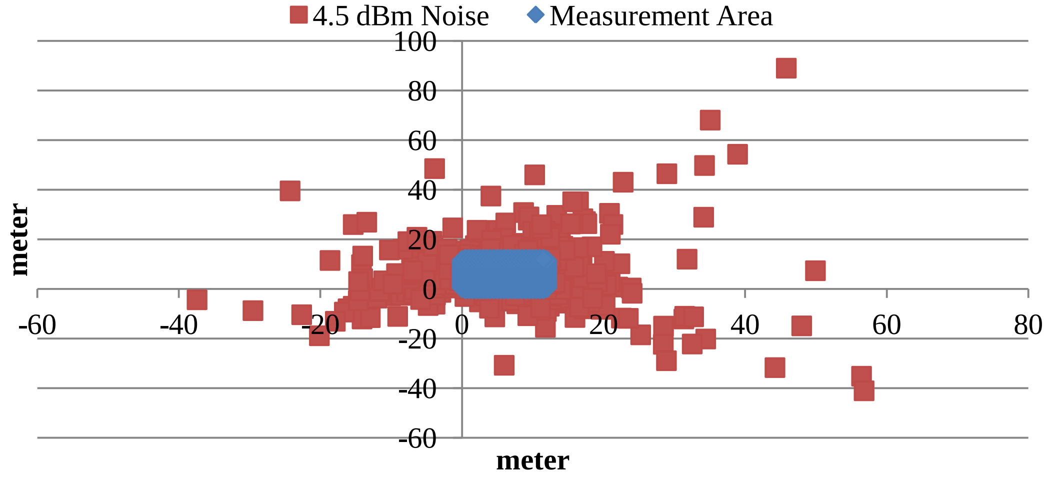


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	7.40	0.11	76.61	7.67

Figure 5.25 Experiment on 4 Noise Environment (12mx12m)

5.2.2.10 12m x 12m (4.5 dBm Noise)

This model is representing when there is 4.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.
Average is 8.41 meter, minimum error is 0.08 meter, maximum error is 86.93 meter and standard deviation is 9.39 meter. (Figure 5.26)

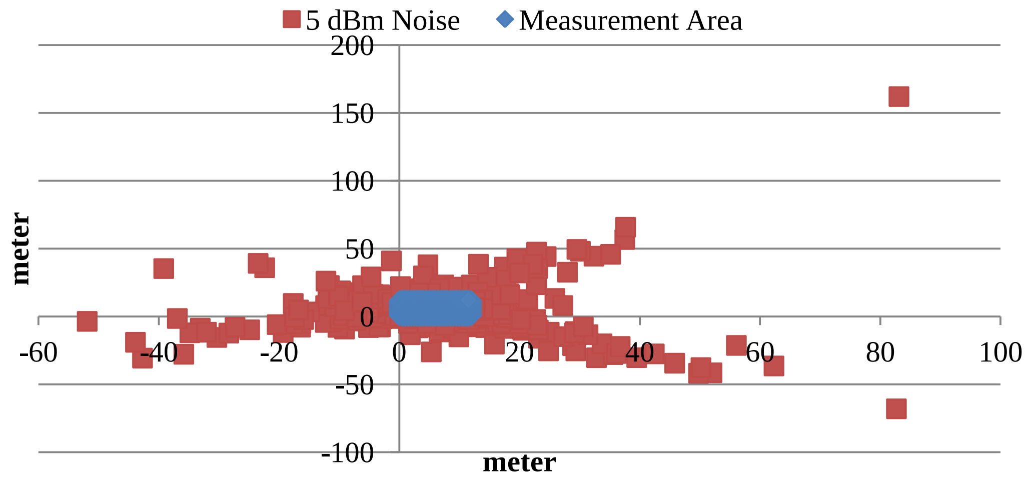


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	8.41	0.08	86.93	9.39

Figure 5.26 Experiment on 4.5 Noise Environment (12mx12m)

5.2.2.11 12m x 12m (5 dBm Noise)

This model is representing when there is 5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 8.41 meter, minimum error is 0.08 meter, maximum error is 86.93 meter and standard deviation is 9.39 meter. (Figure 5.27)

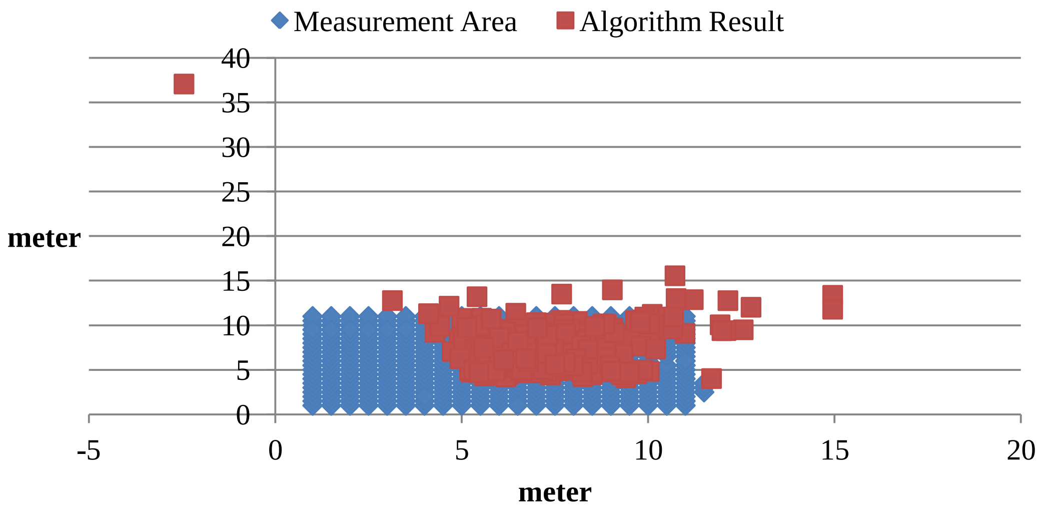


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	10.32	0.24	166.62	13.35

Figure 5.27 Experiment on 5 Noise Environment (12mx12m)

5.2.2.12 Experiment with Real Data

In chapter 3, environment with real data is described. $AP1, AP2$ and $AP3$ is used during experiment. Average is 3.3 meter, minimum error is 0.29 meter, maximum error is 29.97 meter, and standard deviation is 2.08 meter. (Figure 5.28)



Average Error	Minimum Error	Maximum Error	Standard Deviation
3.3	0.29	29.97	2.08

Figure 5.28 Experiment on Real Data (12mx12m)

5.2.3 24m x 24m Measurement Area

Circle figures represent access point placement. There are 2397 test nodes, however we ignore nodes where it is access point coordinates. 2393 data features were used within an interval of 0.5 meter in an area of 24 square meters (m^2). (Figure 5.29)

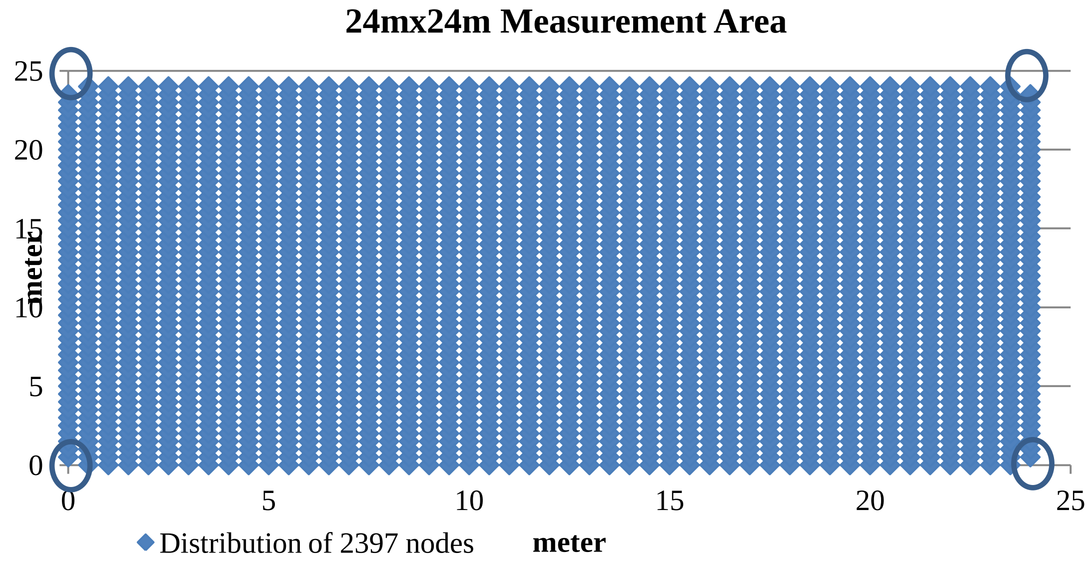
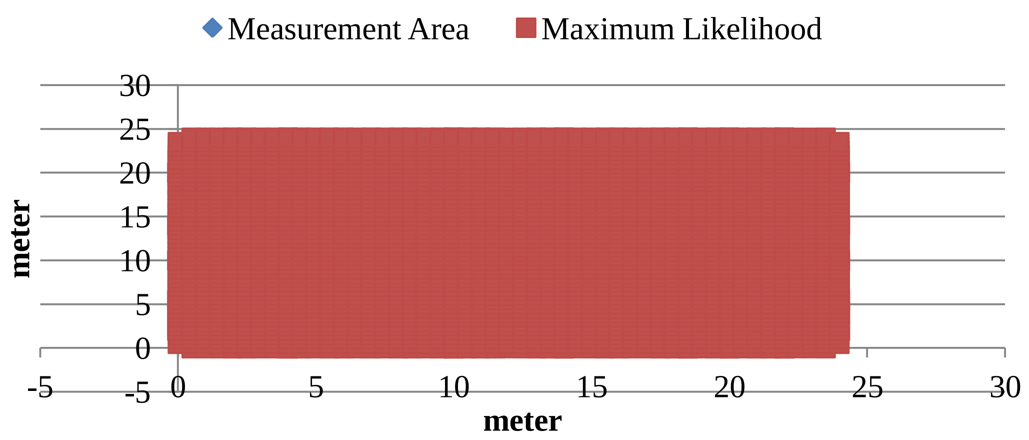


Figure 5.29 24mx24m Measurement Area-Access Point Placement

5.2.3.1 24m x 24m (LOS)

There are not any obstacles between transmitter and receiver in LOS environment. This model is representing when there is any signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 0.0 meter, minimum error is -0.01 meter, maximum error is 0.01 meter and standard deviation is 0.00 meter. (Figure 5.30)

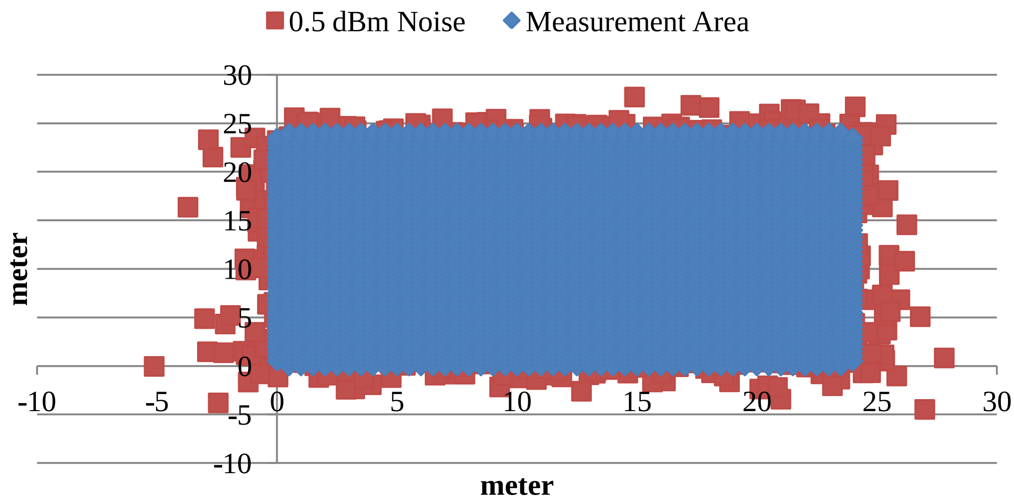


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	0.00	0.00	0.03	0.00

Figure 5.30 Experiment on LOS Environment (24mx24m)

5.2.3.2 24m x 24m (0.5 dBm Noise)

This model is representing when there is 0.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.
Average is 1.28 meter, minimum error is 0.01 meter, maximum error is 6.31 meter and standard deviation is 0.80 meter. (Figure 5.31)

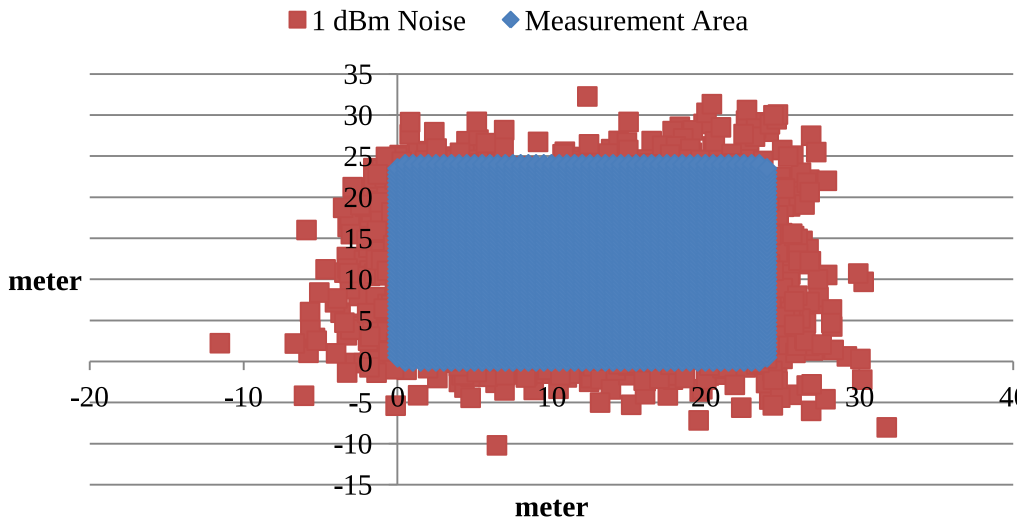


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	1.28	0.01	6.31	0.80

Figure 5.31 Experiment on 0.5 Noise Environment (24mx24m)

5.2.3.3 24m x 24m (1 dBm Noise)

This model is representing when there is 1 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.
Average is 3.10 meter, minimum error is 0.07 meter, maximum error is 27.60 meter and standard deviation is 3.43 meter. (Figure 5.32)



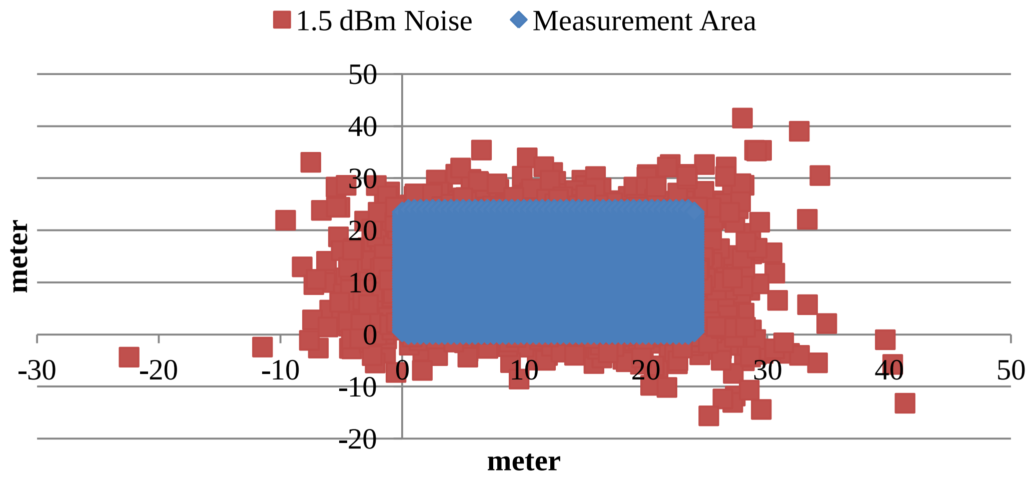
N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	3.10	0.07	27.60	3.43

Figure 5.32 Experiment on 1 Noise Environment (24mx24m)

5.2.3.4 24m x 24m (1.5 dBm Noise)

This model is representing when there is 1.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.

Average is 4.38 meter, minimum error is 0.09 meter, maximum error is 39.69 meter and standard deviation is 3.95 meter. (Figure 5.33)

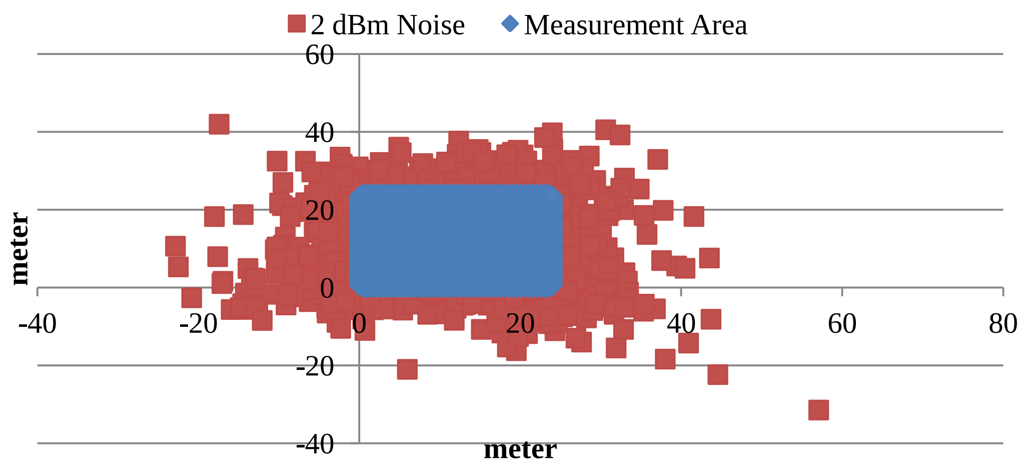


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	4.38	0.09	39.69	3.95

Figure 5.33 Experiment on 1.5 Noise Environment (24mx24m)

5.2.3.5 24m x 24m (2 dBm Noise)

This model is representing when there is 2 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 5.93 meter, minimum error is 0.05 meter, maximum error is 46.35 meter and standard deviation is 4.90 meter. (Figure 5.34)

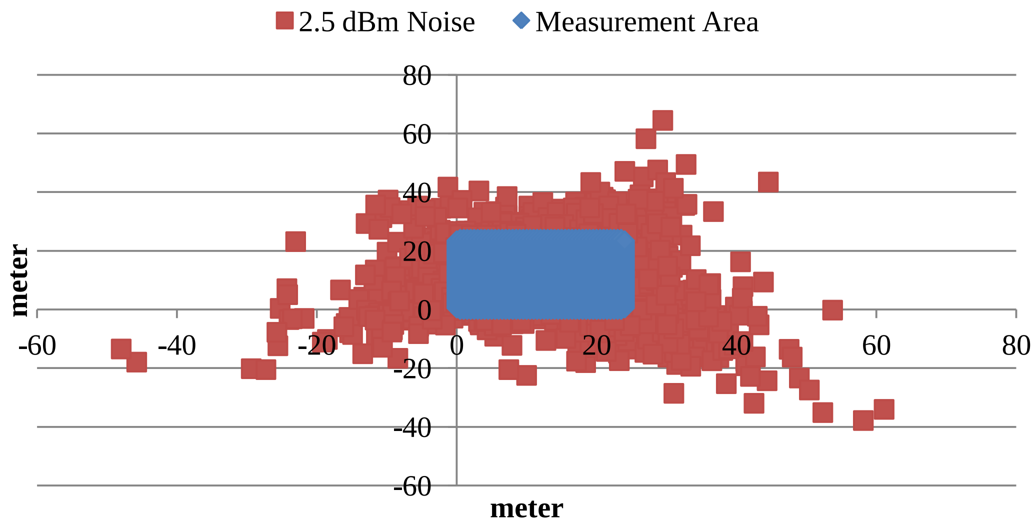


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	5.93	0.05	46.35	4.90

Figure 5.34 Experiment on 2 Noise Environment (24mx24m)

5.2.3.6 24m x 24m (2.5 dBm Noise)

This model is representing when there is 2.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.
Average is 7.74 meter, minimum error is 0.09 meter, maximum error is 58.35 meter and standard deviation is 6.74 meter. (Figure 5.35)

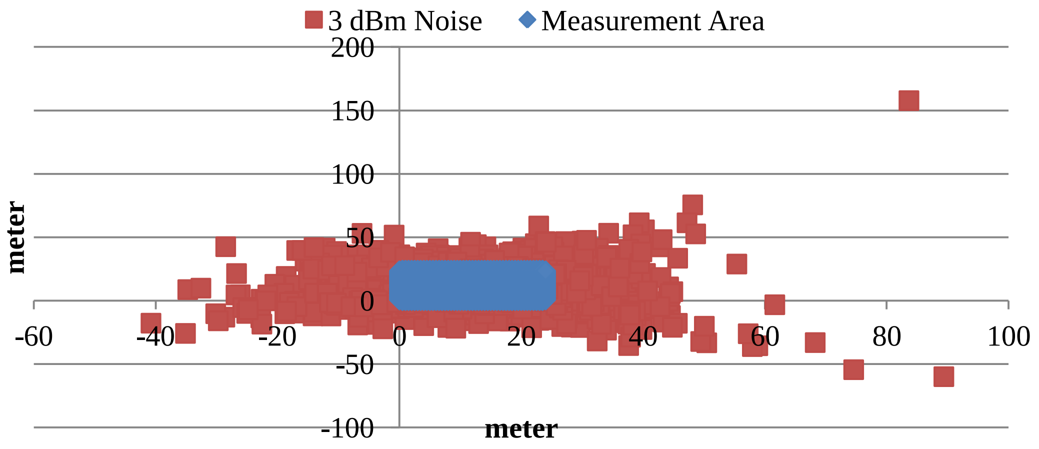


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	7.74	0.09	58.35	6.74

Figure 5.35 Experiment on 2.5 Noise Environment (24mx24m)

5.2.3.7 24m x 24m (3 dBm Noise)

This model is representing when there is 3 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.
Average is 9.53 meter, minimum error is 0.26 meter, maximum error is 147.47 meter and standard deviation is 8.75 meter. (Figure 5.36)

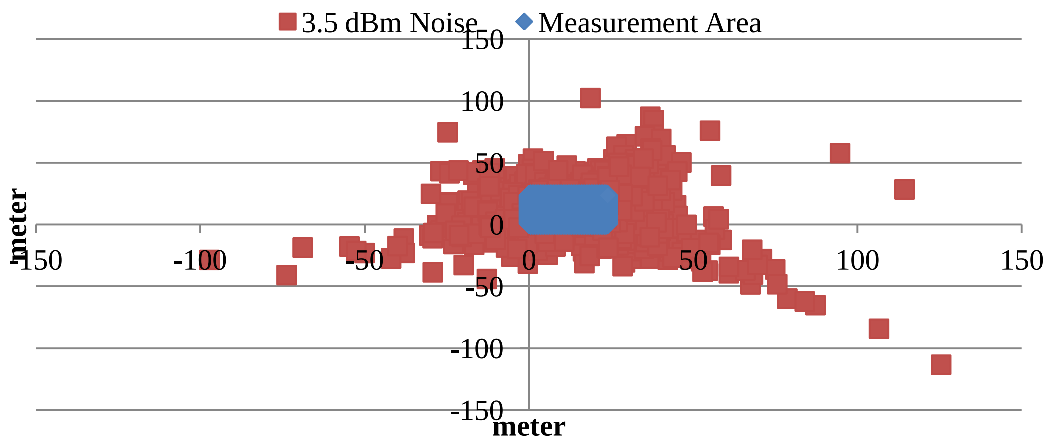


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	9.53	0.26	147.47	8.75

Figure 5.36 Experiment on 3Noise Environment (24mx24m)

5.2.3.8 24m x 24m (3.5 dBm Noise)

This model is representing when there is 3.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 11.70 meter, minimum error is 0.12 meter, maximum error is 164.78 meter and standard deviation is 12.04 meter. (Figure 5.37)

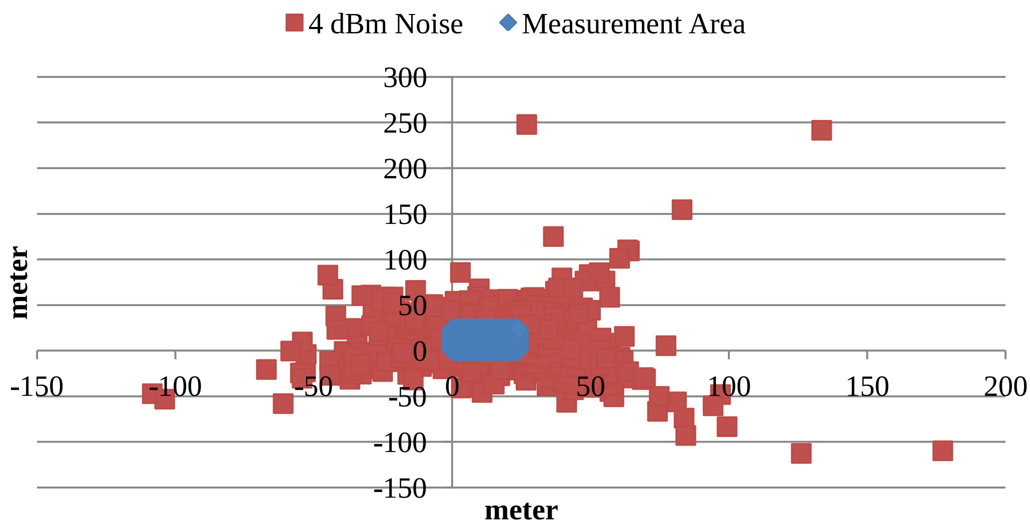


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	11.70	0.12	164.78	12.04

Figure 5.37 Experiment on 3.5 Noise Environment (24mx24m)

5.2.3.9 24m x 24m (4 dBm Noise)

This model is representing when there is 4 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 14.48 meter, minimum error is 0.12 meter, maximum error is 249.67 meter and standard deviation is 16.46 meter. (Figure 5.38)

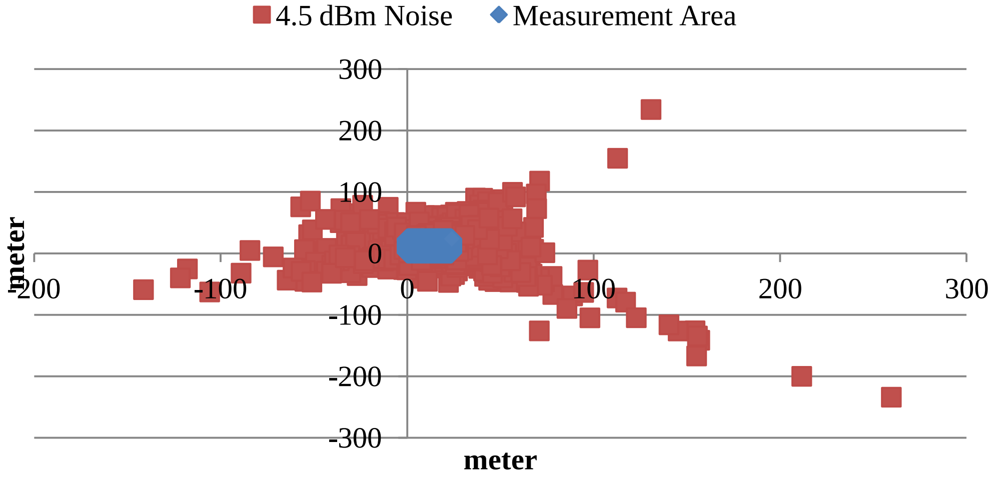


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	14.48	0.12	249.67	16.46

Figure 5.38 Experiment on 4 Noise Environment (24mx24m)

5.2.3.10 24m x 24m (4.5 dBm Noise)

This model is representing when there is 4.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 17.43 meter, minimum error is 0.33 meter, maximum error is 337.61meter and standard deviation is 21.66 meter. (Figure 5.39)

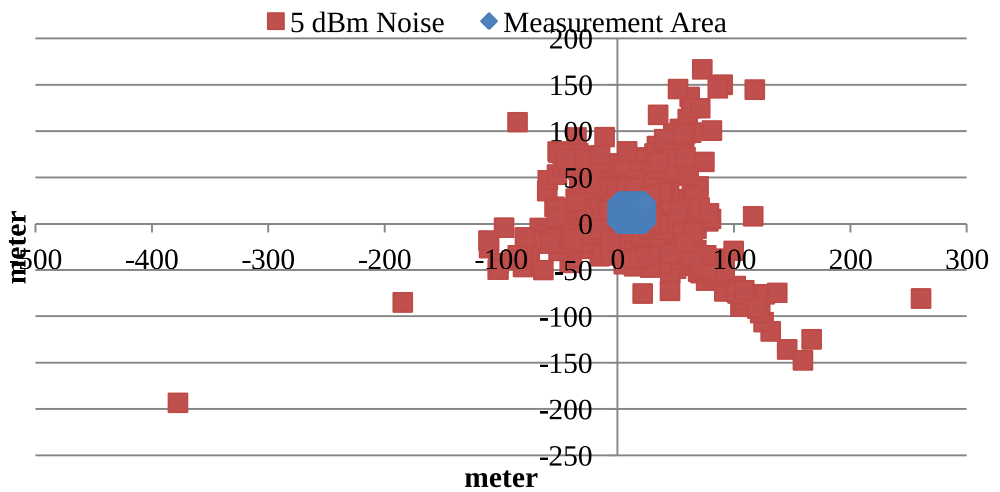


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	17.43	0.33	337.61	21.66

Figure 5.39 Experiment on 4.5 Noise Environment (24mx24m)

5.2.3.11 24m x 24m (5 dBm Noise)

This model is representing when there is 5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 20.17 meter, minimum error is 0.22 meter, maximum error is 427.49 meter and standard deviation is 24.84 meter. (Figure 5.40)



N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	20.17	0.22	427.49	24.84

Figure 5.40 Experiment on 5 Noise Environment (24mx24m)

5.3 Experiment Result Summary Table

Table 5.1 is shown all measurement area result in a summary table. 4* is representing restricted area experiment. Summary table is clearly shown us, in maximum likelihood algorithm, while expanding measurement area and increasing noise, errors are getting increased.

Best accuracies are measured in LOS environment in 3 different experiment areas. However LOS environment is not a good example of indoor environment, so algorithm gave best accuracy in 6 square meter area with 0.5 dBm noisy environment. Also experiment show that when we restrict area, accuracy increased with 86%.

Table 5.1 Maximum Likelihood Experiment Results Summary Table

MAXIMUM LIKELIHOOD														
	6mx6m					12mx12m					24mx24m			
dBm	avg	min	max	std		avg	min	max	std		avg	min	max	std
0	0.01	0	0.01	0.01	0	0.01	0	0.01	0.01	0	0.01	0	0.01	0.01
0.5	0.33	0.03	1.4	0.2	0.5	0.64	0.02	2.54	0.38	0.5	1.28	0.01	6.13	0.8
1	0.55	0.02	2.14	0.38	1	1.31	0.02	5.06	0.76	1	3.1	0.07	27.6	3.43
1.5	1.03	0.05	4.49	0.66	1.5	2.05	0.09	10.72	1.47	1.5	4.38	0.09	39.69	2.95
2	1.55	0.07	12.33	1.39	2	2.81	0.06	12.72	1.91	2	5.93	0.05	46.35	4.9
2.5	1.73	0.03	13.06	1.39	2.5	3.68	0.15	26.06	3.08	2.5	7.74	0.09	58.35	6.74
3	2.26	0.1	12.73	1.83	3	4.73	0.05	72.97	5.4	3	9.53	0.26	147.47	8.75
3.5	2.8	0.2	17.41	2.76	3.5	5.28	0.25	38.72	4.56	3.5	11.7	0.12	164.78	12.04
4	3.35	0.06	23.1	3.23	4	7.4	0.11	76.61	7.67	4	13.48	0.12	249.67	16.46
4*	1.9	0.06	5.73	1.1	4.5	8.41	0.08	86.93	9.39	4.5	17.43	0.33	337.61	21.66
4.5	4.1	0.51	26.3	4.32	5	10.32	0.24	166.62	13	5	20.17	0.22	427.49	25
5	4.88	0.43	31.6	4										
Real Data	2.15	0.16	16.16	1.63	Real Data	3.3	0.29	29.97	2.08					

CHAPTER 6

Fuzzy Logic

6.1 Fuzzy Logic Algorithm

Fuzzy set theory has been introduced by Zadeh in 1965. According to [25], a fuzzy set is characterized by membership function which assigns to each object a grade of membership ranging between one and zero. In real world, there are not exactly defined classes. For example, we can characterize weather with terms like hot, warm or cold. This condition like hot or warm is called membership function. A set of membership function is connected linguistic term, in our example temperature. [26] Fuzzy logic works on the level of possibilities of input to achieve the defined output. To sum up, fuzzy logic helps to deal with uncertainty. By using fuzzy logic system we can obtain more accurate results.

Fuzzy logic indoor positioning system (FLIPS) is widely using method. By designing fuzzy logic system, target location can be found in indoor environment.

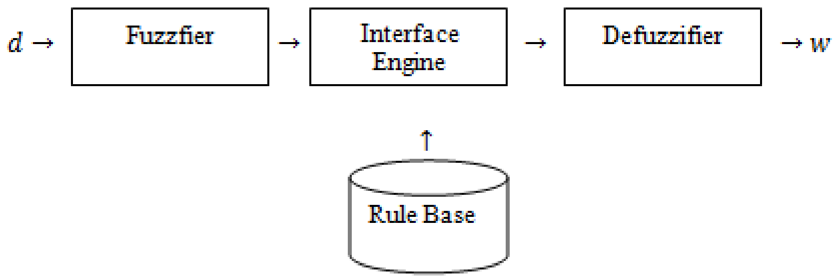


Figure 6.1 Fuzzy Logic System Design

In the FLIPS, w is representing weight of coordinate of each anchor nodes. *Fuzzier* represents triangular membership function. *Interface engine* represents madmani max-min method. *Defuzzifier* represents center of gravity method. And d represent distance between target node and anchor nodes, APs.

We used [31]' fuzzy logic membership and algorithm to estimate target nodes. Fuzzy memberships;

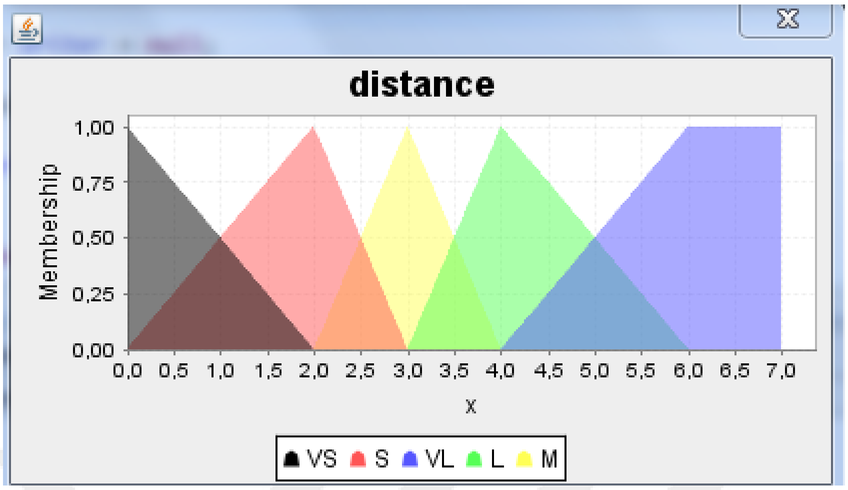


Figure 6.2 Fuzzy Logic Membership Function [31]

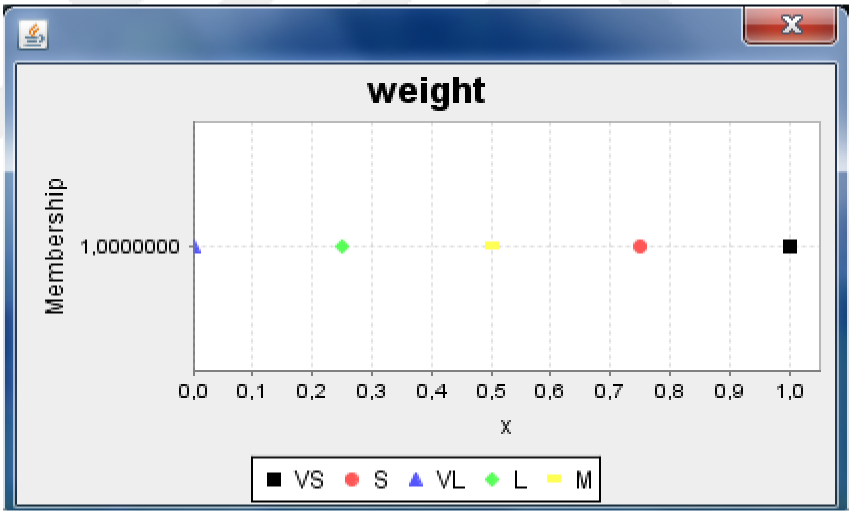


Figure 6.3 Fuzzy Logic Membership Function(continued) [31]

In Figure 6.2, membership functions are divided into 5 subsets; VS means very small, S means small, M means medium, L means large and finally VL means very large. The values of membership has values between [0, 1] range. In Figure 6.3, we defined fuzzy set rules. According to figure;

Rule 1: IF distance is VS, THEN weight is VS;

Rule 2: IF distance is S, THEN weight is S;

Rule 3: IF distance is M, THEN weight is M;

Rule 4: IF distance is L, THEN weight is L;

Rule 5: IF distance is VL, THEN weight is VL.

According to these rules, we are getting coordinates for each anchor nodes. In order to estimate target location;

$$x_0 = \frac{x_1 * w_1 + \cdots + x_N * w_N}{\sum_{i=1}^{N} w_i} \tag{6.1}$$

$$y_0 = \frac{y_1 * w_1 + \cdots + y_N * w_N}{\sum_{i=1}^{N} w_i} \tag{6.2}$$

In equations (6.1),(6.2) x, y are real coordinates of anchor nodes and w is a variable that we are getting from fuzzy logic member rules by using anchor node distance to target node. By using these equations, target node location can be estimated.

Fuzzy Logic algorithm required jFuzzyLogic library in order to work with membership function. [32]

6.2 Test Bed

Fuzzy Logic algorithm requires 4 access points; $AP1, AP2, AP3$ and $AP4$. In equation (4.1); $r_1, r_{2,} r_3$ and r_4 are representing$AP1, AP2, AP3$ and $AP4$'s distance from measurement point.

In order to find distance from measurement point, we are going to use Log-distance path loss model that we mentioned in chapter 2. Estimated distances in each feature were measured using equation (6.1) and (6.2).

6.3 Experimental Results

Synthetic dataset were used as an input of proposed system. In chapter 3, synthetic dataset explained, in 6mx6m experimental area 256 features, in 12mx12m experimental area 625 features, in 24mx24 experimental area 2397 features were used. Fuzzy Logic required 4 access points, each access point were placed at the corner of experimental area.

6.3.1 6mx6m Experimental Area

Fuzzy Logic algorithm is using membership function in order to estimate location of target point Figure 1.25. [31]'s membership function is used.

Circle figures represent access point placement. There are 256 test nodes, however we ignore nodes where it is access point coordinates. 253 data features were used within an interval of 0.4 meter in an area of 6 square meters (m^2).

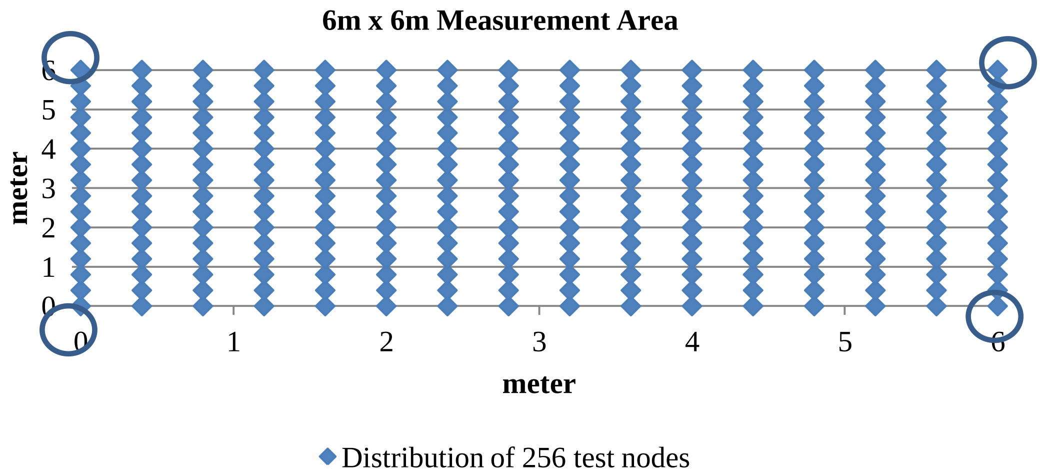
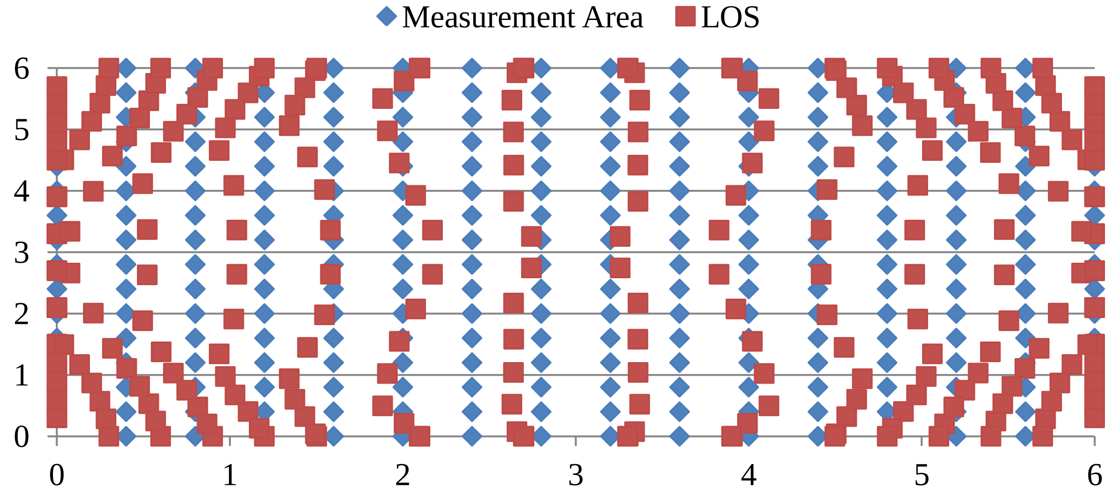


Figure 6.4 6mx6m Experiment Area- Access Point Placement

6.3.1.1 6mx6m Area (LOS)

There are not any obstacles between transmitter and receiver in LOS environment. This model is representing when there is any signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 0.52 meter, minimum error is 0.08 meter, maximum error is 0.931 meter and standard deviation is 0.23 meter. (Figure 6.5)

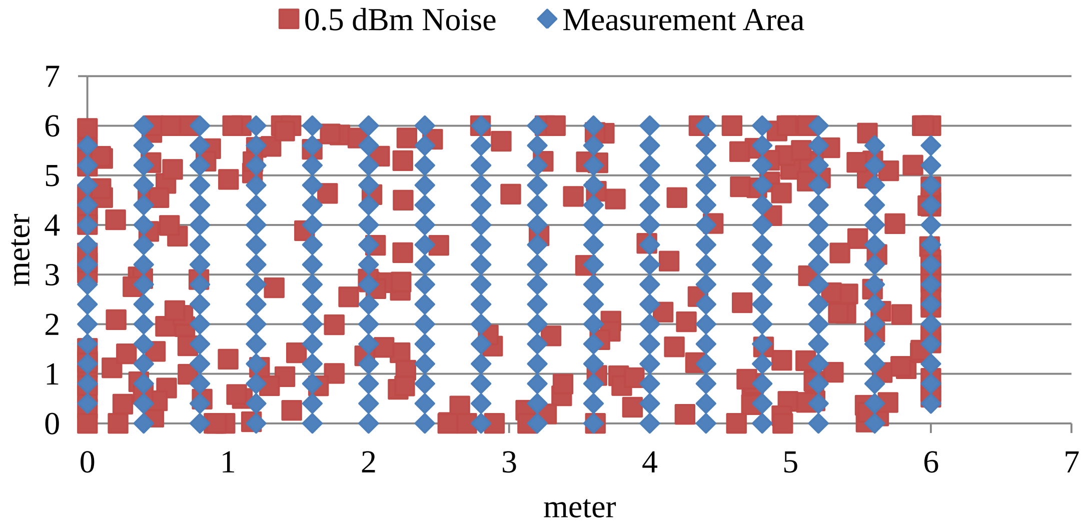


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	0.52	0.08	0.93	0.23

Figure 6.5 Experiment on LOS Environment

6.3.1.2 6mx6m Area (0.5 dBm Noise)

This model is representing when there is 0.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 0.55 meter, minimum error is 0.02 meter, maximum error is 1.31 meter and standard deviation is 0.28 meter. (Figure 6.6)

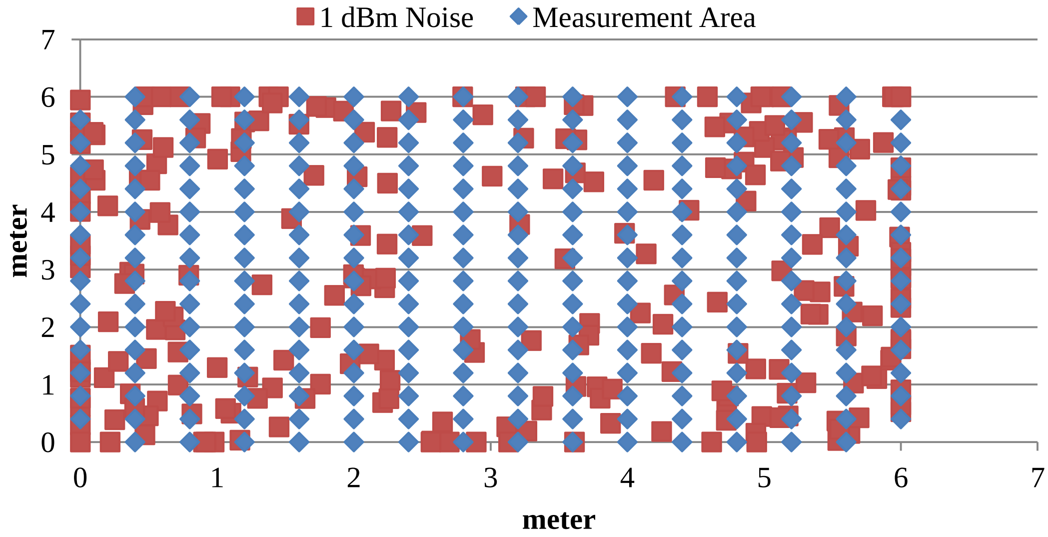


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	0.55	0.02	1.31	0.28

Figure 6.6 Experiment on 0.5 dBm Noise Environment

6.3.1.3 6mx6m Area (1 dBm Noise)

This model is representing when there is 1 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 0.64 meter, minimum error is 0.01 meter, maximum error is 1.63 meter and standard deviation is 0.36 meter. (Figure 6.7)

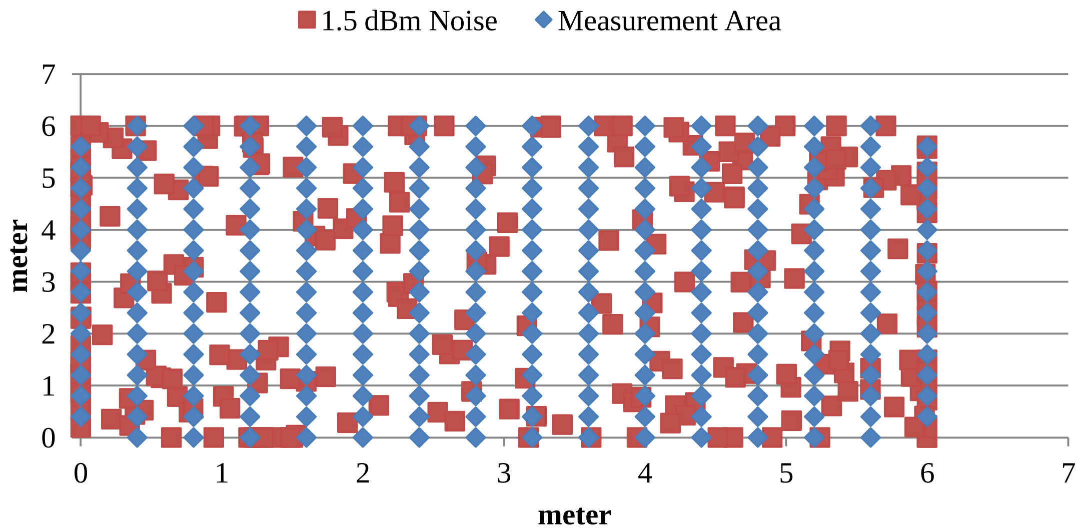


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	0.64	0.01	1.63	0.36

Figure 6.7 Experiment on 1 dBm Noise Environment

6.3.1.4 6mx6m Area (1.5 dBm Noise)

This model is representing when there is 1.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 0.77 meter, minimum error is 0.18 meter, maximum error is 2.13 meter and standard deviation is 0.44 meter. (Figure 6.8)

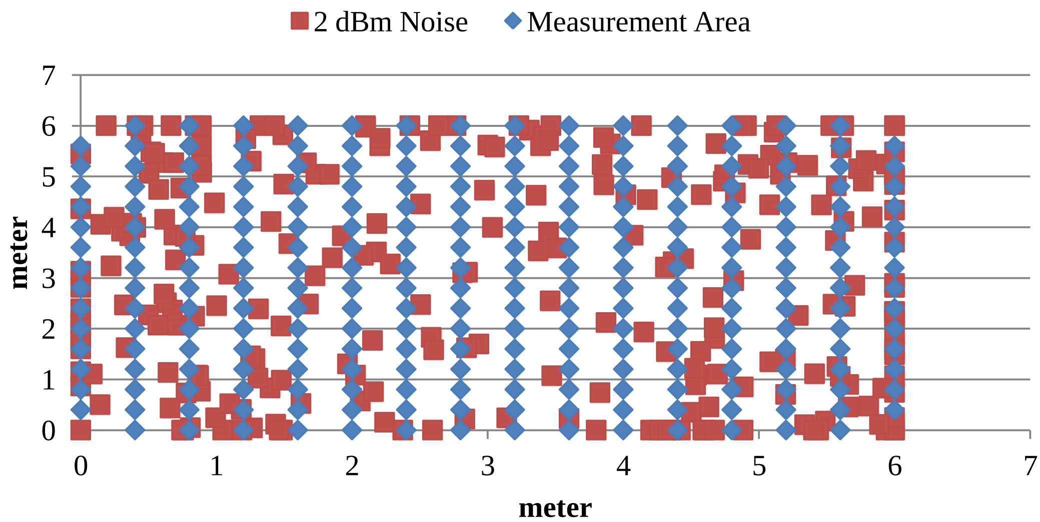


N	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	0.77	0.18	2.13	0.44

Figure 6.8 Experiment on 1.5 dBm Noise Environment

6.3.1.5 6mx6m Area (2 dBm Noise)

This model is representing when there is 2 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 0.87 meter, minimum error is 0.40 meter, maximum error is 2.12 meter and standard deviation is 0.47 meter. (Figure 6.9)



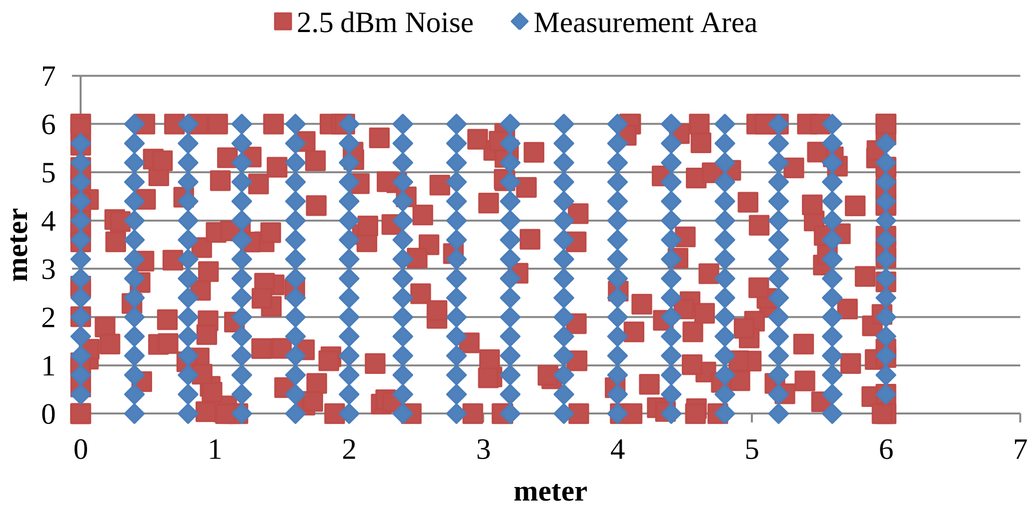
N	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	0.87	0.40	2.12	0.47

Figure 6.9 Experiment on 2 dBm Noise Environment

6.3.1.6 6mx6m Area (2.5 dBm Noise)

This model is representing when there is 2.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.

Average is 1.01 meter, minimum error is 0.00 meter, maximum error is 3.42 meter and standard deviation is 0.59 meter. (Figure 6.10)



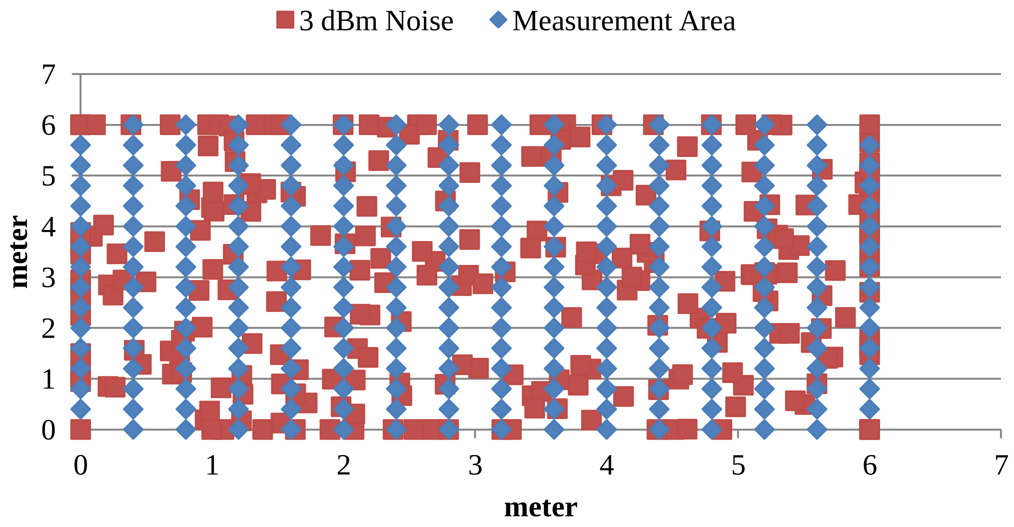
N	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	1.01	0.00	3.42	0.59

Figure 6.10 Experiment on 2.5 dBm Noise Environment

6 .3.1.7 6mx6m Area (3 dBm Noise)

This model is representing when there is 3 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.

Average is 1.19 meter, minimum error is 0.01 meter, maximum error 3.26 meter and standard deviation is 0.67 meter. (Figure 6.11)



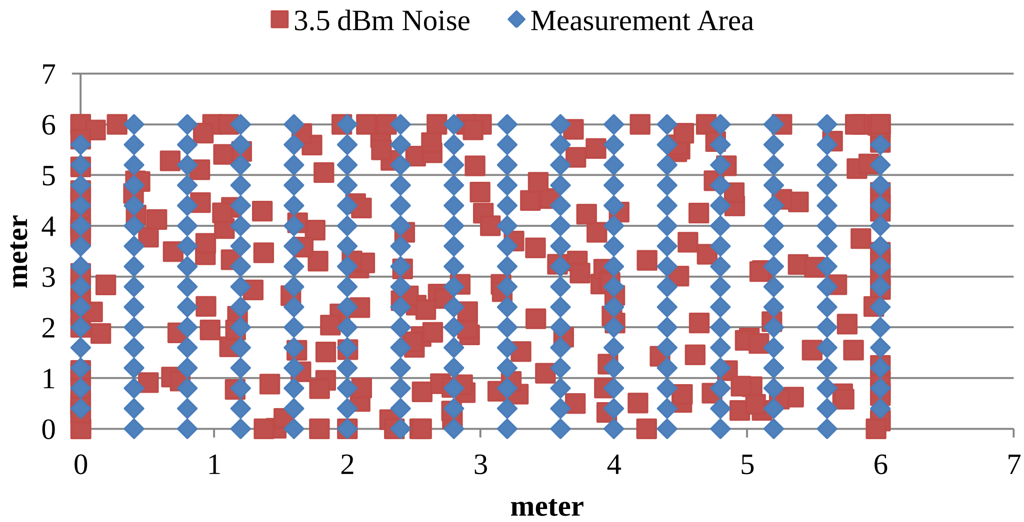
N	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	1.19	0.01	3.26	0.67

Figure 6.11 Experiment on 3 dBm Noise Environment

6.3.1.8 6mx6m Area (3.5 dBm Noise)

This model is representing when there is 3.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.

Average is 1.29 meter, minimum error is 0.01 meter, maximum error 3.81 meter and standard deviation is 0.75 meter. (Figure 6.12)



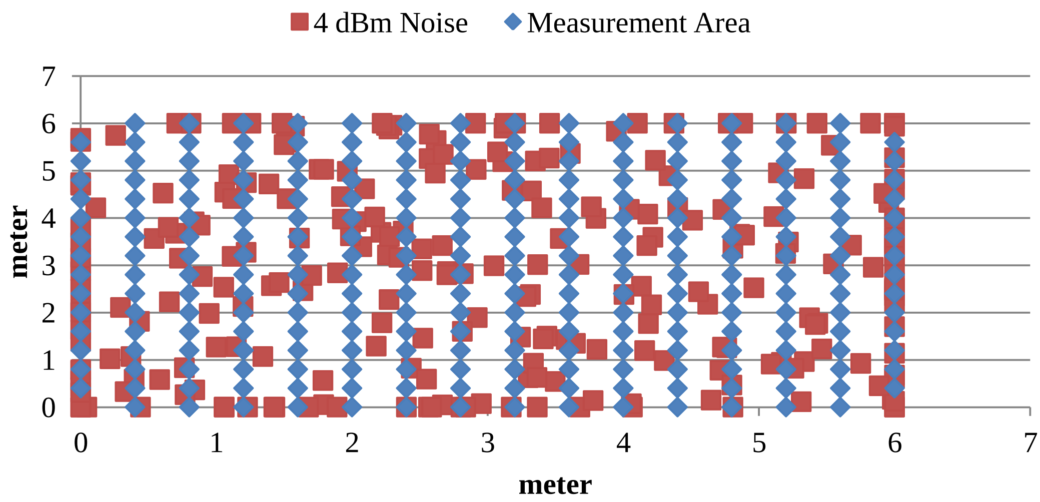
N	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	1.29	0.01	3.81	0.75

Figure 6.12 Experiment on 3.5 dBm Noise Environment

6.3.1.9 6mx6m Area (4 dBm Noise)

This model is representing when there is 4 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.

Average is 1.46 meter, minimum error is 0.01 meter, maximum error 5.11 meter and standard deviation is 0.88 meter. (Figure 6.13)



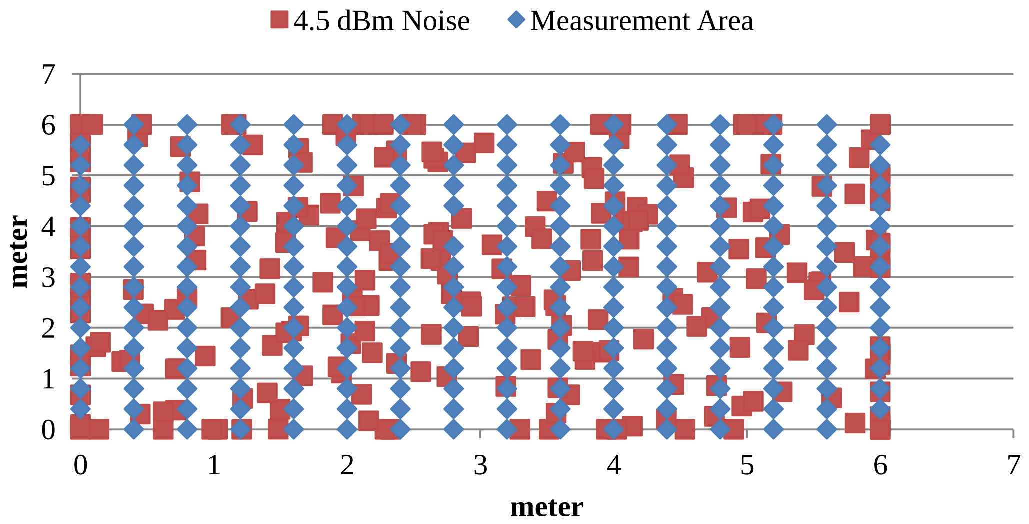
N	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	1.46	0.01	5.11	0.88

Figure 6.13 Experiment on 4 dBm Noise Environment

6.3.1.10 6mx6m Area (4.5 dBm Noise)

This model is representing when there is 4.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.

Average is 1.59 meter, minimum error is 0.07 meter, maximum error 5.38 meter and standard deviation is 0.91 meter. (Figure 6.14)

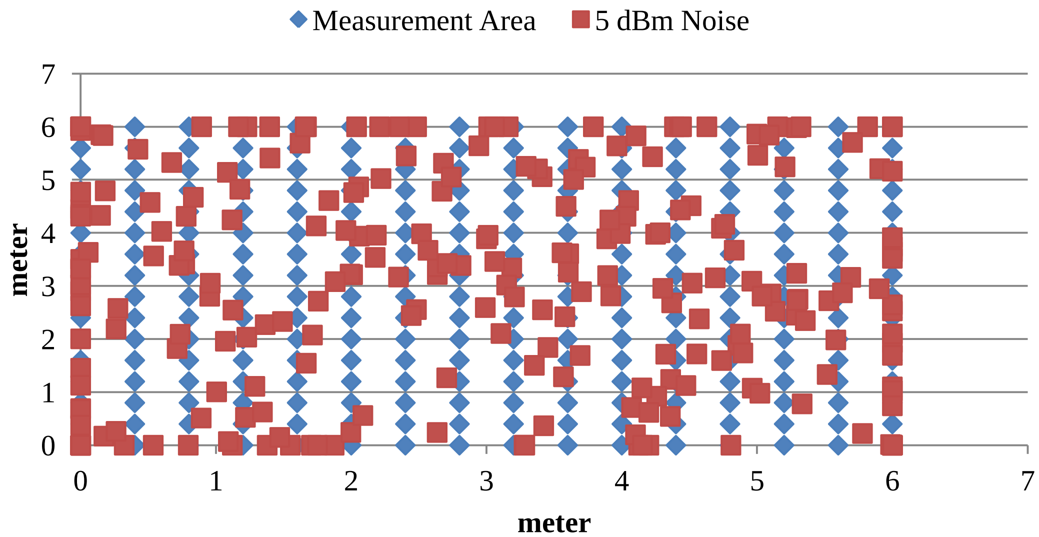


N	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	1.59	0.07	5.38	0.91

Figure 6.14 Experiment on 4.5 dBm Noise Environment

6.3.1.11 6mx6m Area (5 dBm Noise)

This model is representing when there is 5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.
Average is 1.67 meter, minimum error is 0.03 meter, maximum error 3.80 meter and standard deviation is 0.89 meter.

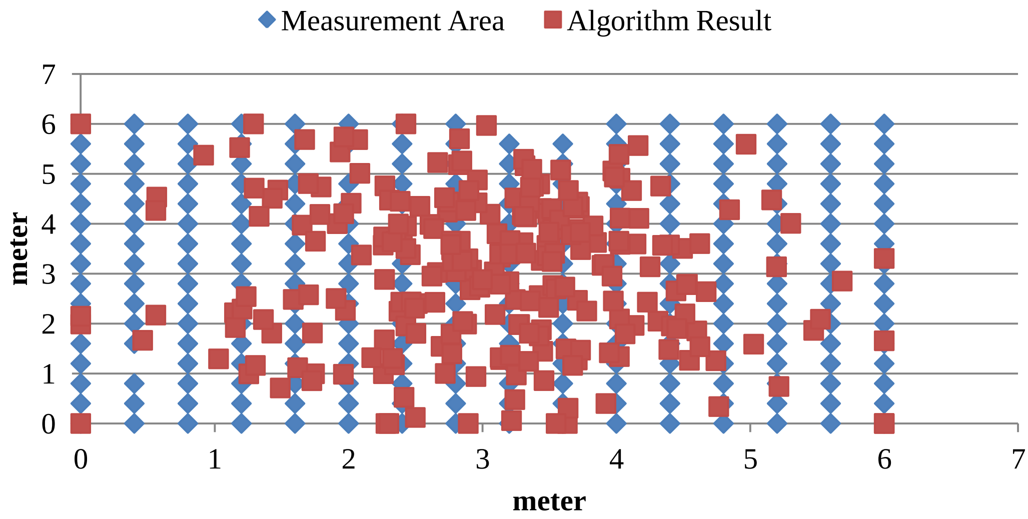


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	1.67	0.03	3.80	0.89

Figure 6.15 Experiment on 5 dBm Noise Environment

6.3.1.12 Experiment with Real Data

In chapter 3, environment with real data is described. $AP1, AP2\ and\ AP3$ is used during experiment. Average is 1.71 meter, minimum error is 0.05 meter, maximum error is 10.74 meter, and standard deviation is 1.05 meter. (Figure 6.16)



Average Error	Minimum Error	Maximum Error	Standard Deviation
1.71	0.05	10.74	1.05

Figure 6.16 Experiment on Real Environment

6.3.2 12m x 12m Measurement Area

[31]'s membership function was limited with 6mx6m area. By using [31]'s membership function logic, new function is used. Fuzzy rules are remained same;

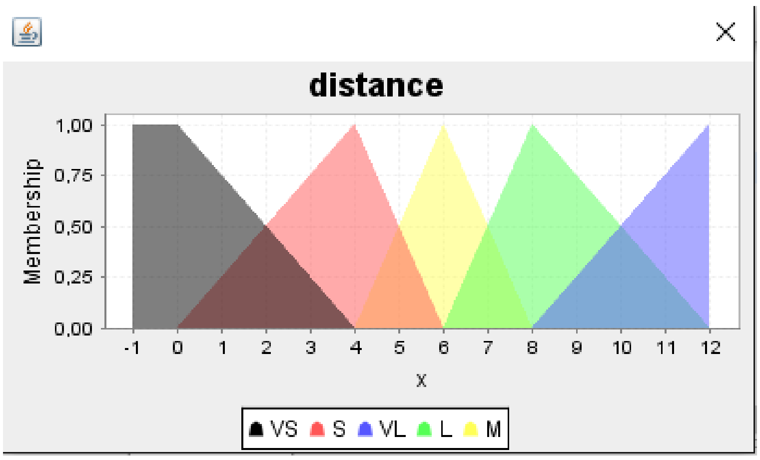
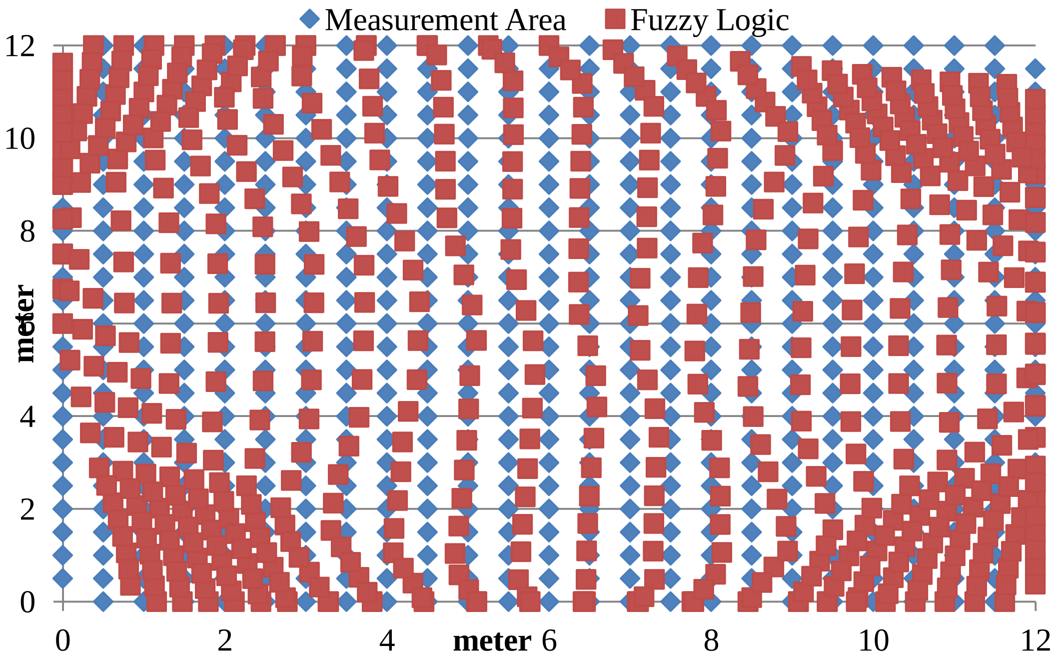


Figure 6.17 12mx12m Fuzzy Membership Function

6.3.2.1 12mx12m Area (LOS)

There are not any obstacles between transmitter and receiver in LOS environment. This model is representing when there is any signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.
Average is 0.96 meter, minimum error is 0.00 meter, maximum error is 2.09 meter and standard deviation is 0.44 meter. (Figure 6.18)

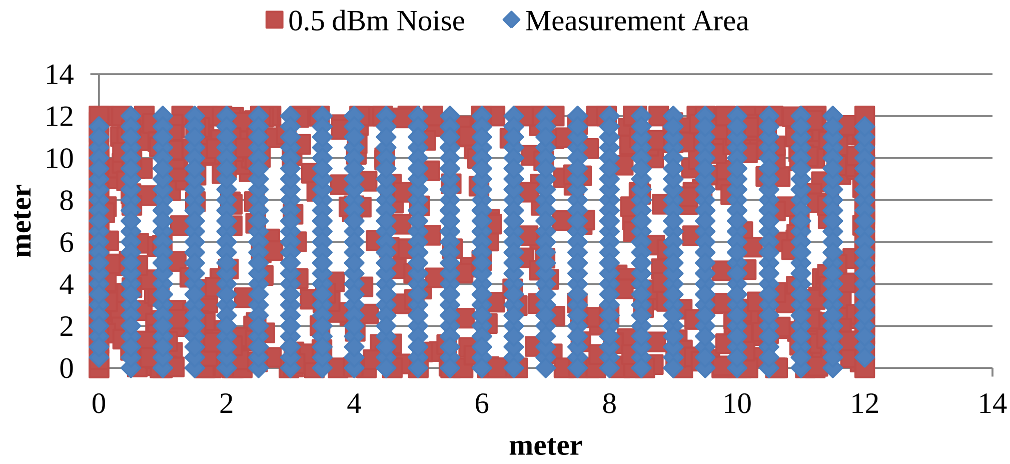


N	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	0.96	0.00	2.09	0.44

Figure 6.18 Experiment on LOS Environment(12mx12m)

6.3.2.2 12mx12m Area 0.5 dBm

This model is representing when there is 0.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.
Average is 1.11 meter, minimum error is 0.01 meter, maximum error 2.59 meter and standard deviation is 0.51 meter. (Figure 6.19)

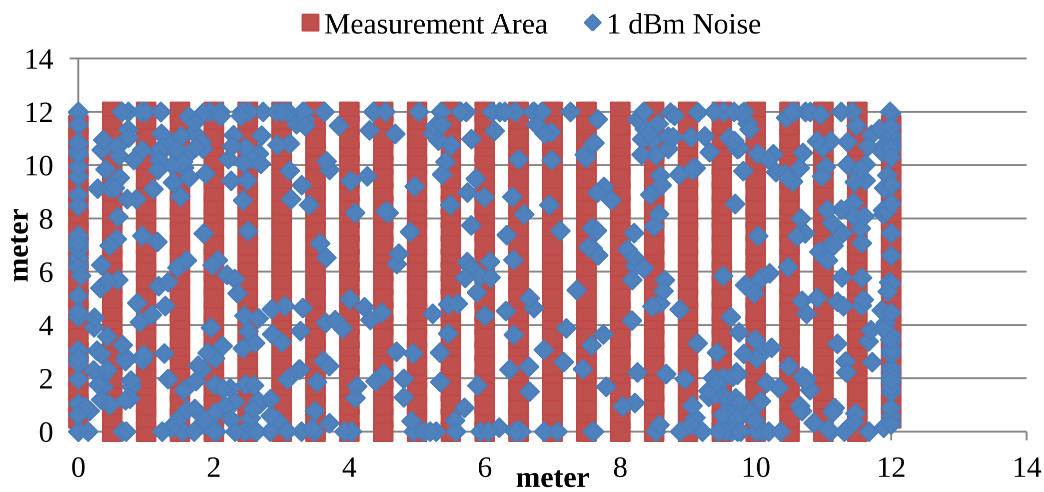


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	1.11	0.01	2.59	0.51

Figure 6.19 Experiment on 0.5 dBm Noise (12mx12m)

6.3.2.3 12mx12m Area (1 dBm Noise)

This model is representing when there is 1 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.
Average is 1.28 meter, minimum error is 0.01 meter, maximum error 3.63 meter and standard deviation is 0.69 meter. (Figure 6.20)



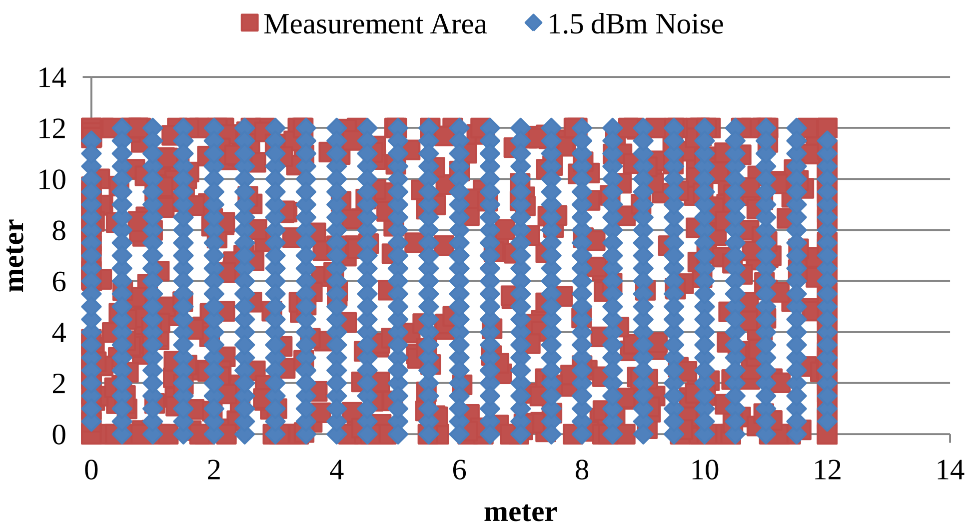
N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	1.28	0.01	3.63	0.69

Figure 6.20 Experiment on 1 dBm Noise (12mx12m)

6.3.2.4 12mx12m Area (1.5 dBm Noise)

This model is representing when there is 1.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.

Average is 1.53 meter, minimum error is 0.01 meter, maximum error 6.02 meter and standard deviation is 0.9 meter. (Figure 6.21)



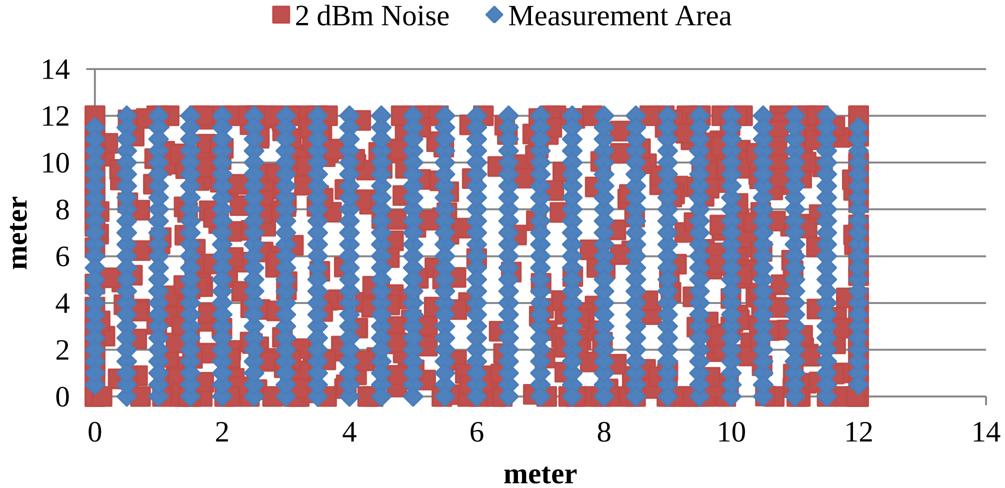
N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	1.53	0.01	6.02	0.9

Figure 6.21 Experiment on 1.5 dBm Noise (12mx12m)

6.3.2.5 12mx12m Area (2 dBm Noise)

This model is representing when there is 2 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.

Average is 1.78 meter, minimum error is 0.06 meter, maximum error 6.40 meter and standard deviation is 1.03 meter. (Figure 6.22)



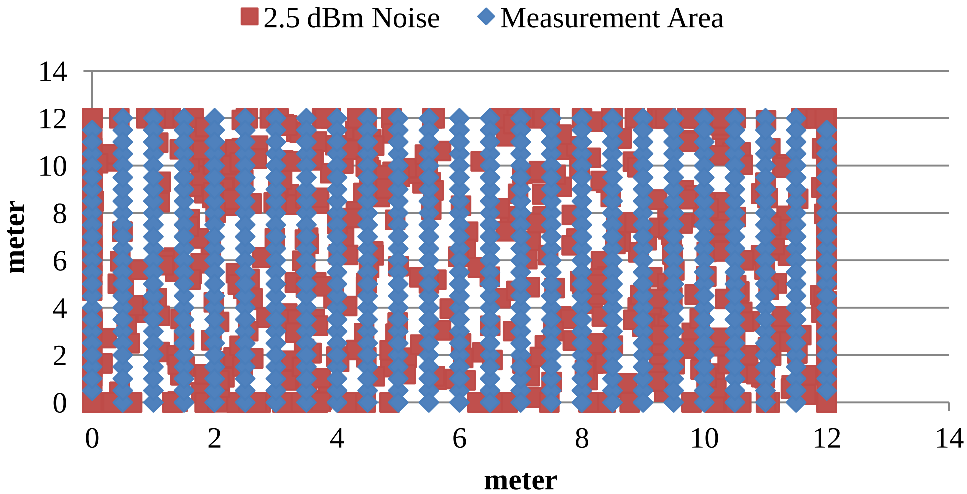
N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	1.78	0.06	6.40	1.03

Figure 6.22 Experiment on 2 dBm Noise (12mx12m)

6.3.2.6 12mx12m Area (2.5 dBm Noise)

This model is representing when there is 2.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.

Average is 2.01 meter, minimum error is 0.02 meter, maximum error 7.45 meter and standard deviation is 1.13 meter. (Figure 6.23)

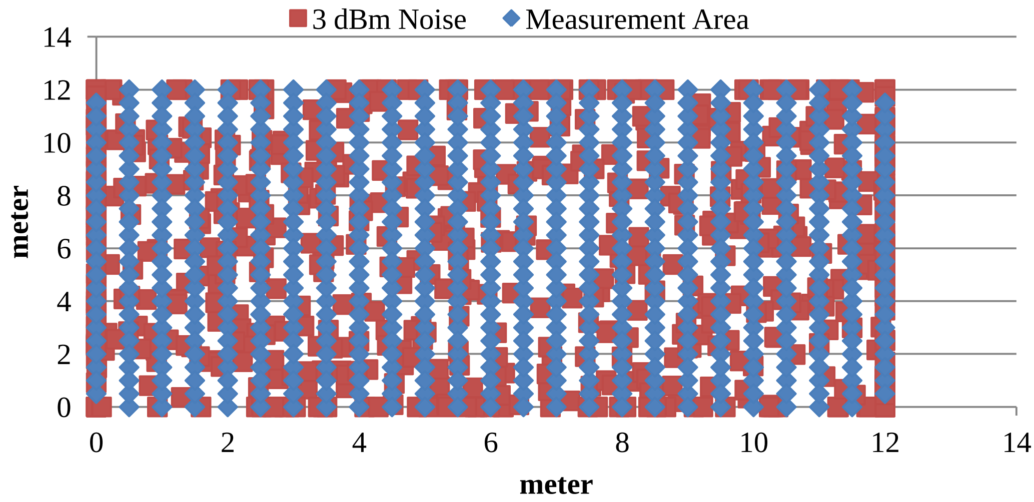


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	2.01	0.02	7.45	1.13

Figure 6.23 Experiment on 2.5 dBm Noise (12mx12m)

6.3.2.7 12mx12m Area (3 dBm Noise)

This model is representing when there is 3 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.
Average is 2.38 meter, minimum error is 0.03 meter, maximum error 7.25 meter and standard deviation is 1.34 meter. (Figure 6.24)

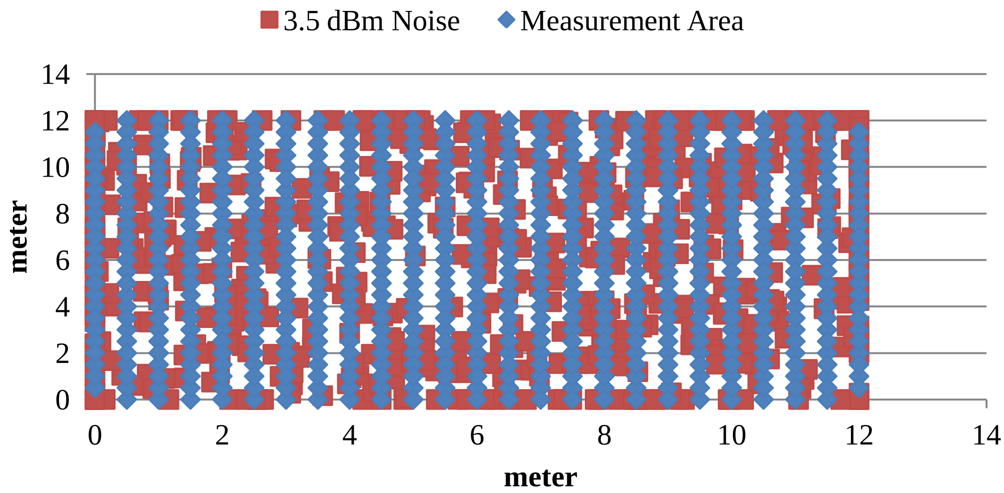


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	2.38	0.03	7.25	1.34

Figure 6.24 Experiment on 3 dBm Noise (12mx12m)

6.3.2.8 12mx12m Area (3.5 dBm Noise)

This model is representing when there is 3.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.
Average is 2.65 meter, minimum error is 0.05 meter, maximum error 9.52 meter and standard deviation is 1.52 meter. (Figure 6.25)

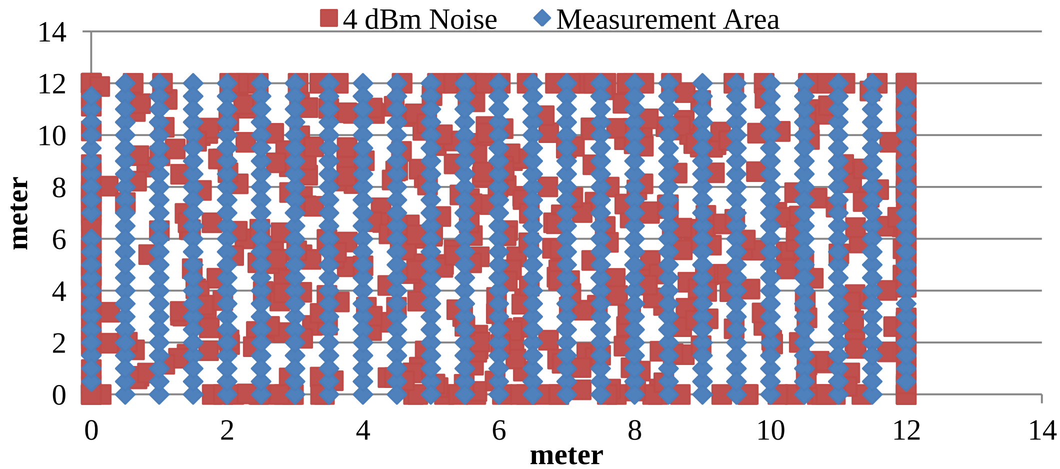


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	2.65	0.05	9.52	1.52

Figure 6.25 Experiment on 3.5 dBm Noise (12mx12m)

6.3.2.9 12mx12m Area (4 dBm Noise)

This model is representing when there is 4 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 3.02 meter, minimum error is 0.08 meter, maximum error 10.53 meter and standard deviation is 1.65meter. (Figure 6.26)

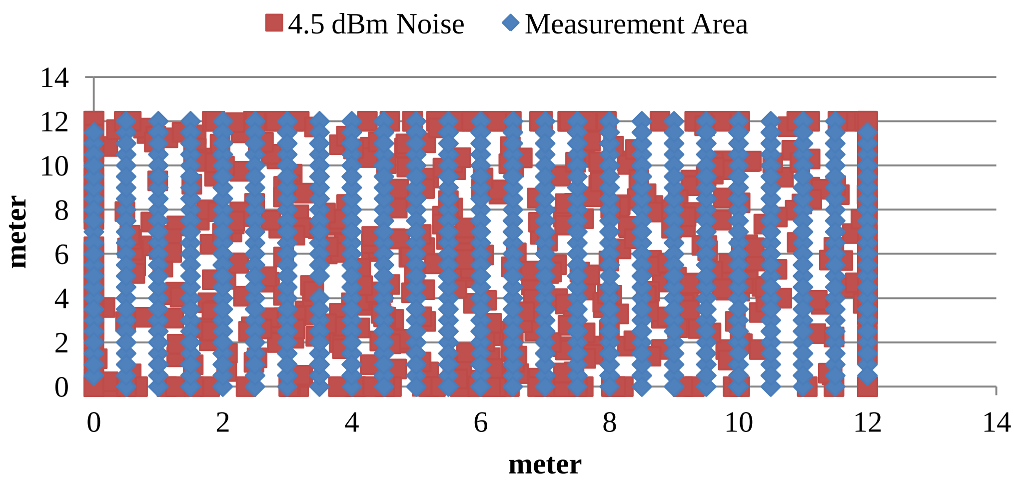


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	3.02	0.08	10.53	1.65

Figure 6.26 Experiment on 4 dBm Noise (12mx12m)

6.3.2.10 12mx12m Area (4.5 dBm Noise)

This model is representing when there is 4.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 3.02 meter, minimum error is 0.08 meter, maximum error 11.11 meter and standard deviation is 1.75 meter. (Figure 6.27)

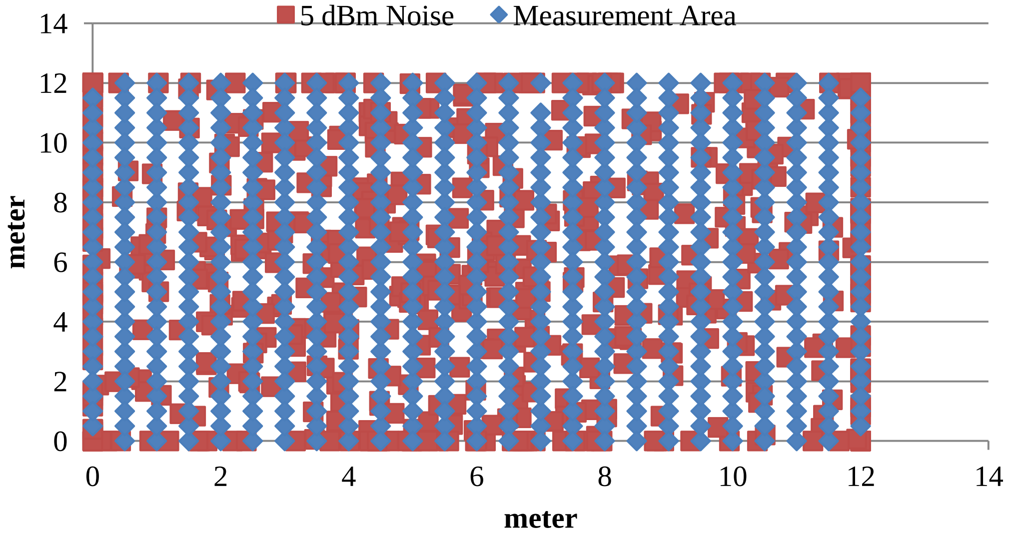


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	3.02	0.02	11.11	1.75

Figure 6.27 Experiment on 4.5 dBm Noise (12mx12m)

6.3.2.11 12mx12m Area (5 dBm Noise)

This model is representing when there is 5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 3.16 meter, minimum error is 0.03 meter, maximum error 10.10 meter and standard deviation is 1.91 meter. (Figure 6.28)

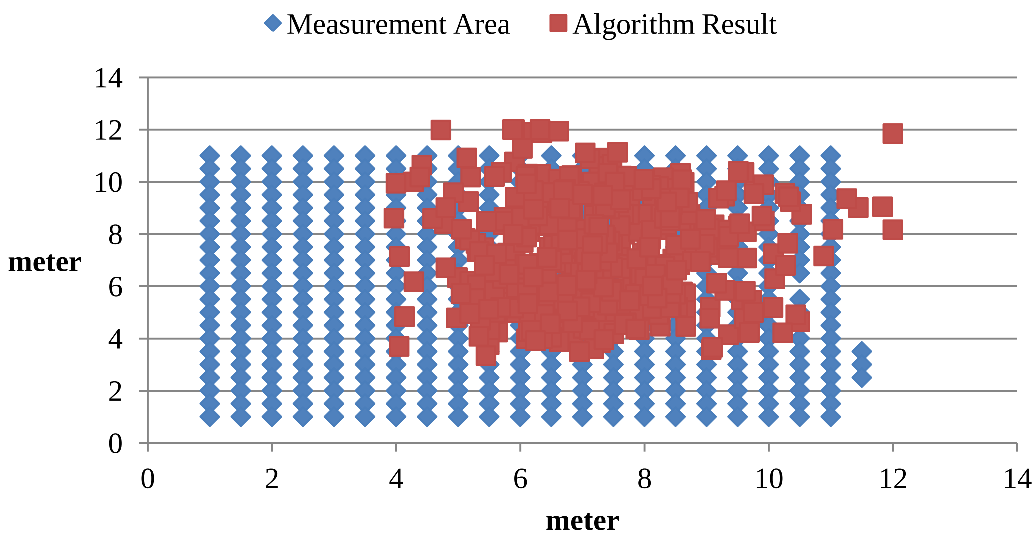


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	3.16	0.03	10.10	1.91

Figure 6.28 Experiment on 5 dBm Noise (12mx12m)

6.3.2.11 Experiment with Real Data

In chapter 3, environment with real data is described. $AP1, AP2$ *and* $AP3$ is used during experiment. Average is 2.32 meter, minimum error is 0.2 meter, maximum error is 10.13 meter, and standard deviation is 1.35 meter. (Figure 6.29)



Average Error	Minimum Error	Maximum Error	Standard Deviation
3.13	0.26	11.36	1.06

Figure 6.29 Experiment on Real Data (12mx12m)

6.3.3 24m x 24m Measurement Area

[31]'s membership function was limited with 6mx6m area. By using [31]'s membership function logic, new function is used. Fuzzy set is remained same;

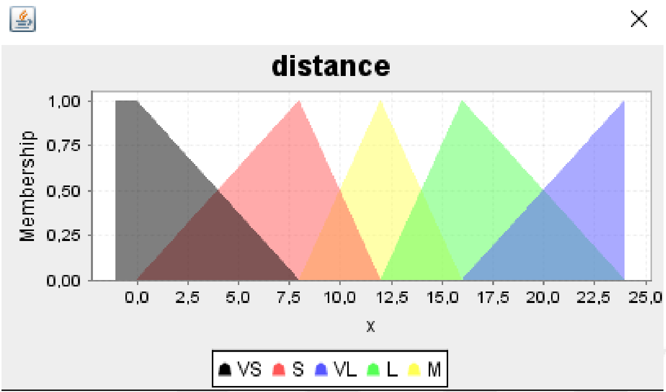
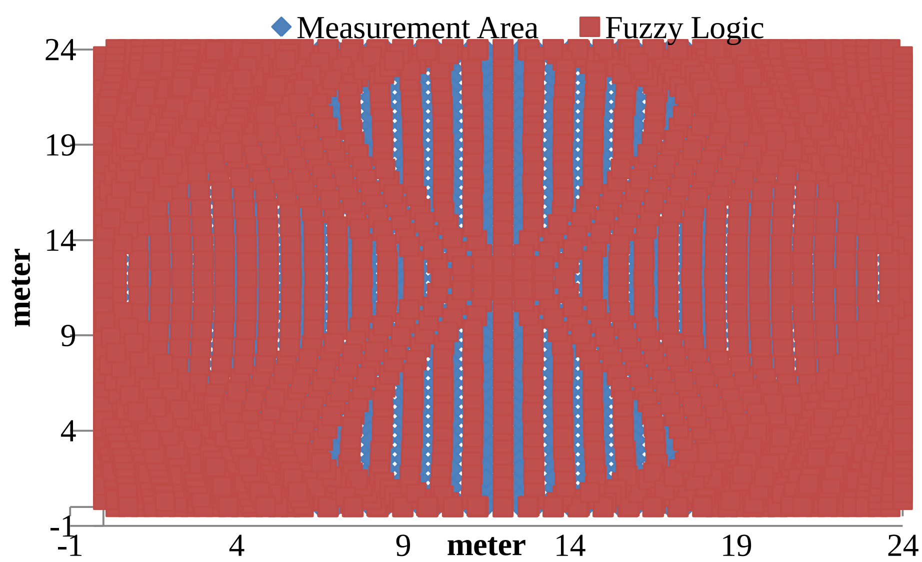


Figure 6.30 24mx24m Fuzzy Membership Function

6.3.3.1 24mx24m Area LOS

There are not any obstacles between transmitter and receiver in LOS environment. This model is representing when there is any signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 2.15 meter, minimum error is 0.00 meter, maximum error is 3.84 meter and standard deviation is 0.91 meter. (Figure 6.31)

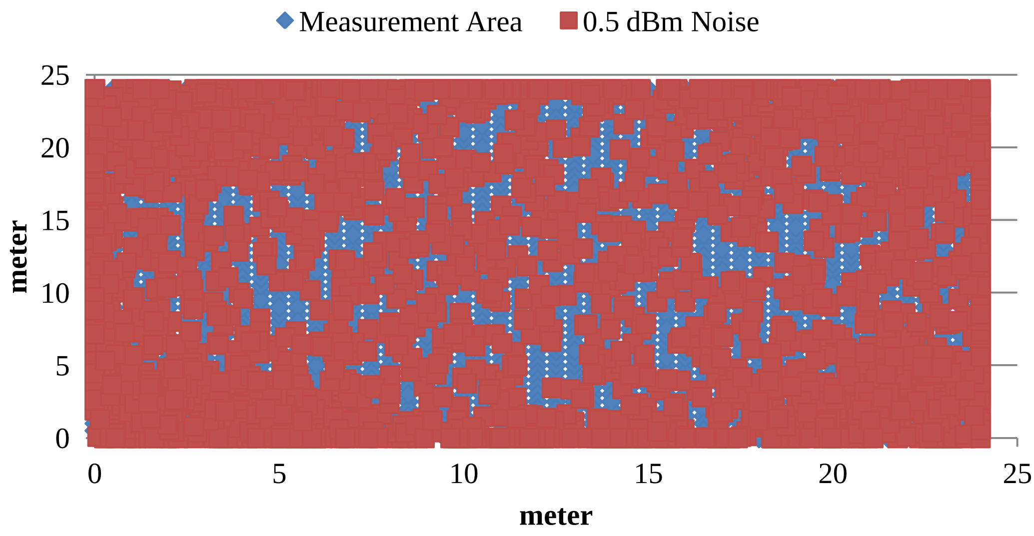


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	2.15	0.00	3.84	0.91

Figure 6.31 Experiment on LOS Environment (12mx12m)

6.3.3.2 24mx24m Area (0.5 dBm Noise)

This model is representing when there is 0.5 dBm signal loss in measurement area. Features’ real location is blue figure; estimated location’s are red figures.
Average is 2.30 meter, minimum error is 0.00 meter, maximum error 6.44 meter and standard deviation is 1.05 meter. (Figure 6.32)

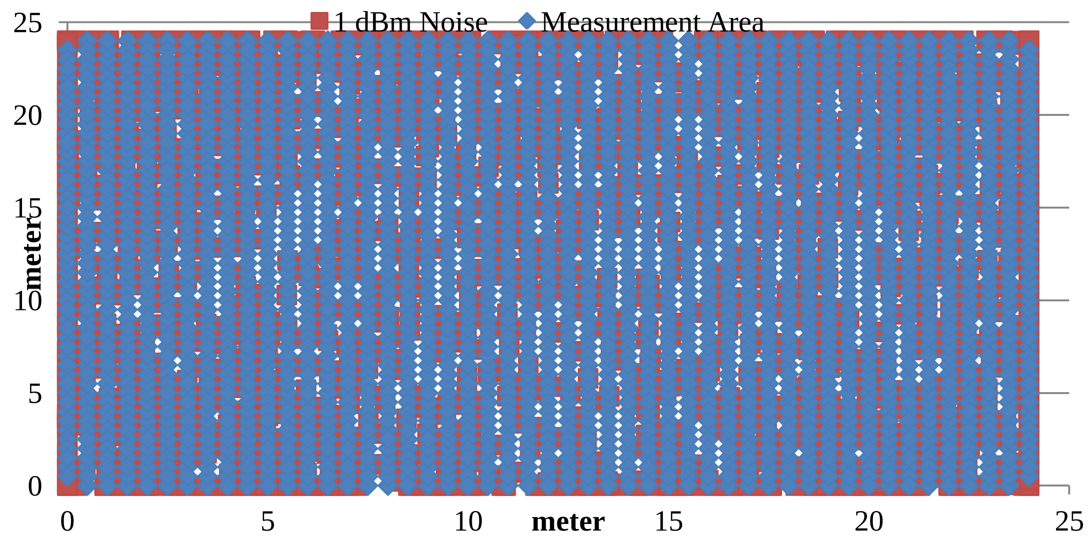


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	2.30	0.00	6.44	1.05

Figure 6.32 Experiment on 0.5 dBm Noise (12mx12m)

6.3.3.3 24mx24m Area (1 dBm Noise)

This model is representing when there is 1 dBm signal loss in measurement area. Features’ real location is blue figure; estimated location’s are red figures.
Average is 3.07 meter, minimum error is 0.03 meter, maximum error 24.29 meter and standard deviation is 3.25 meter. (Figure 6.33)

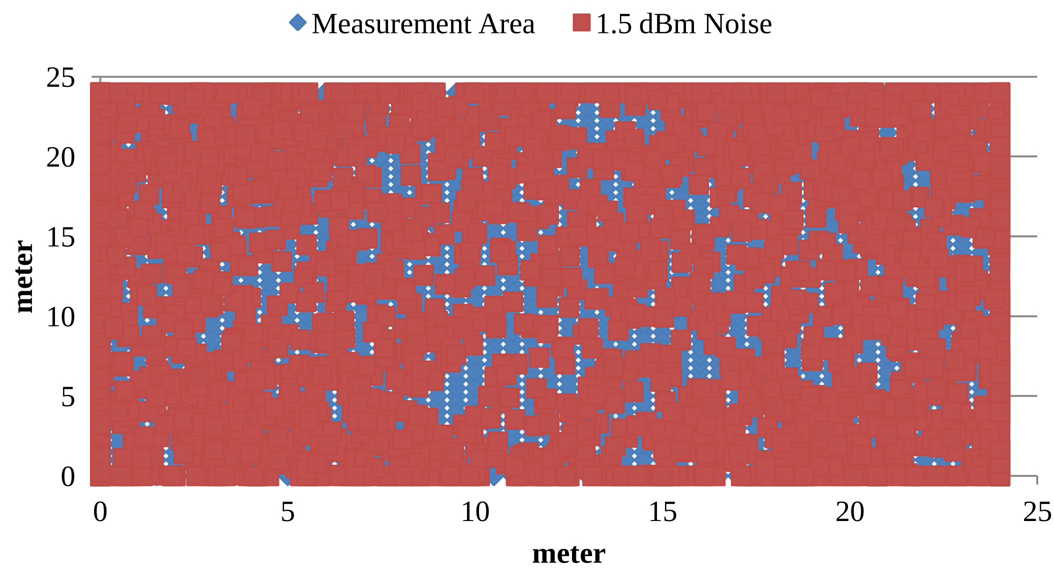


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	3.07	0.03	24.29	3.25

Figure 6.33 Experiment on 1 dBm Noise (12mx12m)

6.3.3.4 24mx24m Area (1.5 dBm Noise)

This model is representing when there is 1.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 3.51 meter, minimum error is 0.00 meter, maximum error 24.99 meter and standard deviation is 3.30 meter. (Figure 6.34)



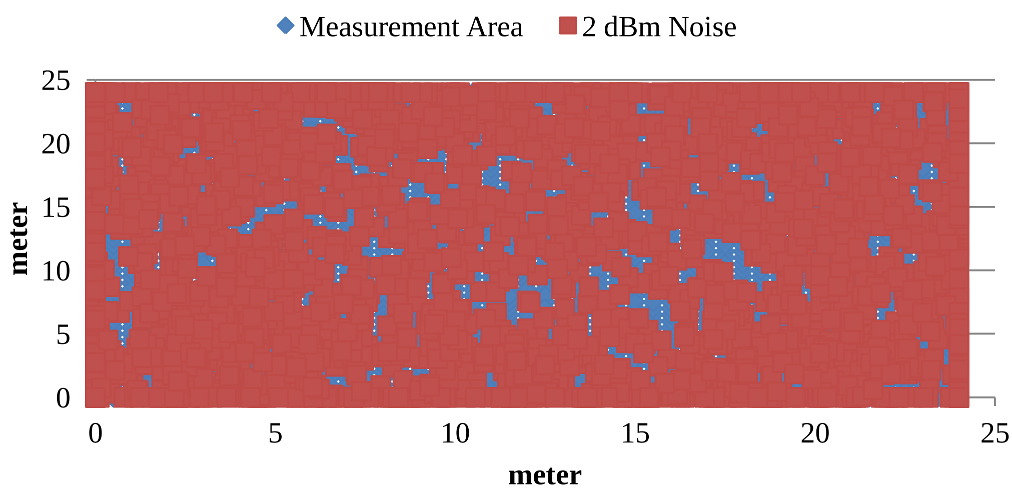
N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	3.51	0.00	24.99	3.30

Figure 6.34 Experiment on 1.5 dBm Noise (12mx12m)

6.3.3.5 24mx24m Area (2 dBm Noise)

This model is representing when there is 2 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.

Average is 4.05 meter, minimum error is 0.08 meter, maximum error 34.55 meter and standard deviation is 3.38 meter. (Figure 6.35)



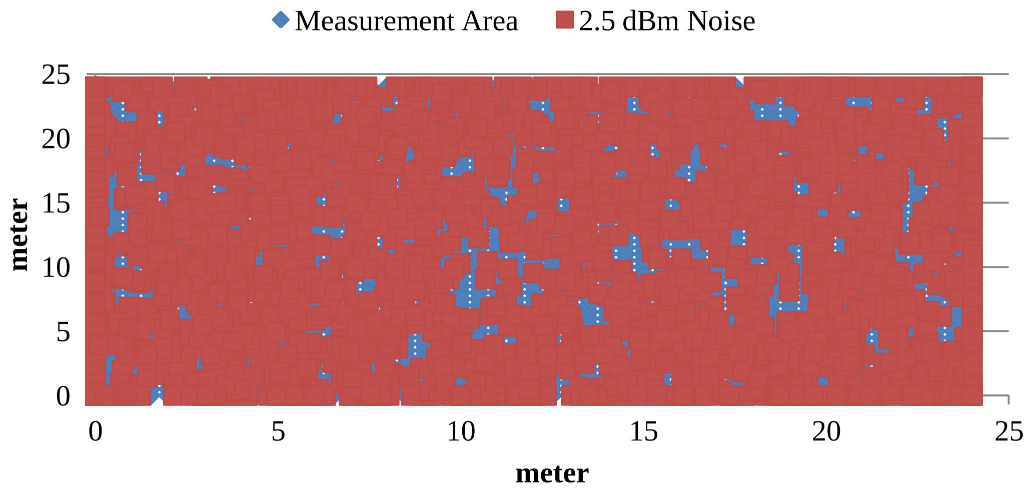
N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	4.05	0.08	34.55	3.38

Figure 6.35 Experiment on 2 dBm Noise (12mx12m)

6.3.3.6 24mx24m Area (2.5 dBm Noise)

This model is representing when there is 2.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.

Average is 4.63 meter, minimum error is 0.03 meter, maximum error 25.60 meter and standard deviation is 3.52 meter. (Figure 6.36)

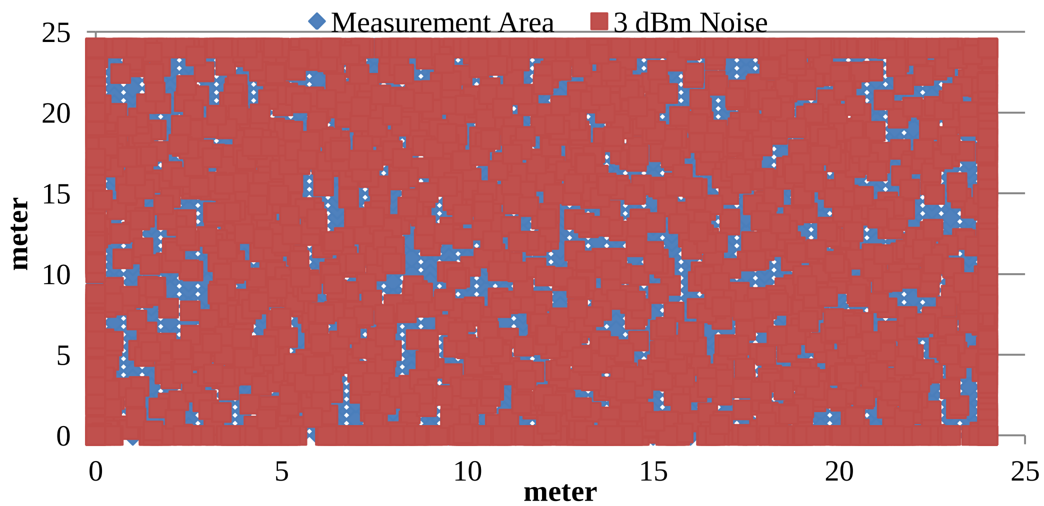


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	4.63	0.03	25.60	3.52

Figure 6.36 Experiment on 2.5 dBm Noise (12mx12m)

6.3.3.7 24mx24m Area (3 dBm Noise)

This model is representing when there is 3 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 5.08 meter, minimum error is 0.04 meter, maximum error 25.46 meter and standard deviation is 3.70 meter. (Figure 6.37)

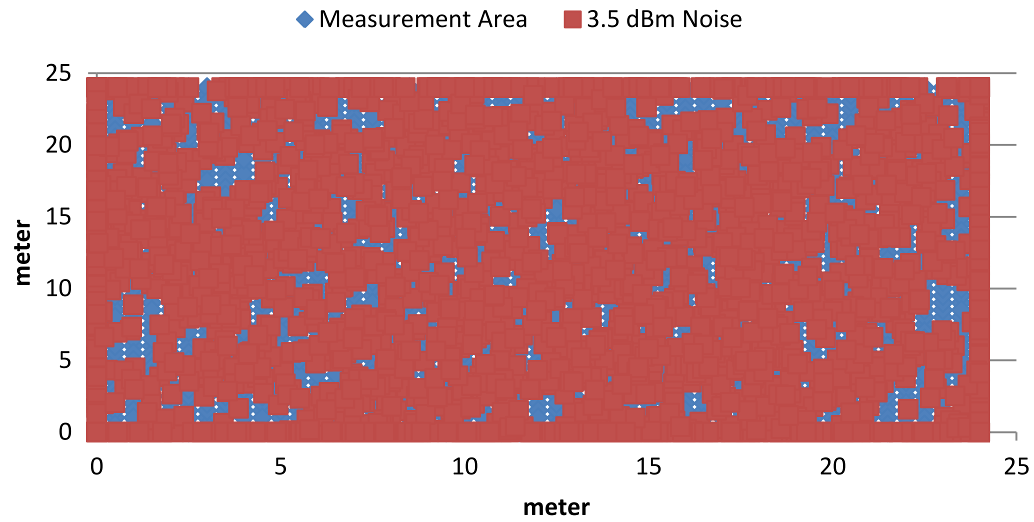


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	5.08	0.04	25.46	3.70

Figure 6.37 Experiment on 3 dBm Noise (12mx12m)

6.3.3.8 24mx24m Area (3.5 dBm Noise)

This model is representing when there is 3.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.
Average is 5.68 meter, minimum error is 0.01 meter, maximum error 26 meter and standard deviation is 3.80 meter. (Figure 6.38)

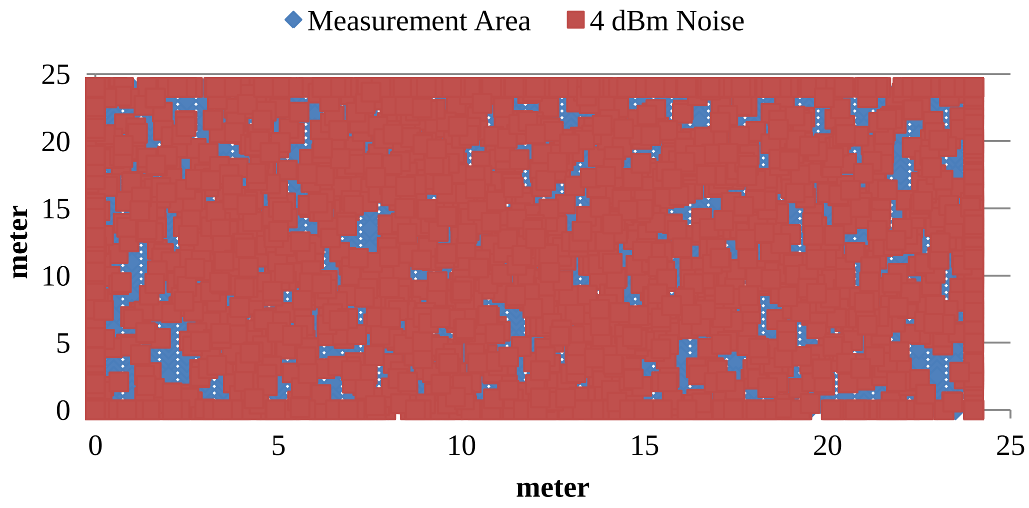


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	5.68	0.01	26	3.80

Figure 6.38 Experiment on 3.5 dBm Noise (12mx12m)

6.3.3.9 24mx24m Area (4 dBm Noise)

This model is representing when there is 4 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures.
Average is 6.08 meter, minimum error is 0.04 meter, maximum error 25.23 meter and standard deviation is 4.01 meter. (Figure 6.39)

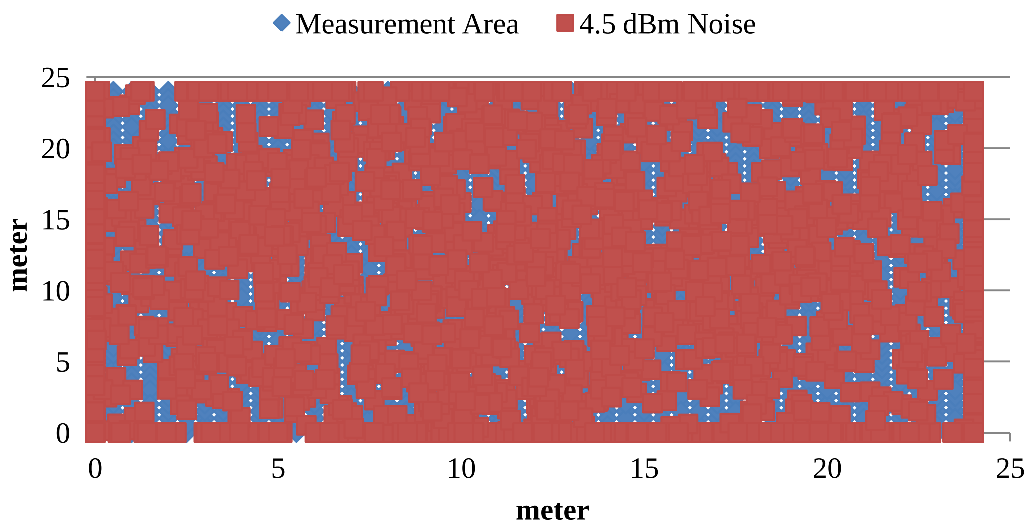


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	6.08	0.04	25.23	4.,01

Figure 6.39 Experiment on 4 dBm Noise (12mx12m)

6.3.3.10 24mx24m Area (4.5 dBm Noise)

This model is representing when there is 4.5 dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 6.59 meter, minimum error is 0.03 meter, maximum error 26.01 meter and standard deviation is 4.17 meter. (Figure 6.40)

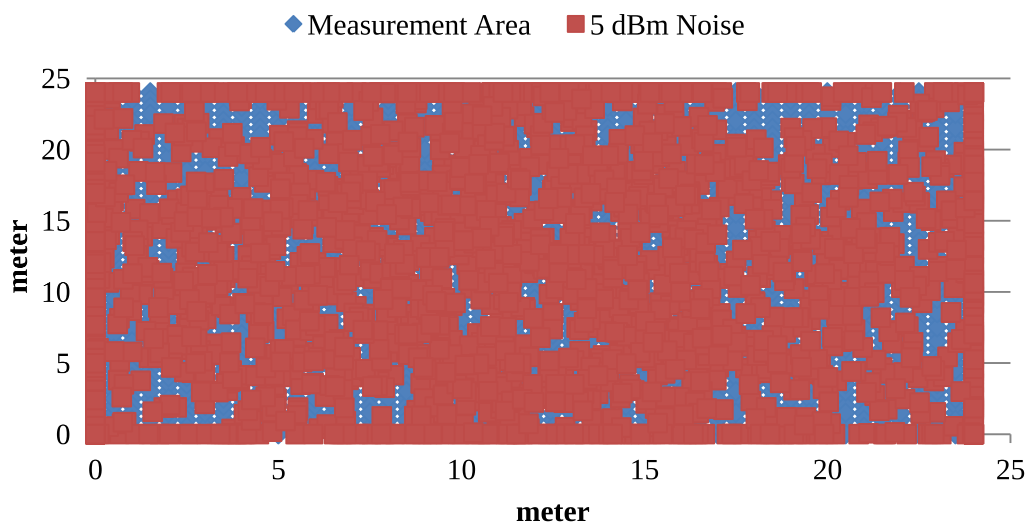


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	6.59	0.03	26.01	4.17

Figure 6.40 Experiment on 4.5 dBm Noise (12mx12m)

6.3.3.11 24mx24m Area (5 dBm Noise)

This model is representing when there is 5dBm signal loss in measurement area. Features' real location is blue figure; estimated location's are red figures. Average is 6.90 meter, minimum error is 0.09 meter, maximum error 27.06 meter and standard deviation is 4.37meter. (Figure 6.41)



N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	6.90	0.09	27.06	4.37

Figure 6.41 Experiment on 5.0 dBm Noise (12mx12m)

6.4 Experiment Results Summary Table

Table 6.1 is shown all measurement area result in a summary table. Summary table is clearly shown us, in fuzzy logic algorithm, while expanding measurement area and increasing noise, errors are getting increased.

Best accuracies are measured in LOS environment in 3 different experiment areas. However LOS environment is not a good example of indoor environment, so algorithm gave best accuracy in 6 square meter area with 0.5 dBm noisy environment. Fuzzy Logic algorithm tolerance is higher than Triangulation and Maximum Likelihood algorithm. This is detail examined in Chapter 8.

Table 6.1 Fuzzy Logic Experiment Results Summary Table

FUZZY LOGIC														
	6mx6m					12mx12m					24mx24m			
dBm	avg	min	max	std		avg	min	max	std		avg	min	max	std
0	0.52	0.08	0.93	0.23	0	0.96	0	2.09	0.44	0	2.15	0	3.84	0.91
0.5	0.55	0.02	1.31	0.28	0.5	1.11	0.01	2.59	0.51	0.5	2.3	0	6.44	1.05
1	0.64	0.01	1.63	0.36	1	1.28	0.01	3.63	0.69	1	3.07	0.03	24.29	3.25
1.5	0.77	0.18	2.13	0.44	1.5	1.53	0.01	6.02	0.9	1.5	3.51	0	24.99	3.3
2	0.87	0.4	2.12	0.47	2	1.78	0.06	6.40	1.03	2	4.05	0.08	34.55	3.38
2.5	1.01	0	3.42	0.59	2.5	2.01	0.02	7.45	1.13	2.5	4.63	0.03	25.6	3.52
3	1.19	0.01	3.26	0.67	3	2.38	0.03	7.25	1.34	3	5.08	0.04	25.46	3.7
3.5	1.29	0.01	3.81	0.75	3.5	2.65	0.05	9.52	1.52	3.5	5.68	0.01	26	3.8
4	1.46	0.01	5.11	0.88	4	3.02	0.08	10.53	1.65	4	6.08	0.04	25.23	4.01
4.5	1.59	0.07	5.38	0.91	4.5	3.02	0.02	11.11	1.75	4.5	6.59	0.03	26.01	4.17
5	1.67	0.03	3.8	1	5	3.16	0.03	10.1	2	5	6.9	0.09	27.06	4
Real Data	1.71	0.05	10.74	1.05	Real Data	3.13	0.26	11.36	1.06					

CHAPTER 7

Signal Finger Print

Fingerprinting is most popular method in indoor environment. In recent years, there are lots of works based on fingerprint algorithm. It has to potential to estimate mobile device accuretly.
Traditional Fingerprinting has two phases; online and offline. Offline phases where the RSSI values are collected, and a radio map is built. On online phase, the object location is estimated by using radio map in database.

7.1 Fingerprinting Algorithm with Least Square Method

Least Square method is most used data fitting algorithm in linear regression. Least square means that minimizes the sum of squared residuals, residuals means that difference between observed value and fitted value in model.

In thesis for first phase, LOS environment dataset is used as first phase, since there is no signal loss in LOS environment, it will be perfect signal data mapping. 1 dBm, 3 dBm, 5 dBm signal loss dataset are used as second phase.

In algorithm, in order to estimate location each node's RSSI values is compared with corresponding RSSI value in train database. In Figure 7.1, a test node's RSSI vector (AP1rssi, AP2rssi, AP3rssi, and AP4rssi) is compared with whole train node's RSSI vector in database. Using least square method, minimum error values is determined as estimated node. (7.1)

$$\sqrt{\sum_{i=1}^{4}(rssiTest_i - rssiTrain_i)^2} \tag{7.1}$$

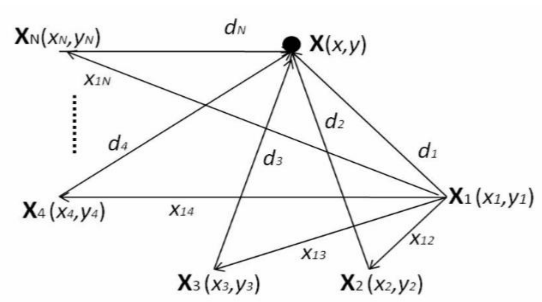


Figure 7.1 Least Square Method Algorithm

7.2 Measurement Results

Fingerprint algorithm is worked with 3 different measurement areas.

7.2.1 6m x 6m Measurement Area

Circle figures represent access point placement. Coordinate of access points respectively: (0, 0), (6, 0), (6, 6) and (0, 6). There are 256 test nodes, however we ignore nodes where it is access point coordinates. 252 data features were used within an interval of 0.4 meter in an area of 6 square meters (m^2).

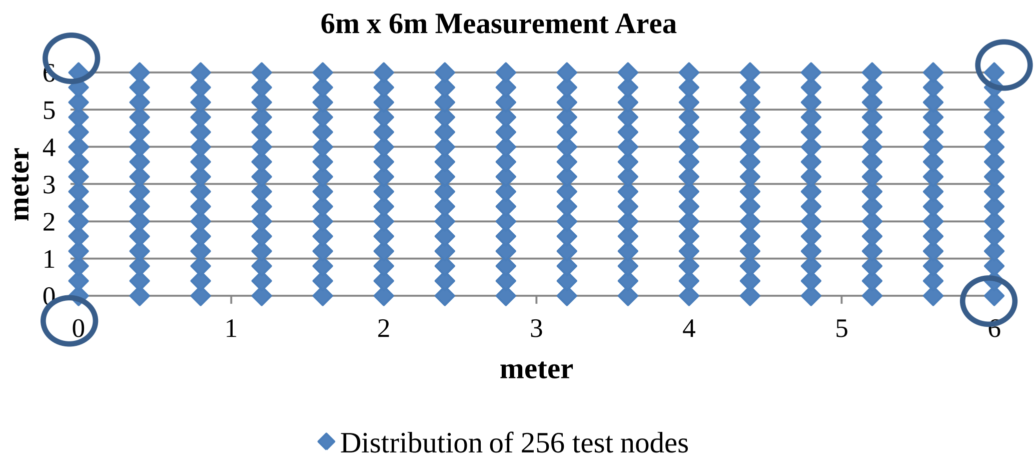
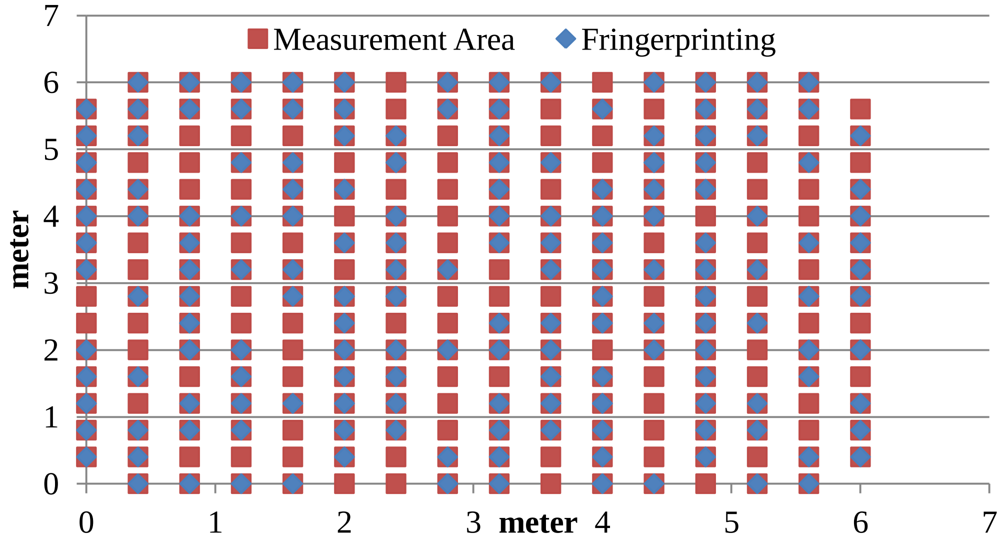


Figure 7.2 6mx6m Measurement Area-Access Point Placement

7.2.1.1 6m x 6m Area (1 dBm Noise)

This model is representing when there is 1 dBm signal loss in measurement area. Radio signal map is blue figure; estimated locations are red figures.
Average is 0.39 meter, minimum error is 0.00 meter, maximum error is 1.44 meter, and standard deviation is 0.34 meter. (Figure 7.3)

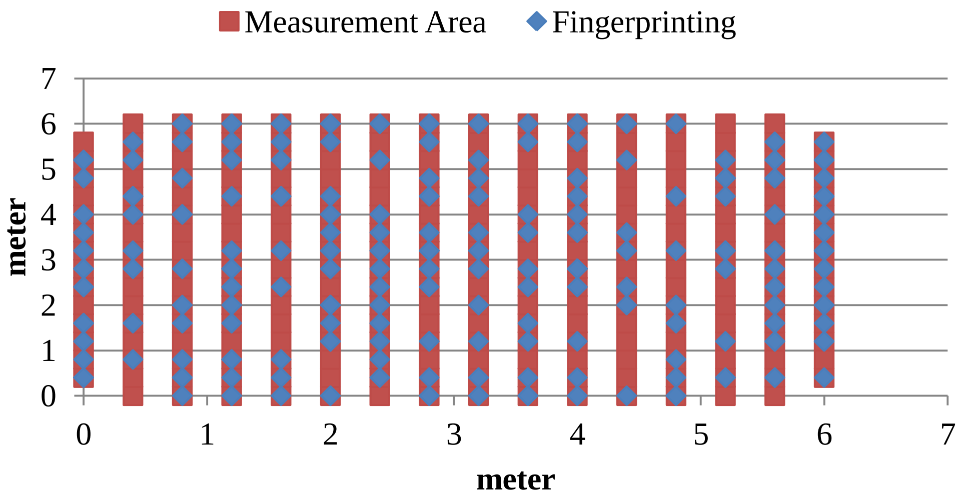


N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	0.39	0.00	1.44	0.34

Figure 7.3 Experiment on 1 dBm Noise (6mx6m)

7.2.1.2 6m x 6m Area 3 dBm

This model is representing when there is 3 dBm signal loss in measurement area. Radio signal map is blue figure; estimated locations are red figures.
Average is 1.00 meter, minimum error is 0.00 meter, maximum error is 3.22 meter, and standard deviation is 0.63 meter. (Figure 7.4)



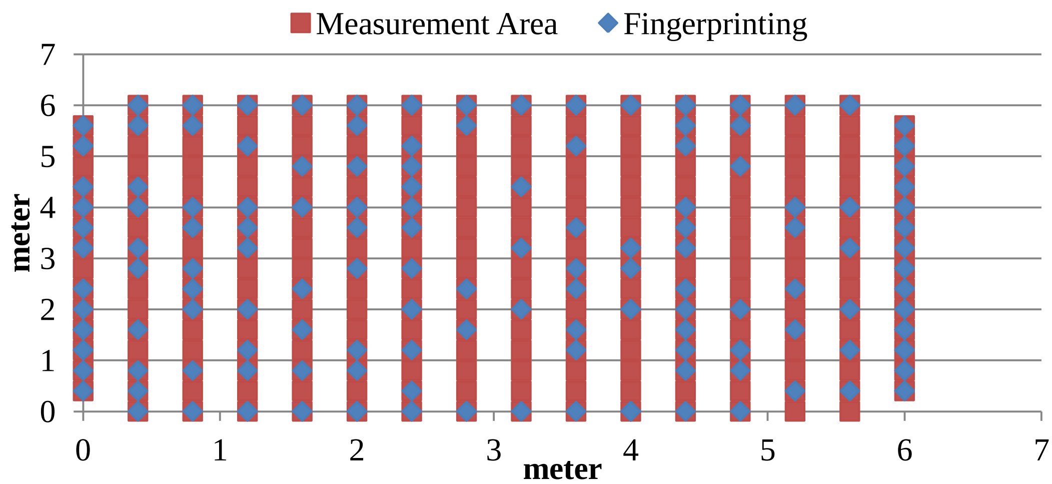
N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	1.00	0.00	3.22	0.63

Figure 7.4 Experiment on 3 dBm Noise (6mx6m)

7.2.1.3 6m x 6m Area 5 dBm

This model is representing when there is 5 dBm signal loss in measurement area. Radio signal map is blue figure; estimated locations are red figures.

Average is 1.56 meter, minimum error is 0.00 meter, maximum error is 4.47 meter, and standard deviation is 1.01 meter. (Figure 7.5)



N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	1.56	0.00	4.47	1.01

Figure 7.5 Experiment on 5 dBm Noise (6mx6m)

7.2.2 12m x 12m Measurement Area

Circle figures represent access point placement. Coordinate of access points respectively: (0, 0), (6, 0), (6, 6) and (0, 6). There are 625 test nodes, however we ignore nodes where it is access point coordinates. 621 data features were used within an interval of 0.5 meter in an area of 12 square meters (m^2).

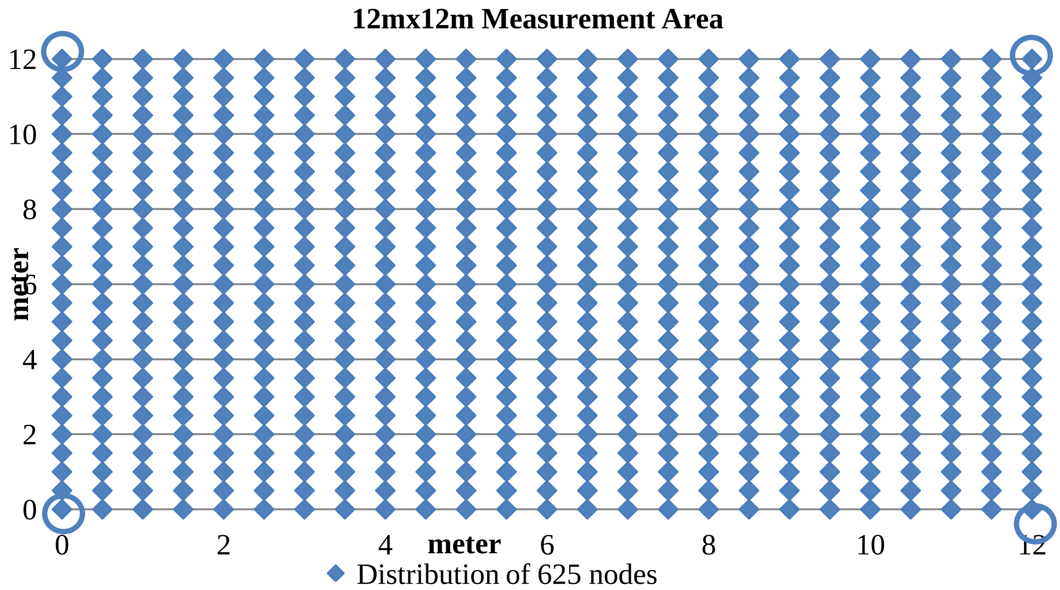
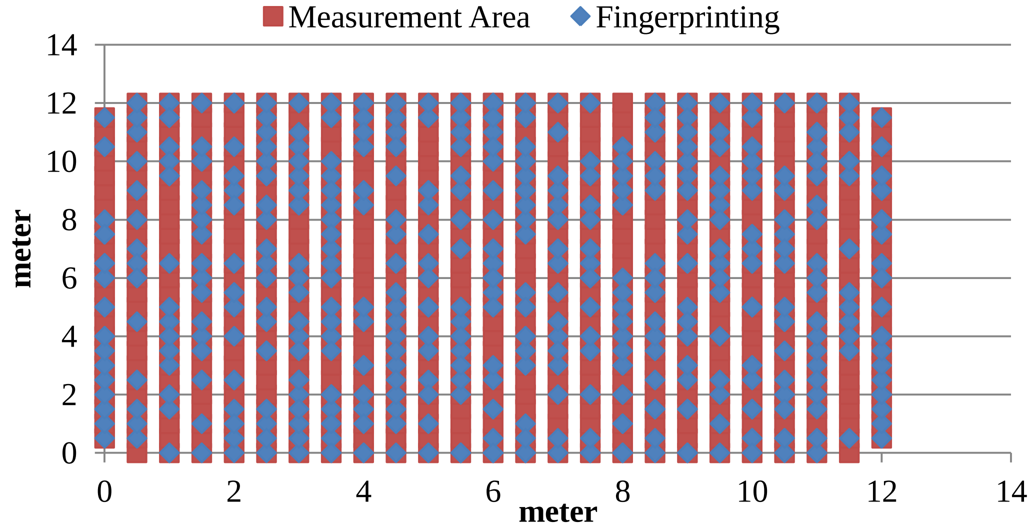


Figure 7.6 12mx12m Measurement Area-Access Point Placement

7.2.2.1 12mx12m Area 1 dBm

This model is representing when there is 1 dBm signal loss in measurement area. Radio signal map is blue figure; estimated locations are red figures.

Average is 0.76 meter, minimum error is 0.00 meter, maximum error is 2.69 meter, and standard deviation is 0.52 meter. (Figure 7.7)



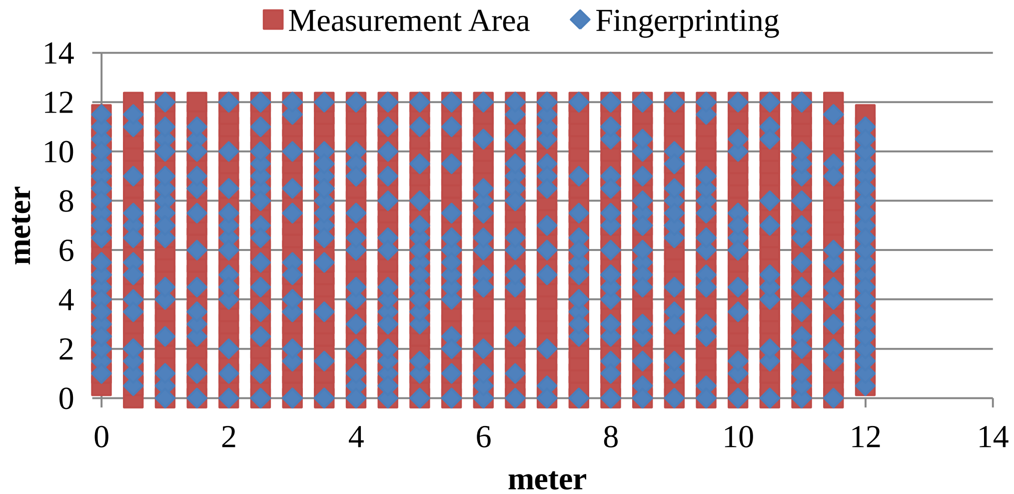
N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	0.76	0.00	2.69	0.52

Figure 7.7 Experiment on 1 dBm Noise (12mx12m)

7.2.2.2 12mx12m Area 3 dBm

This model is representing when there is 3 dBm signal loss in measurement area. Radio signal map is blue figure; estimated locations are red figures.

Average is 2.04 meter, minimum error is 0.00 meter, maximum error is 6.80 meter, and standard deviation is 1.31 meter. (Figure 7.8)



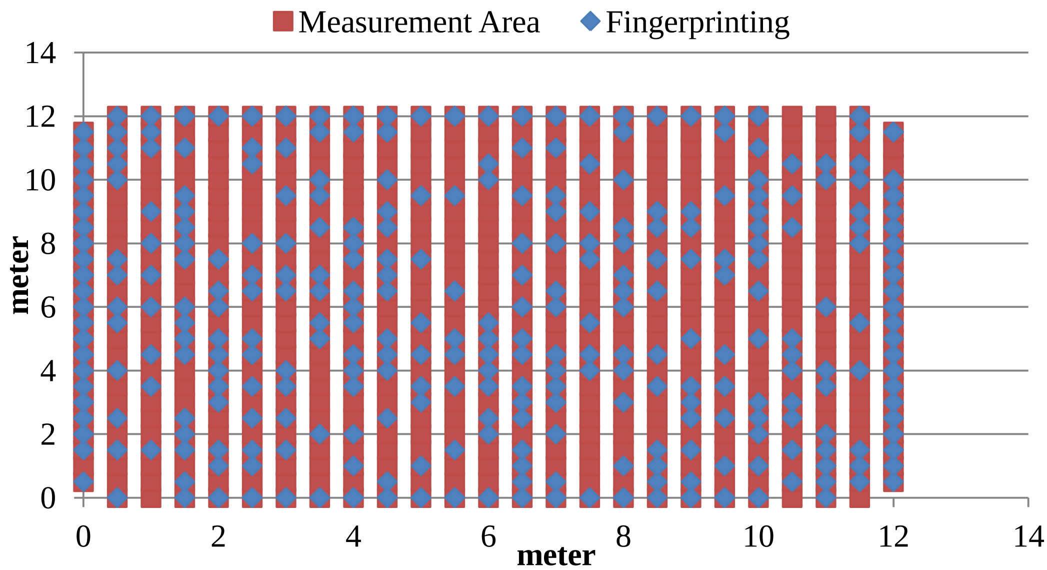
N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	2.04	0.00	6.80	1.31

Figure 7.8 Experiment on 3 dBm Noise (12mx12m)

7.2.2.3 12mx12m Area 5 dBm

This model is representing when there is 5 dBm signal loss in measurement area. Radio signal map is blue figure; estimated locations are red figures.

Average is 2.93 meter, minimum error is 0.00 meter, maximum error is 10.11 meter, and standard deviation is 1.95 meter. (Figure 7.9)



N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	2.93	0.00	10.11	1.95

Figure 7.9 Experiment on 5 dBm Noise (12mx12m)

7.2.3 24m x 24m Measurement Area

Circle figures represent access point placement. . Coordinate of access points respectively: (0, 0), (6, 0), (6, 6) and (0, 6) There are 2397 test nodes, however we ignore nodes where it is access point coordinates. 2393 data features were used within an interval of 0.5 meter in an area of 24 square meters (m^2). (Figure 7.10)

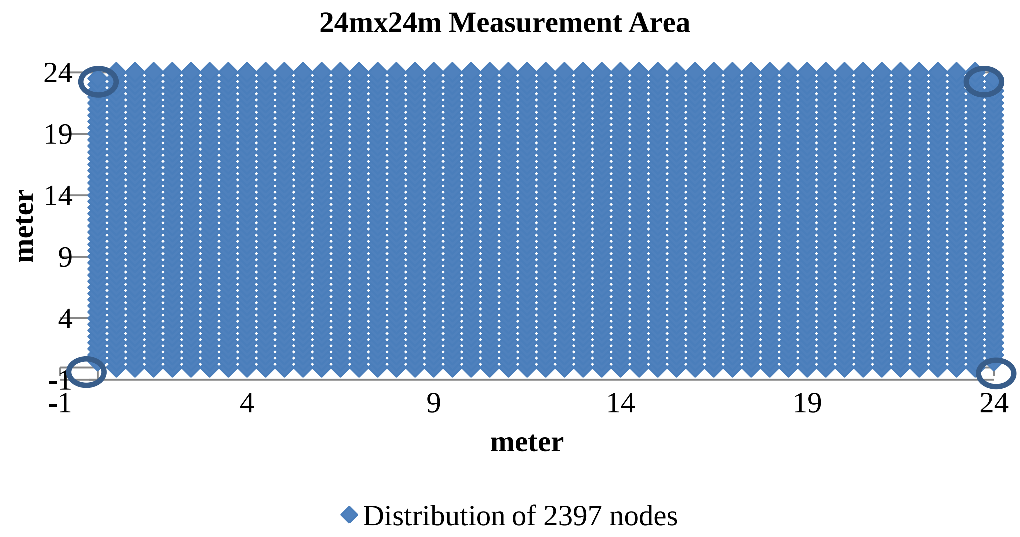
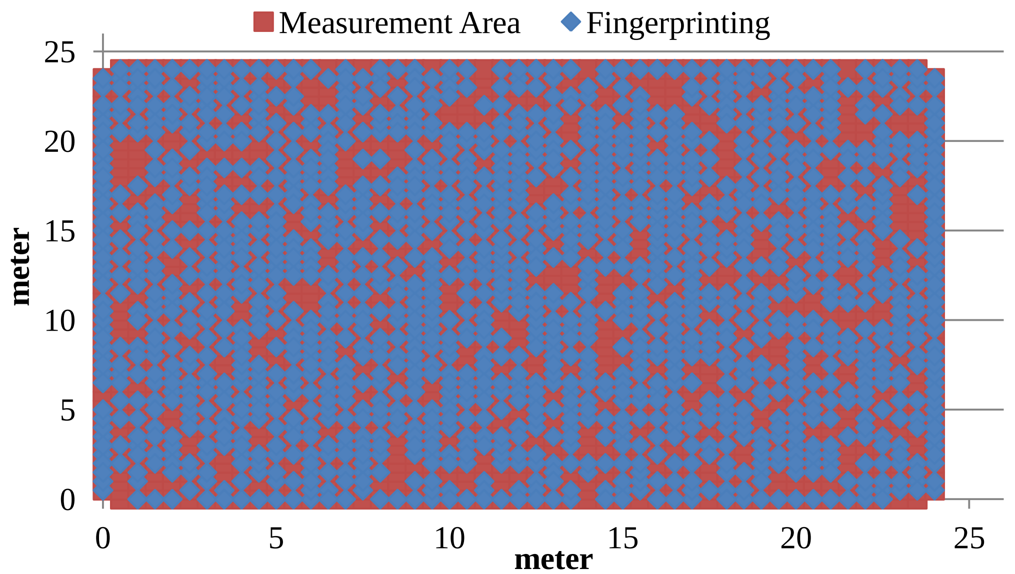


Figure 7.10 24mx24m Measurement Area-Access Point Placement

7.2.3.1 24m x 24m Area 1 dBm

This model is representing when there is 1 dBm signal loss in measurement area. Radio signal map is blue figure; estimated locations are red figures.

Average is 1.55 meter, minimum error is 0.00 meter, maximum error is 6.04 meter, and standard deviation is 0.98 meter. (Figure 7.11)



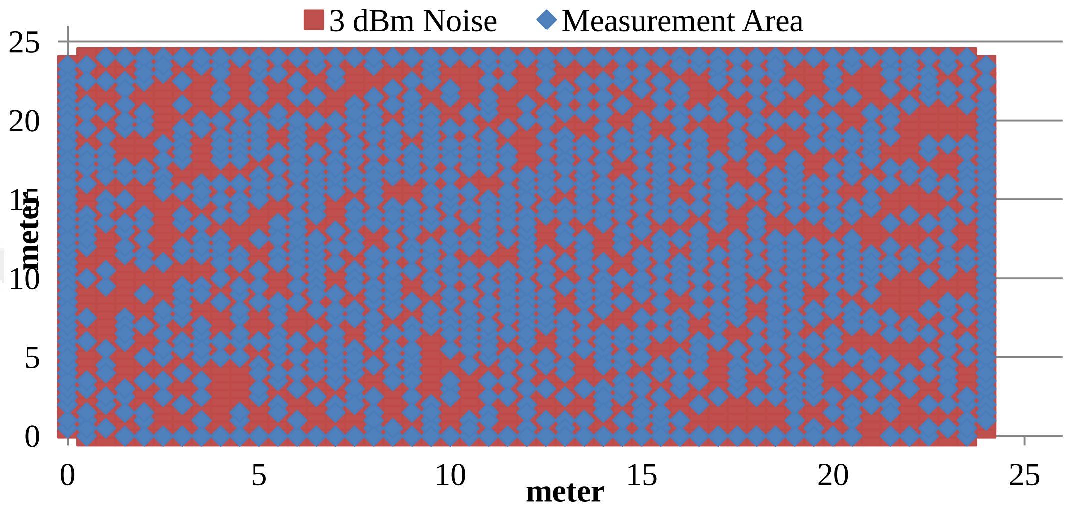
N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	1.55	0.00	6.04	0.98

Figure 7.11 Experiment on 1 dBm Noise (24mx24m)

7.2.3.2 24m x 24m Area 3 dBm

This model is representing when there is 3 dBm signal loss in measurement area. Radio signal map is blue figure; estimated locations are red figures.

Average is 4.03 meter, minimum error is 0.00 meter, maximum error is 14.92 meter, and standard deviation is 2.51meter. (Figure 7.12)



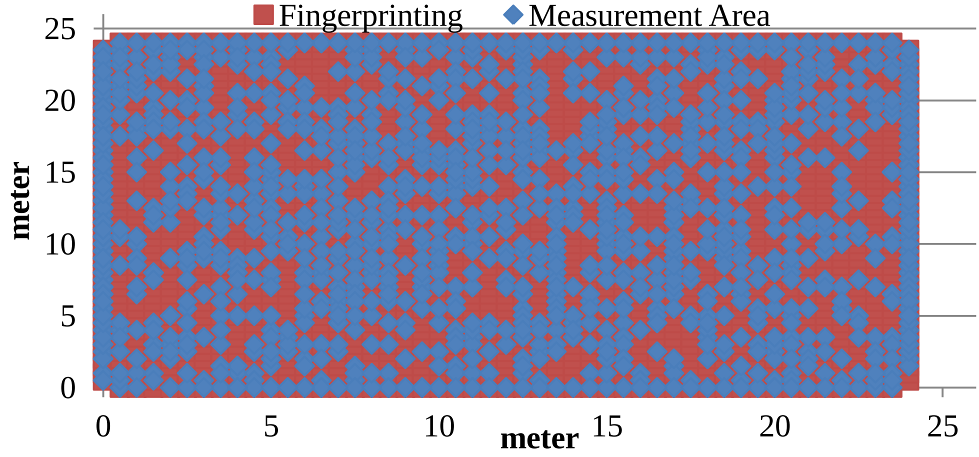
N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	4.03	0.00	14.92	2.51

Figure 7.12 Experiment on 3 dBm Noise (24mx24m)

7.2.3.2 24m x 24m Area 5 dBm

This model is representing when there is 5 dBm signal loss in measurement area. Radio signal map is blue figure; estimated locations are red figures.

Average is 6.11 meter, minimum error is 0.00 meter, maximum error is 22.94 meter, and standard deviation is 3.91 meter. (Figure 7.13)



N value	Average Error	Minimum Error	Maximum Error	Standard Deviation
2.18	6.11	0.00	22.94	3.91

Figure 7.13 Experiment on 5 dBm Noise (24mx24m)

7.3 Experiments Results Summary Table

Table 7.1 is shown all measurement area result in a summary table. Summary table is clearly shown us, while expanding measurement area and increasing noise, errors are getting increased. In 6 square meters area with 1 dBm noisy environment gave best accuracy, average error 0.39 meter, when we compared to other measurement areas. Moreover, Finger Printing algorithm gave best accuracy when compared to other 3 algorithms. In Chapter 9, this detail examined.

Table 7.1 Finger Print Experiments Result Summary Table

FINGER PRINTING														
	6mx6m					12mx12m					24mx24m			
	avg	min	max	std		avg	min	max	std		avg	min	max	std
0	-	-	-	-	**0**	-	-	-	-	**0**	-	-	-	-
0.5	-	-	-	-	**0.5**	-	-	-	-	**0.5**	-	-	-	-
1	0.39	0.01	1.44	0.34	**1**	0.76	0	2.69	0.52	**1**	1.55	0	6.04	0.98
1.5	-	-	-	-	**1.5**	-	-	-	-	**1.5**	-	-	-	-
2	-	-	-	-	**2**	-	-	-	-	**2**	-	-	-	-
2.5	-	-	-	-	**2.5**	-	-	-	-	**2.5**	-	-	-	-
3	1	0	3.22	0.68	**3**	2.04	0	6.8	1.31	**3**	4.04	0	14.92	2.51
3.5	-	-	-	-	**3.5**	-	-	-	-	**3.5**	-	-	-	-
4	-	-	-	-	**4**	-	-	-	-	**4**	-	-	-	-
4.5	-	-	-	-	**4.5**	-	-	-	-	**4.5**	-	-	-	-
5	1.56	0	4.47	1	**5**	2.93	0	10.11	2	**5**	6.11	0	22.94	4

CHAPTER 8

Comparison of IPS Algorithms

8.1 Comparison with Data Type

There were two types of data in order to understand how effected estimating location indoor environment. Data- with-no-noise represented LOS environment, data-with-noise is representing different level of obstacles in environment.

8.1.1 Data-with-no-Noise

LOS environment is an ideal environment which there is no obstacles between transmitter and receiver. Fingerprint algorithm is using data-with-no-noise dataset to build RSSI map in measurement area; so algorithm comparison with fingerprinting is ignored. Triangulation and Maximum Likelihood algorithms estimate target location with 100%. However Fuzzy Logic algorithm estimates location with 1 meter error in 6mx6m and 12mx12m areas, 2.15 meter in 24mx24m area (Table 8.1). This experiment is not good example of indoor environment, it is not possible to find perfect environment without losing any signal in wireless system. But also it is important to understand that Triangulation and Maximum Likelihood algorithms are perfectly working when we close to ideal environment.

Table 8.1 Algorithm Performance in LOS Environment

	Triangulation		Maximum Likelihood		Fuzzy Logic	
LOS	Average (meter)	Maximum (meter)	Average (meter)	Maximum (meter)	Average (meter)	Maximum (meter)
6mx6m	0	0.01	0	0.01	0.52	0.93
12x12m	0	0.02	0.01	0.01	0.96	2.09
24mx24m	0	0.02	0.01	0.01	2.15	3.84

8.1.2 Data-with-Noise

Typical indoor environments were modeled. Fuzzy Logic, Maximum Likelihood and Triangulation run with 5 different noise levels of data. . Noise is increased with 0.5

dBm starting with LOS environment up to 5 dBm. Fingerprinting algorithms is run with 1, 3 and 5 dBm data loss. In experiments it is observed that each algorithm gave a different reaction with noise. Estimating location success is decreasing with increased noise and large area. Algorithms gave worst result in noise data with 5 dBm in 24 square meters (m^2).

Fingerprinting algorithm gave best result compared to Triangulation, Maximum Likelihood and Fuzzy Logic algorithms. However, there are lots of differences inside of each algorithm. The most obvious differences is that Fingerprinting algorithm is not calculating distance with propagation model. It is difficult to calculate distance due to noise of wireless signals and interference on indoor locations. Calculating distance is one of most challenging issue in other 3 algorithm. [34]

7.1.2.1 6mx6m Environment Comparison

In figure, we can observe relationship between average error and noisy environment. In the beginning with less noisy environment, algorithms' success on estimating location is close each other. Triangulation and Maximum Likelihood algorithm are exceeding 2 meter average error with 2 dBm noisy environment. However, Fuzzy Logic algorithm average error in 5 dBm is 1.67 meter and Fingerprinting algorithm average error in 5 dBm is 1.56 meter .(Table 8.2)

Experiment show that in 6 square meter area Fingerprinting algorithm gave best result in average error based. But also Fuzzy Logic algorithm results are really close to fingerprinting. They are following same pattern in Figure 8.1. Moreover, Maximum Likelihood algorithm tolerance in noisy environment is better than Triangulation algorithm. Generally success on estimation is; Fingerprinting= Fuzzy Logic > Maximum Likelihood > Triangulation

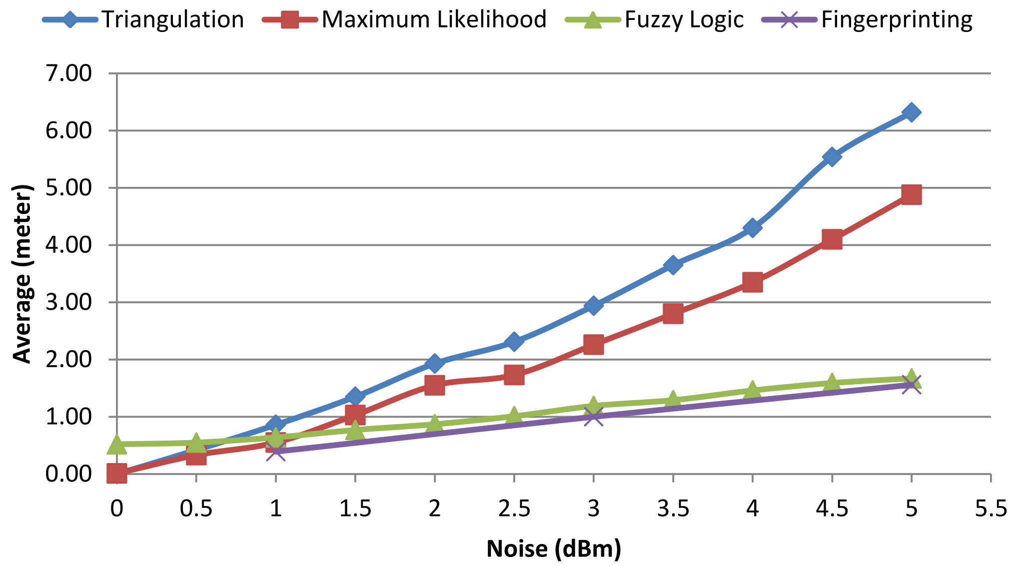


Figure 8.1 6mx6m Measurement Area Algorithm Performance

Table 8.2 6mx6m Measurement Area Algorithm Performance

	Triangulation		Maximum Likelihood		Fuzzy Logic		Fingerprinting	
Noise	**Average**	**Maximum**	**Average**	**Maximum**	**Average**	**Maximum**	**Average**	**Maximum**
0	0	0	0.01	0.01	0.01	0.01	-	-
0.5	**0.42**	1.82	0.33	1.4	0.55	1.31	-	-
1	0.86	4.01	**0.55**	2.14	0.64	1.63	**0.39**	1.44
1.5	1.35	7.14	1.03	4.49	**0.77**	2.13	-	-
2	1.93	10.66	1.55	12.33	**0.87**	2.12	-	-
2.5	2.31	9.36	1.73	13.06	**1.01**	3.42	-	-
3	2.94	18.31	2.26	12.73	**1.19**	3.26	**1**	3.22
3.5	3.65	30.5	2.8	17.41	**1.29**	3.81	-	-
4	4.3	28.38	3.35	23.1	**1.46**	5.11	-	-
4.5	5.54	42.07	4.1	26.3	**1.59**	5.38	-	-
5	6.32	62.4	4.88	31.6	**1.67**	3.8	**1.56**	4.47

8.1.2.2 12mx12m Environment Comparison

Experiment show that in 12 square meter area Fingerprinting algorithm gave best result. In figure, we can observe relationship between average error and noisy environment. In the beginning with less noisy environment, algorithms' success on estimating location is close each other. After 1 dBm Noise both Triangulation and Maximum Likelihood algorithm exceed 2 meter average error. Moreover, their maximum errors after 2 dBm noisy environment are higher than 20 meter. It is observing that estimation location is exceeding measurement area. However, Fuzzy

Logic and Fingerprinting algorithms are keeping estimated location in measurement area. Thus, Success on estimation is; Fingerprinting= Fuzzy Logic > Maximum Likelihood > Triangulation (Table 8.3)

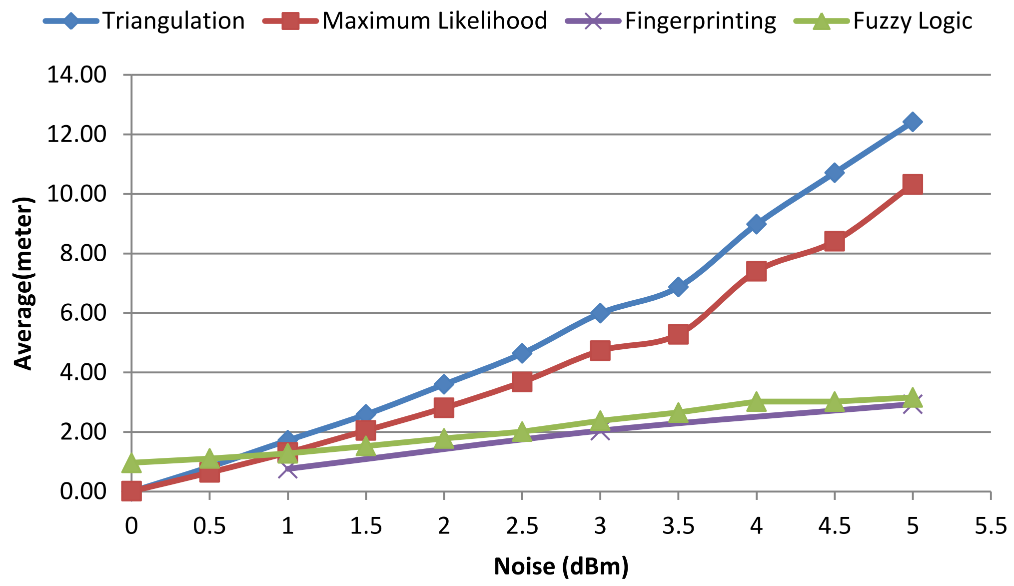


Figure 8.2 12mx12m Measurement Area Algorithm Performance

Table 8.3 12mx12m Measurement Area Algorithm Performance

	Triangulation		**Maximum Likelihood**		**Fuzzy Logic**		**Fingerprinting**	
Noise	**Average**	**Maximum**	**Average**	**Maximum**	**Average**	**Maximum**	**Average**	**Maximum**
0	0	0.02	0.01	0.01	0.01	0.01	-	-
0.5	0.83	4.54	**0.64**	2.54	1.11	2.59	-	-
1	1.72	8.08	1.31	5.06	**1.28**	3.63	**0.76**	2.69
1.5	2.59	**24.46**	2.05	10.72	**1.53**	6.02	-	-
2	3.6	**27.14**	2.81	12.72	**1.78**	6.40	-	-
2.5	4.64	**36.81**	3.68	**26.06**	**2.01**	7.45	-	-
3	5.99	**95.27**	4.73	**72.97**	**2.38**	7.25	**2.04**	6.8
3.5	6.87	**74.84**	5.28	**38.72**	**2.65**	9.52	-	-
4	8.98	**218.34**	7.4	**76.61**	**3.02**	10.53	-	-
4.5	10.71	**123.22**	8.41	**86.93**	**3.02**	11.11	-	-
5	12.42	**219.42**	10.32	**166.62**	**3.16**	10.1	**2.93**	10.11

7.1.2.3 24m x 24m Environment Comparison

Experiment show that in 24 square meter area Fingerprinting algorithm gave best result. In figure, we can observe relationship between average error and noisy environment. In the beginning with less noisy environment, algorithms' success on estimating location is close each other. However, if we increase noise in environment, tolerance of estimating location is decreasing. Maximum Likelihood and Triangulation algorithm is estimate location inside of measurement area; Fuzzy Logic and Fingerprinting algorithms are keeping estimated location inside of area like in 12mx12m. Although Fuzzy Logic and Fingerprinting algorithms are following similar pattern, Fingerprinting tolerance in 24mx24m area is better than Fuzzy Logic. Thus, Success on estimation is; Fingerprinting>Fuzzy Logic > Maximum Likelihood > Triangulation (Table 8.4)

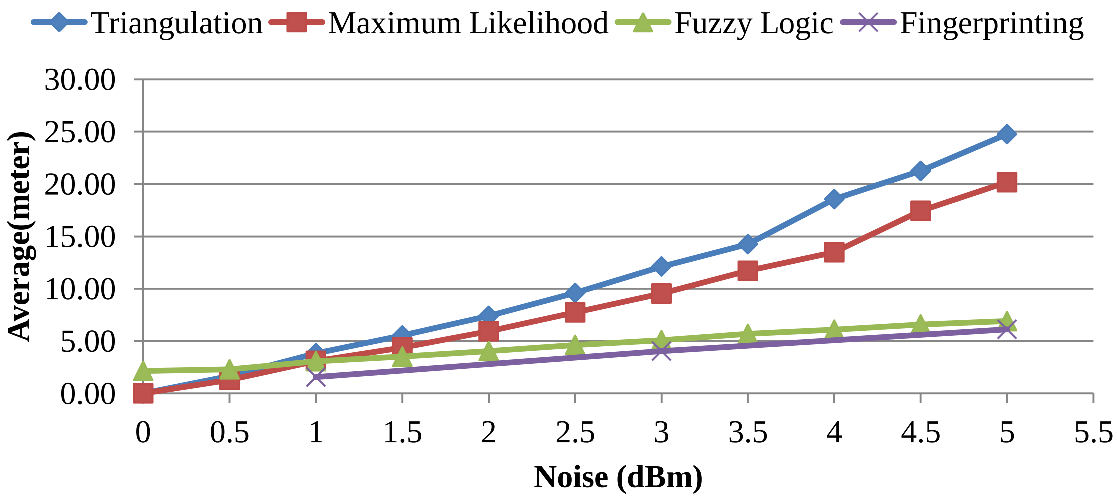


Figure 8.3 24mx24m Measurement Area Algorithm Performance

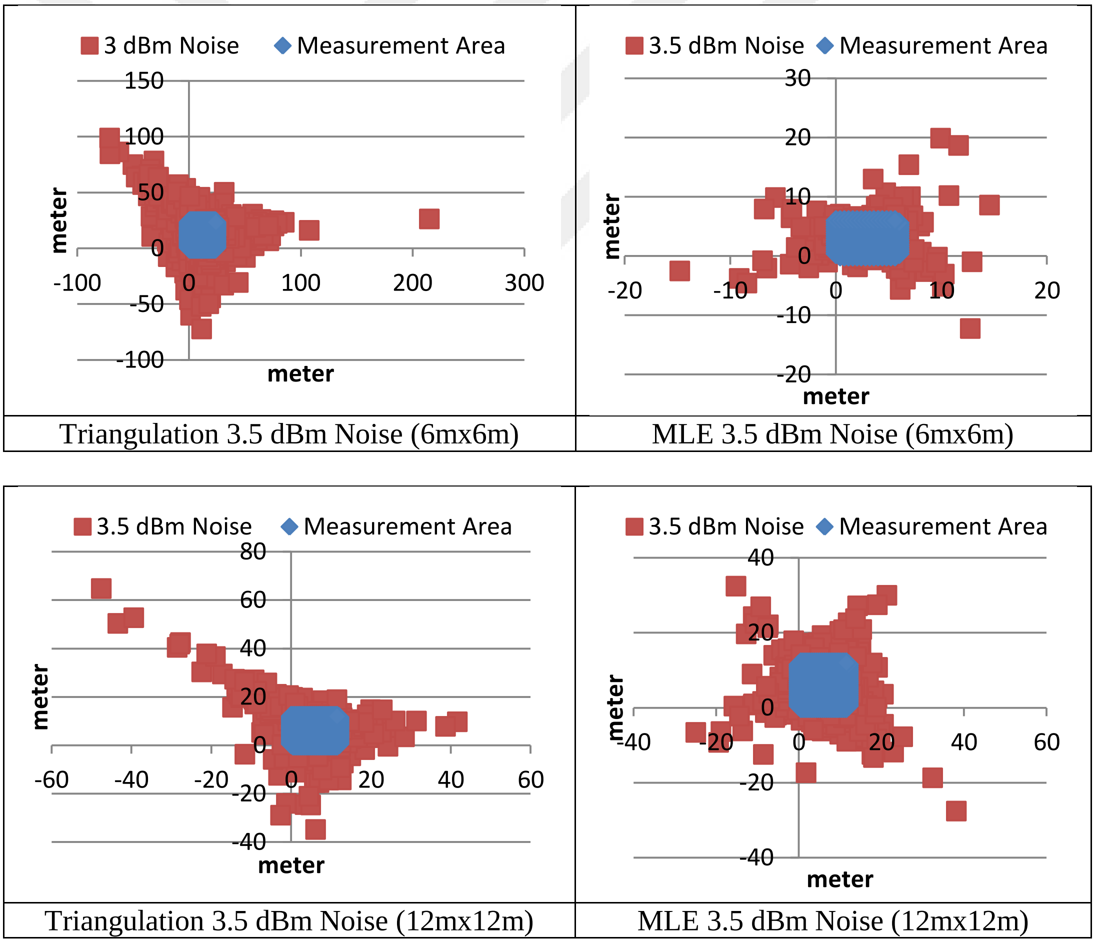
Table 8.4 24mx24m Measurement Area Algorithm Performance

	Triangulation		**Maximum Likelihood**		**Fuzzy Logic**		**Fingerprinting**	
Noise	**Average**	**Maximum**	**Average**	**Maximum**	**Average**	**Maximum**	**Average**	**Maximum**
0	0	0.02	0.01	0.01	0.01	0.01	-	-
0.5	**1.65**	8.88	1.28	6.13	2.3	6.44	-	-
1	3.84	30.94	3.1	27.6	**3.07**	24.29	**1.55**	6.04
1.5	5.53	37.36	4.38	39.69	**3.51**	24.99	-	-
2	7.4	**81.68**	5.93	46.35	**4.05**	34.55	-	-
2.5	9.59	**83.69**	7.74	58.35	**4.63**	25.6	-	-
3	12.12	**191.46**	9.53	**147.47**	**5.08**	25.46	**4.04**	14.92
3.5	14.25	**157.52**	11.7	**164.78**	**5.68**	26	-	-
4	18.55	**331.2**	13.48	**249.67**	**6.08**	25.23	-	-
4.5	21.24	**316.41**	17.43	**337.61**	**6.59**	26.01	-	-
5	24.76	**578.28**	20.17	**427.49**	**6.9**	27.06	**6.11**	22.94

8.2 Comparison of Access point Usage

Maximum Likelihood and Triangulation algorithm is similar with each other. MLE requires 4 access points, Triangulation requires 3 access points. We observed that generally in 3 different area and 5 different noisy level, MLE algorithm is successful than Triangulation.

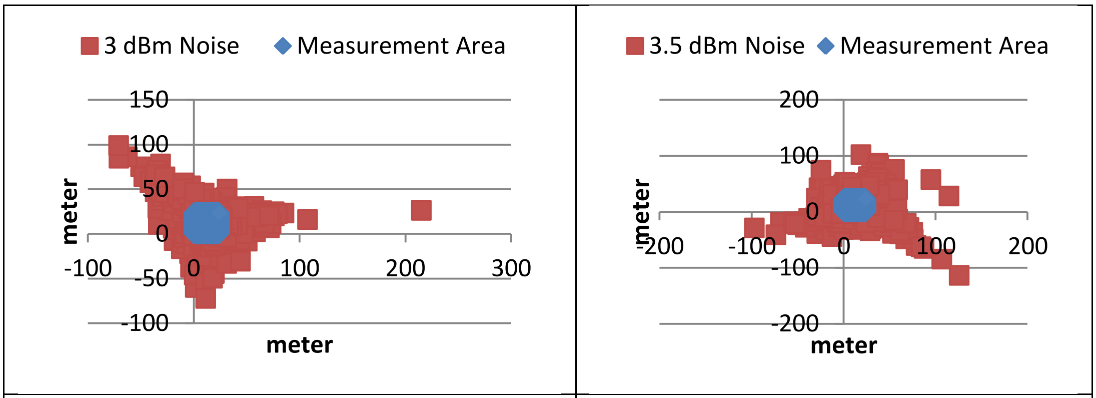
In figures we can see Triangulation algorithm and Maximum Likelihood algorithms' distribution of estimated location. In Triangulation graphs, estimated locations agglomerate with left side where access point signals are coming. On the other hand, Maximum Likelihood graphs estimated locations are distributed with measurement area. We can say that access point number increase success on estimation location.



Triangulation 3.5 dBm Noise (6mx6m) | MLE 3.5 dBm Noise (6mx6m)

Triangulation 3.5 dBm Noise (12mx12m) | MLE 3.5 dBm Noise (12mx12m)

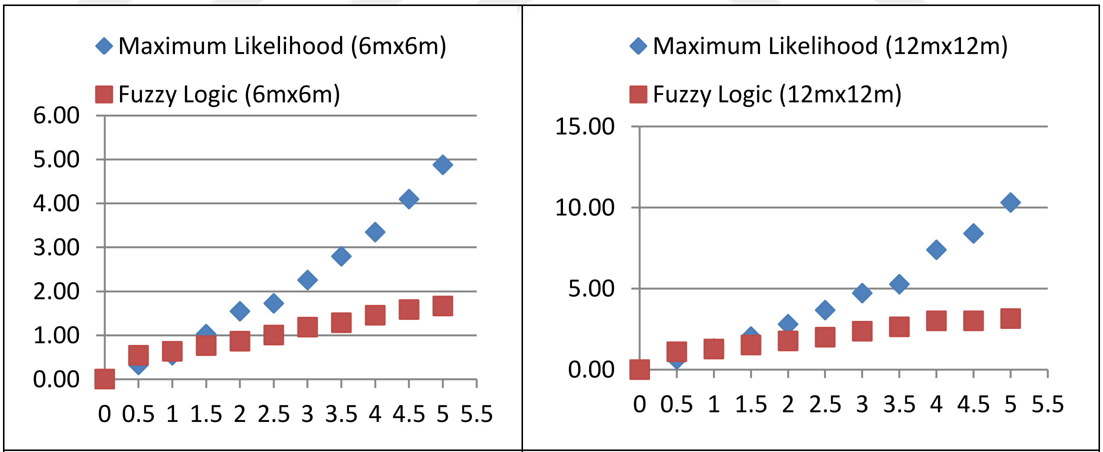
Figure 8.4 Comparison of Access Point Usage in 6mx6m, 12mx12m Areas



Triangulation 3.5 dBm Noise (24mx24m)	MLE 3.5 dBm Noise (24mx24m)

Figure 8.5 Comparison of Access Point Usage 24mx24m Area

Fuzzy Logic and Maximum Likelihood algorithm requires 4 access point. In Fuzzy Logic algorithm, we restrict estimated location within measurement area. Unlike Maximum Likelihood algorithm, all estimated location is keeping inside of area. In this way, we observe that success of finding location is increasing. It can be easily observe in 5 dBm noise and 24 square meter area; Fuzzy Logic average error is 6.9 meter, Maximum Likelihood average error is 24.76.



Performance in 6mx6m Area	Performance in 12mx12m Area

Figure 8.6 Comparison Performance in 6mx6m, 12mx12m Areas

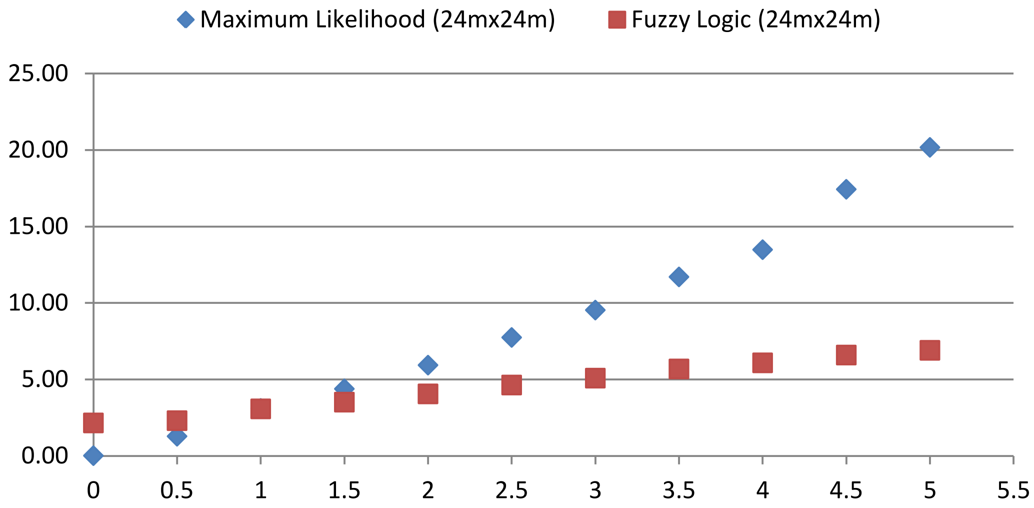


Figure 7.4 Comparison of Access Point Usage 24mx24m Area

8.3 Measurement Area Restriction

Experiment show that, if algorithm estimates location inside of area averaging error is decreasing. Fuzzy Logic and Fingerprinting algorithm is keeping target node inside of measurement area. However Maximum Likelihood and Triangulation are exceeding measurement area while estimating location. We implemented restriction on algorithms. We observed that results are getting better. If algorithm estimates location outside of measurement area, we assumed that estimated location on border of measurement area.

Table 8.5 Measurement Area Restriction Comparison

	Restriction		Non-restriction		
	Average	Maximum	Average	Maximum	
6mx6m	**2.05**	6.73	**4.3**	28.38	TRI
	1.90	5.73	**3.35**	23.1	MLE
12mx12m	**3.55**	11.88	**5.99**	**95.27**	TRI
	3.03	11.17	**4.73**	**72.97**	MLE

8.4 General Approach

Fingerprinting algorithm gave best result on 3 different measurement areas. Fuzzy Logic algorithm is following this success. It is observed that two algorithm has similar pattern through measurement areas with different noisy level. Both algorithms are recognizing measurement area. Fuzzy Logic is using membership function which is giving weight coefficient for finding distance, Fingerprinting is using radio signal mapping. Recognizing measurement area is a key factor success on IPS system.

Triangulation and Maximum Likelihood using similar formulation as we discuss in section 8.2. However, Triangulation is using 3 access points and Maximum Likelihood is using 4 access points. We observed that increasing source of radio signal is increasing success on IPS system.

Fuzzy Logic and Fingerprinting algorithms are keeping estimated location inside of measurement area. However, Maximum Likelihood and Triangulation algorithms might estimate location inside of area. It is observed that when we increase noise in environment, estimated locations are not inside of area. However, algorithm has restriction about measurement area, average error is decreasing. Determining measurement area border and knowing structure of area is important for IPS systems.

CHAPTER 9

Conclusion

Indoor positioning one of most challenging and important topic in recent years, there are lots of research has been doing in this field. Every work on this field is giving opportunity to make improve existing algorithms.

During our research we observed that Wi-Fi technologies provide less costly methods on indoor environment. These methods are easy to implement any indoor environment without needed any extra materials and cost. For that reason we focused on Wi-Fi technologies. However we observe that, with Wi-Fi technologies it is really challenging factor to calculate distance from RSSI values. RSSI values are easily affected with noisy and interference environment. Moreover, RSSI behavior can be change through access point models.

In thesis experiment part, we briefly introduce existing IPS techniques and analysis 4 different IPS algorithms which is using WLAN technologies. We choose algorithm that two of them are using lateration method which is perfectly fitting with distance, and others are using recognition method which is easily accommodating with environment. We analyze algorithms performance with different measurement area and different noise level environment.

Our experiment show that, when we exceed measurement area and increase signal noise, errors are increasing. It is shown that algorithms have different tolerance of measurement area and signal loss. In 3 dBm noisy environment and 3 different measurement area (6 square meter, 12 square meter and 24 square meter) algorithm gave following results respectively, Finger Printing algorithm's average errors: 1 meter, 2.04 meter and 4.04 meter. Fuzzy Logic algorithm's average errors 1.19 meter, 2.38 meter and 5.08 meter. Maximum Likelihood algorithm's average errors: 2.26 meter, 4.73 meter and 9.53 meter. Triangulation algorithm's average errors: 2.94 meter, 5.99 meter and 12.12 meter. We observe that both recognize method algorithm gave better results when we compared to lateration method algorithm. Finger printing algorithm gave best accuracy when we compared to other algorithms.

In thesis aim to analysis various indoor positioning methods and comparison between each other. Based on our experiment, we suggest recognize algorithms which are giving better accuracy. Making improvement on these algorithms, it can be obtained better results.

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Curriculum Vitae

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